

Green Energy and Technology

G.N. Tiwari
Lovedeep Sahota



Advanced Solar-Distillation Systems

Basic Principles, Thermal Modeling, and
Its Application

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Basic Principles, Thermal Modeling,
and Its Application

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This book is dedicated to our respected teacher and guru ji, Padmashri Prof. M.S. Sodha, FNA, on his 85th birthday (February 08, 2017).

Preface

Sunlight and Its Utilization

One of the greatest problems facing humankind in the 21st century is the lack of available potable water. The reason behind the origins of this precarious problem is the limited natural water-resources available on the planet earth. The rate of potable-water use is growing drastically with time and has almost quadrupled over the past century. Therefore, it is now necessary to find alternatives to challenge water-related problems to protect the limited natural water-resources remaining on the earth.

In this universe, only the sun is available as one of the most ample and unlimited energy resources. There would be no life on the earth without sunlight. Electromagnetic radiation in the form of sunlight reaches the earth through the atmosphere. Sunlight consists of ultraviolet, visible, and infrared light. Statistically, every year 6×10^9 J/m² of solar radiation is incident on the earth (based on an average of 6 hours of sunlight a day), which is a very large amount. For a 10-m² roof, the amount of energy received is approximately three times more than the energy used in a typical house per day. These are the reasons that solar energy has gained much-attention worldwide. For efficient utilization of solar energy, is essential to understand the basic science of solar energy, including solar radiation and heat transfer.

Objective

The availability of clean potable water is expected to be the biggest problem that humanity will encounter in the next few decades. Therefore, to reduce the gap between the demand and supply of clean potable water using renewable sources of energy, the main focus of our book is on solar-distillation systems. With our teaching and research experience of many years on the subject, we choose to write a

book on solar distillation by incorporating many concepts such as fundamentals of solar radiation, i.e., heat and mass transfer as well as various solar-distillation systems including solar still integrated with photovoltaic thermal (PVT) flat-plate collector (PVT-FPC), evacuated tubular collector (ETC), and PVT–compound parabolic concentrator (PVT-CPC). The feasibility of any system depends on its return in terms of revenue, cost, and energy produced by the system over its entire life. Therefore, to analyze the feasibility of solar-distillation systems, energy and exergy analysis, parametric study of solar-distillation systems, energy matrices, and economic and exergoeconomics analysis of solar-distillation systems must also be extensively elaborated.

The main purpose of writing this book is to provide a suitable text for teaching the subject to engineering and science students as well as a reference book for scientists and professionals. For better understanding of the subject, some solved examples, problems, and objective questions are given at the end of each chapter.

The first chapter (General Introduction) comprises the increasing demand, resources, and availability of potable water. It also describes various types of water pollution and their effects on human health. The historical background of solar distillation and various desalination technologies are vital to understand. Therefore, this chapter emphasizes some simple and some advanced techniques for potable-water production from contaminated or saline water.

Chapter 2 (Solar Radiation and Heat Transfer) summarizes the basics of solar radiation including solar angles and solar radiation on horizontal and inclined surfaces. The section on heat and mass transfer deals with different types of heat- and mass-transfer mechanisms involved in the solar-distillation process. Different kind of thermal efficiencies are also discussed in this chapter.

Chapter 3 (History of Solar-Distillation Systems) presents the history of various types of passive solar-distillation systems. It describes modifications in the design of the solar still in recent times. Different cases of the wick-type solar still and modified designs of the single-slope solar still are discussed. In some advanced solar stills using recent technologies, various effects with the use of phase-changing materials (PCM), vacuum, and nano-fluids is also explained.

Chapter 4 (Solar Collectors) includes different varieties of solar collectors that can be integrated with a solar still to optimize and enhance the performance of passive/conventional solar stills. This is a prerequisite to understand the basics of solar collectors before proceeding further, which is explained in this chapter. Different cases of solar collectors—such as partially covered, fully covered as well as natural and forced mode of operation—are discussed. A glimpse of conventional solar thermal collectors integrated with photovoltaic modules (PV), i.e., photovoltaic thermal (PVT) solar collectors, has been provided in order to understand active solar stills. The effect of reflectors on the performance of the solar still is also briefly described in this chapter.

Chapter 5 (Thermal Modeling of Active Solar-Distillation Systems) summarizes the mathematical modeling of active solar-distillation systems, which basically describes a solar still integrated with photovoltaic thermal (PVT) flat-plate collector (PVT-FPC), evacuated tubular collector (ETC), and PVT–compound parabolic

concentrator (PVT-CPC). To compare the performance of different solar stills, characteristic equations are essential tools; hence, the last section of this chapter is devoted to the characteristic equations of different passive and active solar stills.

Chapter 6 (Parametric Study of Solar Distillation and Its Application) summarizes the effect of different climatic and design parameters (such as water depth, absorptivity of basin, wind velocity, effect of dye, transmissivity of glass cover, insulation thickness, etc.) on the performance of various passive and active solar stills. An insight for optimizing the performance of solar stills by choosing the appropriate values of different parameters is provided in this chapter.

Chapter 7 (Energy and Exergy Analysis of Solar Distillation) is dedicated to the analysis of the energy and exergy of active and passive solar stills. In addition to the energy and exergy analysis of the conventional solar still, it also describes energy and exergy analysis of photovoltaic thermal (PVT) flat-plate collector (PVT-FPC), evacuated tube collector (ETC) and PVT-compound parabolic concentrator (PVT-CPC). The results are discussed in detail.

Chapter 8 (Energy Matrices of Solar-Distillation Systems) presents embodied energies of different types of passive and active solar stills. The corresponding energy matrices, i.e., energy-payback time (EPBT), energy-production factor (EPF), life-cycle conversion efficiency (LCCE) are discussed. This chapter also includes the positive impact on environment from solar stills (a renewable source of energy).

Chapter 9 (Exerconomics of Solar-Distillation Systems) introduces fundamental equations that include the general balance equation, thermodynamic-balance equations, and economic-balance equations. Essential terms—such as “waste energy,” “exergy-loss rates,” “capital cost of equipment,” and “ratio of thermodynamic loss rate-to-capital cost”—are explained. Exergetic analysis of the partially covered photovoltaic thermal flat-plate collector (PVT-FPC) solar-distillation system is discussed as an example, which includes the experimental set-up and thermal modeling of this hybrid system. The results and conclusion has been given in the last section.

The last chapter (Economic Analysis of Solar-Distillation Systems) deals with important terminology regarding the economic viability of solar-distillation systems, essential formulae that include capital-recovery factor (CRF), uniform annual cost (UNACOST), sinking-fund factor (SFF) and benefit-cost ratio. It also contains a discussion of cash-flow diagram and cost comparison. Four crucial methods (single present-value method, Annual Cost Method, capitalized-cost method, and fourth method) of cost comparison for unequal duration are explained in detail.

SI units have been used throughout the book. Appendixes are given at the end of the book.

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With great pleasure we express our gratitude to Professor Brian Norton, Ireland; Professor T. Muneer, UK; Professor Yogi Goswami, USA; Professor T.T. Chow, Hong Kong; Professor Christophe Menezo, France; Professor Wolfram Sparber, Italy; Professor Ibrahim Dincer, Canada; Professor B.K. Bala, Bangladesh; Dr. Alok Srivastava, USA; and our other colleagues in India and abroad.

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The main motive for writing this book was to provide a great insight into the subject of solar desalination particularly aimed at the researchers doing work in this field. We warmly welcome the constructive suggestions and comments, if any, from all readers for further improvement of the book in the next edition. We acknowledge with thanks the authors of different books on this topic, namely, *Solar Distillation Practices for Water Desalination* (Professor G.N. Tiwari and Professor A.K. Tiwari), *Advanced Renewable Energy Systems* (Professor G.N. Tiwari and Dr. R.K. Mishra), and *Handbook of Solar Energy* (Professor G.N. Tiwari, Dr. A. Tiwari, and Dr. Shyam), which helped us in writing this book. We are also thankful to the Department of Science and Technology (DST), India.

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Prof. Dr. G.N. Tiwari born in Ballia (UP), India, received his higher education from Banaras Hindu University (BHU). Since 1977, he has been actively involved in the teaching and research programmes at the Centre of Energy Studies, Indian Institute of Technology Delhi (IIT Delhi), Delhi, India. His research interest is in renewable energy sources including solar energy. He has guided 80 doctoral students and published 600 research papers in international journals of repute. He has authored 22 books published by national and international publishers. He was the co-recipient of the Hariom Ashram Prerit S. S. Bhatnagar Award in 1982 and the Vigyan Ratna Award by the Council of Science & Technology (CST), UP in year 2007. He was also a visiting European Fellow in 1997 and has been to the University of Ulster (U.K.) in 1993. In addition, he was nominated for the International IDEA Award in the past. He is responsible for the development of the Solar Energy Park at IIT Delhi. Dr. Tiwari had visited many countries, namely, Italy, Canada, USA, UK, Australia, Sweden, Germany, Greece, France, etc., for invited talks, to chair international conferences, to serve as an expert in renewable energy, to present research papers, etc. He successfully co-coordinated many research projects funded by the Government of India in the recent past. He is the Associate Editor of *Solar Energy Journal* (SEJ) in the area of solar distillation and editor of the *International Journal of Energy Research* since 2007. He is also the

Chief-Editor of *Fundamental of Renewable Energy Applications* and a reviewer for many international journals. He has organized two international conference—SOLARIS 2007 and SOLARIS 2012—at IIT Delhi, Delhi, and Banaras Hindu University (BHU), Varanasi. He is also the Founder President of the Bag Energy Research Society (www.bers.in), which is responsible for energy education in rural India.



Mr. Lovedeep Sahota was born on November 11, 1988, at Jhinger Kalan, Dasuya, Hoshiarpur (Punjab), India. He received his Bachelor of Science degree, Physics Honors School (B.Sc. Hons.) from Guru Nanak Dev University, Amritsar (Punjab), India, in 2008; and Master of Science (M.Sc.) degree in Physics from the Indian Institute of Technology Delhi (IIT Delhi), Delhi, India, in 2010. During his M.Sc. program, he worked on power coupling of waveguide devices and solved coupled-mode equations by programming in MATLAB to analyze the exchange of power in the planner and tapered directional couplers. His M.Sc. dissertation was titled “Numerical Modeling and Analysis of Waveguide Devices” in fibre optics. He qualified for the State-Level University Entrance Examination in 2005, Joint Admission Test for M.Sc. (IIT JAM) examination in 2008, Graduate Aptitude Test in Engineering (GATE) in 2012, and University Grant Commission-National Eligibility Test (UGC-NET) for Lectureship in June 2014. He worked as an Assistant Professor at the Shivdan Singh Institute of Technology and Management (SSITM), Aligarh, from July 2010 to July 2012 and taught Basic Engineering Physics, Laser, and Electromagnetic Theory at the graduate level. Presently, he is pursuing his doctorate under the supervision of Prof. G.N. Tiwari at the Centre for Energy Studies, Indian Institute of Technology Delhi (IIT Delhi), Delhi, India. He has published eight papers in different reputed journals. He also participated in the international conference (Energy Systems 2016) organized by Elsevier in London (UK). His areas of research interest

are solar distillation (modeling and experimental), solar thermal collectors, photovoltaics, heat and mass transfer, exergy, CO₂ mitigation, and exergoeconomic analyses.

Approximate Values of Some Constants in Solar Energy

S. no	Constants	Actual value	Approximate value
1	Diameter of the Sun	1.39×10^9 m	1.50×10^9 m
2	Distance of the Sun from the Earth	1.5×10^{11} m	150×10^9 m
3	Black-body temperature of the Sun	5777 K	6000 K
4	Centre-core temperature	$8\text{--}40 \times 10^6$ K	$9\text{--}30 \times 10^6$ K
5	Energy generated in the centre core	90%	90%
6	Diameter of the Earth	1300 km	1.5×10^6 m
7	Solar constant	1367 W/m ²	1500 W/m ²
8	Short-wavelength radiation	0.23–2.6 μ m	0.3–3.0 μ m
9	Average temperature of the Earth	298 K	300 K
10	Stefan–Boltzmann constant	5.67×10^{-8} W/m ² K ⁴	60×10^{-9} W/m ² K ⁴
11	Wein’s displacement law (λT)	2897.6 μ m K	3000 μ m K
12	Long-wavelength radiation from the Earth	10 μ m	9 μ m
13	Wavelength radiation from the Earth	0–30 μ m	0–30 μ m
14	Sunshine hour at the equator	12 h	12 h
15	Sunshine hour at the North Pole	24 h	24 h
16	Optimum tilt angle for maximum solar radiation	$\phi \pm 15$	$\phi \pm 15$
17	Convective heat-transfer coefficient for air	$2.8 + 3V$	$3(1 + V)$
18	Sky temperature (T_{sky})	$(T_a - 12) ^\circ\text{C}$	$(T_a - 12) ^\circ\text{C}$
19	Long-wavelength radiation exchange between ambient and sky	60 W/m ²	60 W/m ²
20	Order of radiative heat-transfer coefficient	6 W/m ² K	6 W/m ² K
21	Convective and radiative heat-transfer coefficient for air	$5.7 + 3.8V$ W/m ² K	$3(2 + v)$ W/m ² K

(continued)

(continued)

S. no	Constants	Actual value	Approximate value
22	Order of convective heat-transfer coefficient between a hot plate and the water		90–300 W/m ² K
23	Overall heat-transfer coefficient for a single glazed FPC		6 W/m ² K
24	FPC-efficiency factor (F')		0.9
25	Insulation thickness	0.10 m	0.09 m
26	Fin efficiency (F)		0.9
27	Flow-rate factor		<0.9
28	Transmissivity of window glass		0.9
29	Threshold intensity		>300 W/m ²
30	FPC connected in series		≤ 3
31	Thermal conductivity of insulating material	0.03–0.04 W/m K	0.03 W/m K
32	Maximum temperature in a concentrating collector		3000 °C
33	Ideal efficiency of solar efficiency	60%	60%
34	Optimum depth of a basin water	0.02–0.03 m	0.03 m
35	Effect of the climatic parameter on a solar still's yield		9–12%
36	Emissivity of the surface	0.9	0.9
37	Optimum water depth in a collection-cum-storage water heater	0.10 m	0.09 m
38	Optimum temperature for fermentation of slurry for biogas production	25–27 °C	27 °C
39	Cooking time by a solar cooker	2–3 h	3 h
40	Latent heat of vaporization	2.3×10^6 J/kg	3.0×10^6 J/kg
41	Band gap for silicon	1.16 eV	1.12 eV
42	Boltzmann's constant (k)	1.38×10^{-23} J/K	12×10^{-24} J/K
43	V group–impurity concentration	10^{15} cm ³	10^{15} cm ³
44	Effective density of states in the conduction band	2.82×10^{19} cm ³	28×10^{18} cm ³
45	Saturation current in reverse bias	10^{-8} A	10^{-8} A
46	Thickness of an n-type semiconductor in a solar cell	0.2 µm	0.3 µm
47	Thickness of a p-type semiconductor in a solar cell	0.5 µm	0.6 µm
48	Diffusion-path length	50–100 µm	60–90 µm
49	Junction near an n-type semiconductor in Si	0.15 µm	0.15 µm
50	Solar intensity in the terrestrial region		≈900 W/m ²

(continued)

(continued)

S. no	Constants	Actual value	Approximate value
51	Efficiency of a solar cell under standard conditions	15%	15%
52	Efficiency of a PV module with an Si- solar cell	12%	12%
53	Standard test condition	1000 W/m ² , 25 °C	900 W/m ² , 24 °C
54	Specific heat of water	4190 J/kg K	4200 J/kg K
55	Specific heat of air	1000 J/kg K	1000 J/kg K
56	Density of air	1.2 kg/m ³	1.2 kg/m ³
57	Absorptivity of a bare surface		≈0.3
58	Absorptivity of a blackened surface		>0.9
59	Heating value of coal	29,000 kJ/kg	30,000 kJ/kg
60	Heating value of biogas	20,000 kJ/kg	21,000 kJ/kg
61	Heating value of wood/straw	15,000 kJ/kg	15,000 kJ/kg
62	Heating value of gasoline/kerosene	42,000 kJ/kg	42,000 kJ/kg
63	Heating value of methane	50,000 kJ/kg	51,000 kJ/kg
64	Energy contained in the infrared region	51.02%	51%
65	Energy contained in the visible region	36.76%	36%
66	Energy contained in the ultraviolet (UV) region	12.22%	12%

Chapter 1

General Introduction

1.1 Background and Importance of Potable Water

The following are the main human birthrights:

- (a) Clean air
- (b) Clean potable water or drinking water
- (c) Clean (healthy) food
- (d) Clean energy

After air, water is the second basic need of all of the living organisms on the planet Earth. The availability of water in our body is two-third of the total body weight. If we do drink, we would stay alive only for a few days. The percentage of water in the human brain is 95%, and that of water in our lungs and blood is 90% and 82%, respectively. A deficiency of just 2% in our body's water supply can start an indication of dehydration. Water plays a very crucial role in the functioning of various parts of human body such that it helps in proper blood circulation, digestion, balancing body temperature, growing tissues, transporting nutrients, and the process of waste removal. People can continue to live for a longer period of time without food; however, they cannot survive for a few days without water. Underground water tables (i.e., groundwater) contain approximately 50% of our water, and another 50% of the water on Earth is available from surface water (rivers, lakes, and reservoirs). Apart for this, water can be available in different forms such that it can be hard or soft, packed or supply water (tap), natural or unnatural, or distilled (sill) or carbonated.

In backward or poor countries, the use of potable water for agriculture is 89%; for industry it is 9%; and for households it is just 2%. However, in advanced countries, agriculture uses 30% potable water, industry 59%, and households just 11%. In some backward as well as advanced countries, the production of potable water is a serious issue.

A person is dependent on natural resources of potable water available on Earth such as rivers, lakes, and underground water reservoirs. However, the demand for potable or clean water is increasing more rapidly; and its availability is becoming insufficient with time; this situation has created water crises in many regions worldwide. This serious problem is primarily due to the unequal sharing of available water resources, rapid growth in population, and water pollution due to industrial progress in the recent past. It has been observed that there will be decrease in the availability of potable water almost to half for many countries by the year 2025 worldwide. The condition would be more frightening in some countries like Tanzania. By 2025, projections indicate that Tanzania will experience water stress (defined as average per capita water resources below 1500 m³) due to population growth and the resulting increase in consumption.

The accessibility of potable water on the Earth is only 2.5–2.75%; the rest of the available water is saline water. Globally, saline water availability is 97% of the total available water including oceans, seas and underground water. Potable water is available in different forms such that 1.75–2% exists in a frozen state (glaciers, ice, and snow); 0.7–0.8% is available as potable groundwater and soil moisture; and the remaining 0.01% is available as surface water (lakes, swamps. and rivers). Figure 1.1 shows potable-water accessibility on planet Earth.

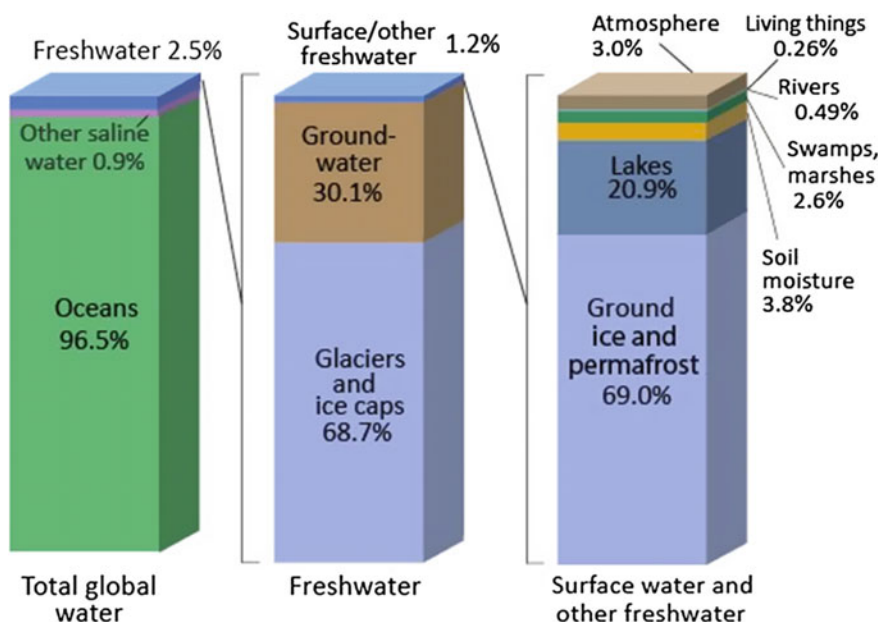


Fig. 1.1 Present scenario of world water availability (source <https://www.en.wikipedia.org>)

Table 1.1 WHO criterions for physical and chemical quality of water

WHO test standards	Permissive	Excessive
Physical turbidity (NTU ^a)	5	25
Appearance		<i>Clear</i>
Chemical odor	Unobjectionable	Unobjectionable
pH	7–8.5	6.5–9.2
Total solids (ppm)	500	1500
Hardness (ppm)	300	600
Chloride (ppm)	200	400
Nitrate (ppm)	20	50
Iron (ppm)	0.3	1
Alkalinity	–	–

^aNephelometric turbidity unit

1.2 Potable-Water Quality

As mentioned in Sect. 1.1, the human body requires a good quality of water for drinking. The quality generally depends on the purpose of use of available water. The water supply for drinking should be free from bacteria, pathogenic organisms, and minerals that would otherwise create physiological effects and cause infections such as bacterial, viral, protozoal infections in the human body. The chemical configuration of accessible water in the world varies from region to region on a wide scale, so it is very difficult to set fixed standards according to their circumstances and conditions [1, 2]. The World Health Organization (WHO) has fixed certain criterions for the physical and chemical quality of water by considering the overall scenario, which is presented in Table 1.1.

1.3 Increasing Demand for Potable Water

A large portion of the Earth is dry, and approximately 80–85% of the total population survives in arid or semiarid parts of the Earth. Following are some significant facts that indicate the increasing demand for potable water on the Earth [3–5]:

- (a) Access to potable water and adequate sanitation are necessary requirements in daily life; however, 785 million populations worldwide do not have access to potable water, and approximately 2.5 billion populations worldwide do not have access to satisfactory sanitation.
- (b) Every year almost 6–8 million people die due to the effects of disasters and water-related health problems in the world.

- (c) During the next 50 years, world population growth will increase to almost 2–3 billion. With the projection of changing diets, this will result in an estimated upswing of food demand of 70% by the year 2050.
- (d) According to the World Health Organization (WHO)/United Nations Children’s Fund (UNICEF) (2010), the urban population is growing drastically every day, and half of the population survives in urban areas on the Earth. Urban areas, although better organized than rural areas, face complications because of the drastic growth rate of the population.
- (e) Both food and energy demand hydropower, and other renewable energy resources are linked together and grow in a directly proportional rate. The increase in agricultural output will substantially increase both water and energy consumption. As explained in previous points, with the probable increase in world population, the demand for food will increase 70% by the 2050.
- (f) In the future, world water consumption in agriculture will increase by almost 20% by 2050. This estimated figure (20%) can grow continuously if there is not be any progress in the technology sector of potable-water production.
- (g) The irrigation and food-production sectors are heavily dependent on potable-water resources. Only the agricultural sector independently consumes approximately 70–75% potable water globally, and even in some fast-developing countries this figure increases up to approximately 90%.
- (h) Almost >40% people in sub-Saharan Africa live in water-scarce areas, and 65% of Africa is either dry or semi-dry.

1.4 Scarcity of Potable Water

Water scarcity arises within a region if there is a gap of availability of water resources to fulfill the demand or requirements of water consumers. Scarcity of potable water is not a problem of one or two nations; it affects every country in the world, and billions of people globally do not have access to clean drinking water.

There are three main concerns that originate or develop water scarcity: water shortages, water crisis, and water stress. Providing potable water is a stressful task as is the difficulty of searching out new sources of potable water targeting to be used for some duration. Therefore, this stress may result in decreasing available water resources on the Earth.

Many areas in the world are affected with water shortages. In general, this problem basically originates due to changes in climate conditions, increased population, floods, excess use of potable water day by day, and simply poor management (i.e., uneven distribution) [1, 4–7]. Figure 1.2 depicts an overview of water crisis. The scenario of water crisis arises if available potable water resources does not fulfill or match the required demands of the population within a certain region.



Fig. 1.2 Hazard view of water crisis (source <https://www.davismamorial.org>)

As discussed earlier, water scarcity originates due to rapid growth of the population using potable water, which results in a decrement of available water resources. The origin of water scarcity is due to two mechanisms:

- (a) Physical water scarcity
- (b) Economic water scarcity

Physical water scarcity is a consequence of insufficient availability of natural potable-water resources to satisfy the demands of particular regions. Another reason for water scarcity is a lack of good policies and tactics, as well as poor supervision, of available water resources. According to the United Nations Development Program (UNDP), many nations in the world have enough water resources to fulfill the demands of their people, however, due to poor management and a lack of proper policies, the supply of potable water falls short of the demand for it. Various governments of both wealthy as well as poor economic nations set goals to decrease the effects of water scarcity globally.

1.4.1 Global Potable-Water Crisis

As explained earlier, when there is gap between the supply of potable water and its demand to fulfill or match the requirements of a population, then the situation is considered a water crisis. The United Nations (UN) and other world organizations

have declared many nations under the threat of water crisis, and this problem is growing at a very fast pace and has become a global concern. The main factors responsible for water crisis are as follows:

(i) climate change (ii) deforestation (iii) limits to water supply, and (iv) pollution and population size.

Some surprising facts about water crisis that are changing the scenario to an even worse one every day include the following [3, 5, 6]:

- (a) The rate of potable water use in the world is growing rapidly has almost quadruple during the past 90 to 100 years.
- (b) Due to an increase in the world population, today approximately 1.5 billion people face the problem of water shortages as well as water stress. According to the United Nations (UN), it has been estimated that the water-stress condition will grow drastically in the future, and two-thirds of the world will suffer through the risk of water stress by the year 2025.
- (c) The excessive withdrawal of groundwater affects agricultural yields as well as decreases the levels of underground water daily.
- (d) Biodiversity can be also affected heavily by the overuse of available water as well as water pollution.
- (e) According to the United Nations (UN), the requirement for potable water will increase almost 25% by the year 2025.
- (f) Polluted water has many hazardous affects on the human body. For example, it has been observed that the natural growth of children in Africa and India is harmed due to polluted water and malnutrition.

Figure 1.3a, b show the worldwide water scarcity in 2007 and 2025, respectively.

1.5 Global Water Pollution

Agricultural, sewage, and industrial wastes are transferred into natural-water resources worldwide every day. In terms of figures, this waste quantity represents 2–2.5 million tons of waste discharged into the natural water resources. According to the United Nations (UN), approximately 1500 km³ of wastewater is generated from the agricultural, sewage, and industrial sectors every day.

In general, water pollution can be defined as mixture of more than one or two substances into water such that it affects health of the users (humans, animals) whose lives depend on it.

According to WHO reports, every day approximately 30,000 deaths can be attributed to serious water-related problems. Even in advance and growing nations, 75–80% causes of illness are due to water [8]. In poor economic nations or underdeveloped nations, 25% children younger than age 4 or 5 die. The reason for

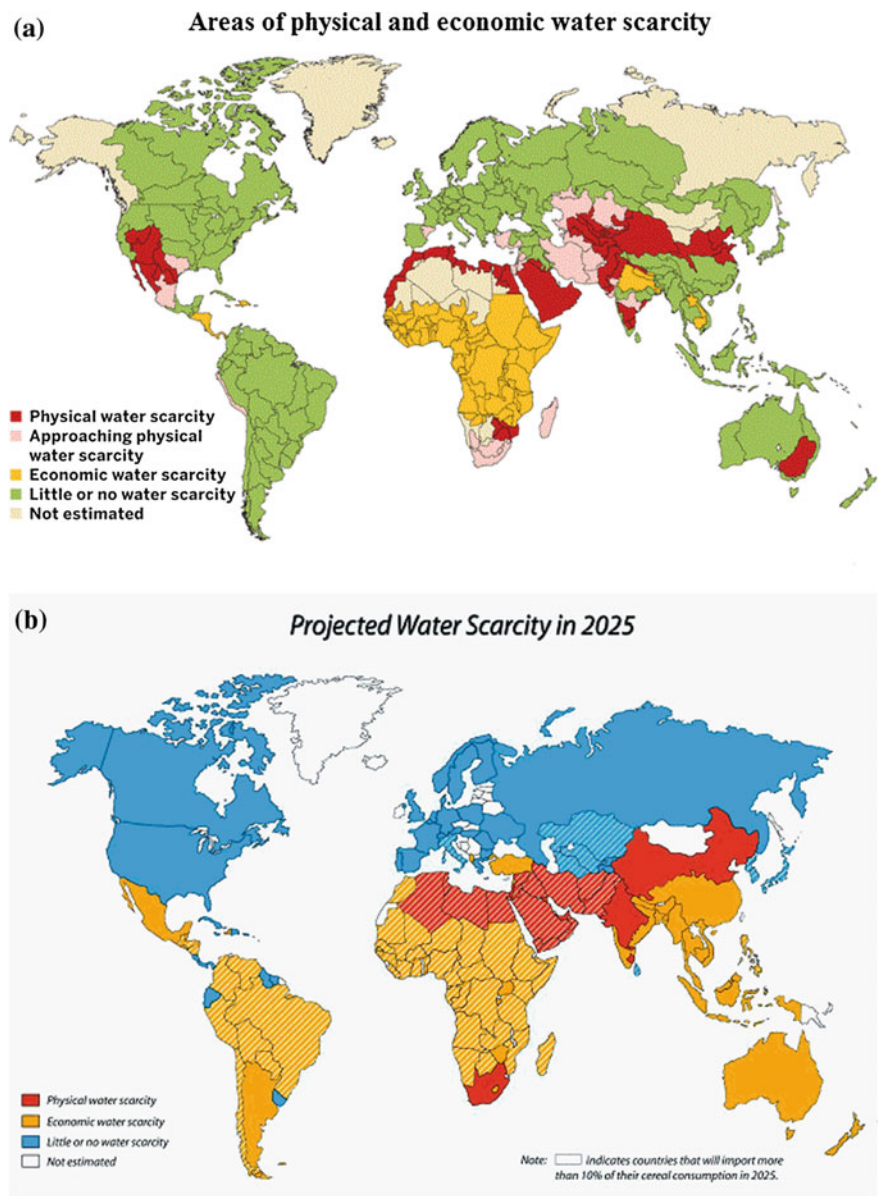


Fig. 1.3 **a** Global water scarcity in 2007 (source comprehensive assessment of water management in agriculture). **b** Global water scarcity in 2025 (source <https://www.fewresources.org>)

these deaths is basically the harmful affects of local water on health resulting in water-related diseases such as bacterial infections, viral infections, protozoal infections, etc., as discussed previously.

We can understand the definition of water pollution in a better way with this simple example: If you release a jug of any dark-color liquid (i.e., black ink) into a river having a huge volume of potable water, you would observe that the dark-color liquid quickly disappears. You would not be able to see it in the river due to very low concentration of discharged dark-color liquid in relation to the huge volume of river water into which it was poured. However, if you release huge amount of the same dark-color liquid, in liters per second then after some time the clean or potable water of the river will become dark. Let us look at this simple example with another aspect such that if the water poured into the river is a mixture of some chemicals or wastes (dark color liquid in a previous example), it will affect the health of the consumers, i.e., the animals, humans, and plants whose lives depend on this river. Thus, the pollution of water critically depends on the quantity and type of substances that are conveyed into the water as well as the volume of the water into which these substances are released. If we spilled some amount of toxic chemicals into the ocean from the ship, it may have a little impact. But, its effect is greater if the same amount of toxic chemicals are released into a lake or river, where the concentration of clean or potable water is too low for the chemicals to be dispersed or to compensate the affects of the hazardous chemicals.

Following are the main types of water pollution:

I. Surface-water pollution

Natural water resources, such as oceans, lakes, rivers etc., available on the Earth are surface waters. Geographically, these natural-water resources are present on the exterior of the Earth's crust. Surface water is affected very commonly every day in different ways, e.g., through industries, agriculture, households, or city wastes, etc. Surface-water pollution of the river and ocean is shown in Fig. 1.4.

II. Groundwater pollution

Water is available in different forms and in many regions. Huge amounts of water are accessible in some portions of underground structures of the Earth known as aquifers, and the water stored in the aquifers (under the Earth) is called "underground water." Groundwater is also polluted very ordinarily, such as surface water, with each passing day. Mostly it is polluted with industrial dump (especially with man-made products, e.g., gasoline oils, chemicals, road salts, etc.), household dump, and agricultural waste as shown in Fig. 1.5.

Waste or used products and materials—such as pesticides and fertilizers, road salt, toxic substances, and household or city dump—can easily be transported from soil to the underground water; hence, it becomes contaminated over time. In addition, used motor oil in garages or oil on industry sites, waste from septic tanks, and dumped toxic chemicals also may get into underground water to contaminate it.

Aquifers play a very important role to feed our rivers and fulfill our needs for drinking water. Today, groundwater pollution, such as surface-water pollution due to hasty growth of the population and industries all over the world, is also a major problem. Particularly, underground water at low levels is polluted due to the heavy



Fig. 1.4 (Surface) water pollution of the river (*above*) and the ocean (*below*) (source <https://www.onliner.gr>)

use of chemical fertilizers for greater agricultural production (only 10% is used whereas 90% gets into the underground water).



Fig. 1.5 Transformation of waste leakage into groundwater

III. Point-source and non-point source pollution

Natural-water resources (surface water and groundwater) are under the constant threat of pollution. There are two another ways water pollution can occur: (a) single and multiple or simply point-source pollution (PSP) and (b) non-point-source pollution (NPSP).

A point source is a solitary, distinguishable source of pollution by way of a pipe or a trench (drain). Common examples of point-source pollution are a discharge of industrial waste into rivers and oceans, an oil slick from a tanker, a release of smoke from a factory chimney, and the release of oil from vehicles. In general, pollution is said to be point-source pollution if it originates from a single position or location such as direct drainage from industries or factories through pipes to rivers and oceans [9].

In contrast, there are many different ways, in which originates non-point source pollution (NPSP). In general, it is combined pollution coming from many diffuse sources. Rainfall and snowmelt plays a vital role to disperse pollution through non-point sources. For example, as runoff flows, it carries away all of the wastes (dumped in an improper manner) that come in through the surface root and transfers all of these into lakes, rivers, and seas. Thus, both single point sources (SPS) and non-point sources (scattered sources) mutually contribute to water pollution worldwide [1, 9]. Figure 1.6 shows examples of both point-source pollution and non-point source pollution.

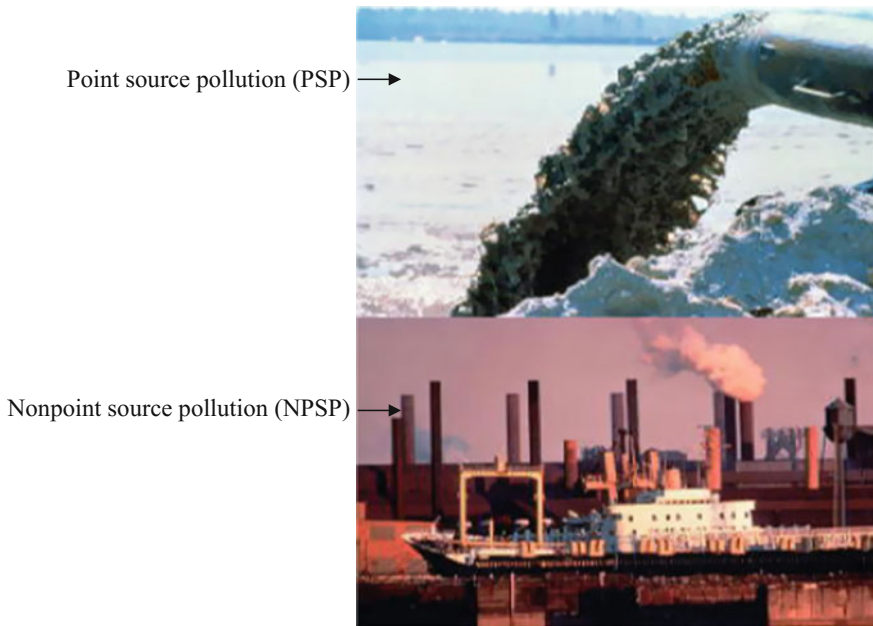


Fig. 1.6 Point source pollution and Nonpoint source pollution sources (*source* US Fish & Wildlife Service Photo Library)

1.6 Causes of Water Pollution and Its Effects on Human Health

Following are discussed the main causes of water pollution that have hazardous effects on living organisms on Earth.

I. Thermal pollution

The physical property of water is affected due to thermal pollution. Rivers and seas support aquatic life, however, by increasing their temperature, the quantity of oxygen in the water becomes decreased, which also decreases the levels of aquatic life [9]. Rivers and oceans are also affected due to heat or thermal pollutions originating from factories and other renewable-energy resources (e.g., power plants). Water is normally used in thermal-power plants as well as by industrial manufacturers as a cooling agent, and after use its physical properties are altered, which causes thermal pollution. In addition, if very cold water is released from the base of a reservoir into hot rivers, the level of thermal pollution increases.

II. Nutrients

Nutrient pollution is an excessive availability of nutrients in water, and it is a basic reason for the eutrophication of surface water. The excessive presence of

nutrients, such as phosphorous and nitrogen, usually triggers the formation of algae and its growth. Algae or plankton is very harmful because it decreases the oxygen quantity in water and affects the lives of the users (humans and animals) that depend on these sources of water directly or indirectly. This is known as a “dead zone.” The Gulf of Mexico is a large example of a dead zone. In every season, the growth of the dead-zone area is almost 18,000 km², which is approximately equal to the area of the state of New Jersey [9].

Today, with the growth of technology in agriculture, farmers use chemical fertilizers to add nutrients to the soil to enhance production from the fields. These all-chemical fertilizer trenches drain into rivers and oceans, which further triggers the consequence of fertilizer and sewage waste. The combined effect of sewage and fertilizers can initiate an excessive upturn in the growth of algae or plankton, and this covers a huge area of rivers and seas. This is known as a “red tide” (RT) because the formation of excessive algae or plankton changes clean water to a red color.

In addition, other sources of nutrient pollution exist, e.g., runoff from agricultural areas, land used for grazing, discharges from septic tanks (a component of small-scale sewage-disposal systems, intensive animal farming (feedlot), and emissions from combustion, etc. [9, 10].

III. Sewage

Dumping of sewage waste is one of the most serious concerns in the world. According to the WHO, following are some facts that originate from sewage waste [9]:

- (a) Forty percent of the population worldwide does not have proper sanitation facilities such as the lack of availability of hygienic toilets; still, the progress rate in lowering this percentage is very slow.
- (b) Almost 16% (approximately 1.6 billion) of the world population does not have safe drinking water.
- (c) As discussed in Sect. 1.5, according to the United Nations (UN), in poor economic or underdeveloped countries, 25% children younger than 4 or 5 years die. The reasons for these deaths are basically the harmful affects of water on health and the development of water-related diseases such as bacterial infections, viral infections, protozoal infections, etc. According to the WHO, it projected that 150 million populations could die due to waterborne diseases by the year 2025.
- (d) Bacterial infections and other water-related viruses are easily travel from one place to other in the environment. Especially, this occurs when people flush chemical and pharmaceutical materials thorough their toilets, which triggers problems through the resultant sewage. This is very common in developed countries. When people fall ill, these harmful viruses and bacterial infections are easily transferred in the environment and pose risks to human health. Every year almost 6–8 million people worldwide die due to effects of disasters and water-related health problems.

If we look at the production of sewage wastes in developed countries, the results are really very surprising and pose alarming threats to the world. In one of the most developed nations—the United States—a large quantity of sewage (approximately 4–5 million tons) was continuously dumped from New York state every year until the early 1990s. The British population generates huge amounts of sewage, approximately 1150 million liters annually, and some part of it still being dumped in an inappropriate way through long pipes into rivers and oceans. The New River, which crosses the border of Mexico and California, carries with it 75–100 million liters of raw sewage daily. Moreover, in many other developed and high-income nations, the repetitive dumping of sewage into oceans continues to occur. In early 2012, the small island of Guernsey, situated between Britain and France, has been used continuously for dumping approximately 15,000 tons of raw sewage into the sea daily. In short, 90% of sewage is water, and it carries all types of other chemicals such as pharmaceutical drugs, plastic, and other materials that are flushed down toilets by the human population [1, 9, 11]. As discussed previously, when people fall ill with viruses and infections, the sewage works as a transporting agent and conveys those viruses into the environment. These harmful viruses further cause health related problems such as hepatitis, typhoid, and cholera, etc.

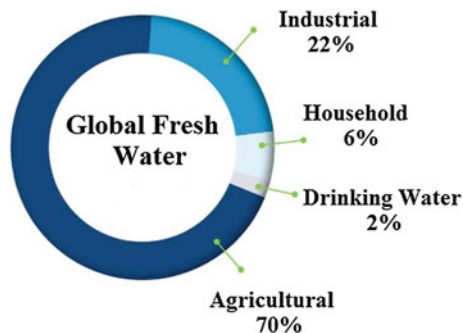
IV. Wastewater

Wastewater is fully contaminated water (containing wastes) that has been released after use, and it is discharged every day by various sectors. Basically it originates from human waste, septic-tank discharge, water used for washing (personal, clothes, floors, dishes, etc.), rain water collected on different sites (roofs, yards, hard-standings) for a longer period of time, etc. In addition, groundwater infiltrated into sewage, highway drainage, surface water polluted with sewage, agriculture and factory-site site drainage, and industrial, toxic, and oil waste, etc., are also responsible for the production of wastewater [3, 9].

Sewage and wastewater are responsible for the pollution of oceans every year. In general, approximately 50% of all ocean pollution is due to sewage and wastewater. In high-income nations, industrial and agricultural waste is dumped in inappropriate way in oceans and rivers annually, which pollutes available water resources worldwide. The quantity of this dumped waste is an approximately 70–75% of all water. Statistically, it has been observed that each litre of contaminated or wastewater pollutes at least 7–9 L of potable water available on the Earth. This means approximately 1300 km³ of the world's water resources are polluted every year and thus are unusable. It is very well understood from this figure that if the rate of polluting water increases at this pace, in parallel with the fast population growth rate, by the year 2050 the water resources available on the Earth would be decreased by some 15–20,000 km³ annually.

Every year, 300–400 billion tons of an industrial waste are generated globally, and for the most part this waste is dumped directly into rivers, oceans, seas, waterways, etc., in inappropriate ways. In the United States, which is one of the most-developed countries in the world, approximately 45,000 factories withdraw

Fig. 1.7 Global fresh water use in industry, household, agriculture, and for drinking (source <https://www.dynamixinc.com>)



water from rivers and oceans. After use, they transfer the polluted water back into the rivers and oceans. However, in recent times many nations have taken the problem of wastewater very seriously, and major improvements are being enacted in the forms of different types of wastewater treatment. For example, the Environmental Protection Agency (USEPA) has spent \$75 billion for improving wastewater-treatment plants; at present, these plants provide service to only 80–85% of the US population [1, 3, 9].

Figure 1.7 shows 92% of global water use for agricultural and industrial purpose, whereas household use accounts for the remaining 8%. In the next 20–30 years, industry will require greater amounts of potable water. Approximately 50% of the Earth's population will live in regions of high water stress by the year 2030.

Factories are in the category of point-source pollution of water, however, through non-point sources much water is also polluted by humans during the course of day-to-day living; in this way, regular useful water turns into wastewater in the first place. Indirectly, everybody releases chemicals through their drains or toilets. As discussed previously in Sect. 1.5, non-point source pollution includes a combination of pollutants from different sources. It contains a mixture of toxic chemicals, salts, agricultural waste from fields, waste materials (i.e., metal, oil, etc.) from factory sites, and pharmaceutical wastes from medical-industry sites [3, 9]. All of these are converted into wastewater through highway runoff during rain or snow melt. If the concentration of this type of waste is very high and is transferred into rivers or oceans, it may kill a huge quantity of fish overnight. In general, it has been observed that some of the wastewater transferred to oceans and rivers from highway runoff during heavy rains and storms can pollute groundwater.

V. Radioactive waste

Radioactive waste or nuclear waste contains radionuclide materials that are no longer useful. From a physics point of view, radionuclides, which are unstable atoms of an element, emit energy in the form of radiation when it decays or disintegrates spontaneously. Radioactivity was discovered by Antoine Henri Becquerel in 1896. Radioactive waste can exist in different forms and vary in wide range such that it can be in solid, liquid, or gaseous form or even something in between.

A physical form of radioactive waste can be basically water, plastic, metal, ash, soil, paper, glass, ceramic, or a combination of other physical forms. Similarly, the chemical form of radioactive waste can be available in different forms. There are so many radioactive elements available in the periodic table. As we know, radioactive waste contains radionuclide (composed of unstable atoms) elements, and these elements can either be heavier or lighter depending on their atomic number and weight [9, 12]. This implies that radioactive wastes may contain radionuclides of heavy as well as light elements. For example, radioactive waste that contains hydrogen radionuclides falls under the category of light elements; in contrast, uranium lies in the category of very heavy elements. On the basis of the radionuclide content available in radioactive waste, it is distinguished in three different levels: high, intermediate, and low. The life of the radioactive waste can be seconds, minutes, or 1 million of years.

If the concentration of radioactive waste is high enough, it can kill, and even in low concentrations it is very harmful for health such that it can trigger problems like cancer and other illnesses. Two factories in Europe are the main sources of radioactive pollution on the Earth, and these factories reprocess waste fuel from nuclear power plants. They release radioactive waste into the sea. Many nations and governments are making efforts to ban nuclear wastes worldwide.

VI. Organic water pollutants

Following are the main organic-waste pollutants:

- (a) Detergents and chemical compounds used in personal cosmetic products.
- (b) Some byproducts, such as chloroform, are used to clean raw water from rivers to make it suitable for drinking.
- (c) Oxygen-demanding substances, such as grease and fat, are normally available in food-processing waste.
- (d) Fuel-combustion byproducts and some hydrocarbons normally include gasoline, diesel fuel, jet fuels, and lubricants (motor oil).
- (e) Volatile compounds, such as industrial solvents, result from improper and untreated storage.
- (f) There is also drug pollution or pharmaceutical waste.

VII. Inorganic water pollutants

Following are the main inorganic-waste pollutants:

- (a) Chemicals, such as sulfur dioxide, from power plants and industry drainages generate acidic effects.
- (b) Ammonia and chemical waste, respectively, from food-processing waste and industrial byproducts.
- (c) Fertilizers are excessively used by farmers for better growth on fields, and these are also used commercially and residentially. These fertilizers contain nutrients, such as nitrates and phosphates, which are found in rain water runoff from agricultural fields and transferred to rivers and oceans.

- (d) A huge amount metal waste is produced on motor vehicle-industry sites as well as acid-mine drainage.

Human-health effects

Water pollution is one of the greatest threats for humanity to secure natural potable-water resources worldwide. Currently water pollution is very serious issue worldwide, and it is growing very rapidly each day. If potable-water resources become polluted at this pace, then it will ultimately affect the lives of all creatures on the Earth. All types of pollutants have various harmful effects on the health of humans and animals as discussed previously. Table 1.2 lists various health impacts of water-borne diseases. Following are some important facts [1, 5–7, 13]:

- (a) As discussed previously, most of the children under the age of 4–5 years living in poor-economic countries worldwide die due to waterborne infectious diseases. It is unsettling that the annual number of deaths due to the consumption of polluted drinking water are greater than that due to violence (including war).
- (b) Water-related disease affects the health of children early on. According to the WHO, 60% of them die just due to a lack of potable-water supply worldwide. Low-income or underdeveloped nations still find it difficult to provide potable water for their population due to insufficient available water resources. In some areas of the world, such as Africa, China, and India, many people are struggling to obtain a potable-water supply for drinking, and many of them are suffering with water-related diseases.
- (c) Polluted water sometimes contains microbiological organisms such that pathogens, eggs of insects, and other waterborne diseases infect humans leading to fever, diarrhea, and even death.
- (d) Three % of the world's population because of a polluted water supply for drinking, improper sanitation, and water-related diseases.
- (e) Due to a polluted or inappropriate water supply, approximately 5 billion cases of diarrhea, 2 million cases of deaths (mostly children younger than 5 years old) are registered annually. The main reason every year for the death of 15–20% children is diarrhea: One child dies every 15 s and in India alone, approximately 50% of the total population of children die due to diarrhea annually.
- (f) In addition, water pollution has harmful affects on the health of animals, such as fish, which cannot survive without water. In many regions of the world, people depend on seafood (such as fish). If a human consumes infected seafood, the diseases or infections are transferred easily and can create more serious health-related problems for consumers.

Table 1.2 Shows some water born disease and their reasons

Cause (infections)	Water borne disease
Bacterial infection	Typhoid, Cholera, Paratyphoid fever, Bacillary dysentery
Viral infections	Infectious hepatitis (Jaundice), Poliomyelitis
Protozoal infections	Amoebic dysentery

- (g) Many people use polluted water for cleaning purposes, however, it is useless because it does not remove accumulated germs and bacteria: It does not yield any advantage. Therefore, it can cause diseases and hence affect human health.
- (h) Water pollution and waterborne diseases affect mostly poor people because they do not have access to or have a supply of potable water, whereas middle- and upper-class populations (i.e., those living above the poverty line with respect to the economy) can afford potable water. In contrast, lower-class population (i.e., those living below the poverty line with respect to the economy) or slums dwellers, for example, face the critical difficulty of securing potable drinking water. Approximately 40–45% of the population in India do not have availability of good-quality drinking water.

Different organizations and the governments of various nations are making efforts and moving ahead to secure available water resources on the Earth to fulfill the demands of their populations for potable or drinking water. Practically, though, it is important to remember that our natural-water resources in this planet are limited. Thus, if the pollution or wastage of grows continuously, humanity will be living at the edge of disease and death.

1.7 Desalination and Its Necessity

As discussed in previous sections regarding serious potable water–related problems, it is important to cooperate in meeting the world’s growing demand for potable water. Basically, it is essential to generate water that should be free from parasitical organisms, bacteria, viruses, soil, chemicals, and other physical contaminants. However, safe drinking water from available water should be produced using those technologies with minimum economic resources, ecological disturbance, and sustainable practices.

1.7.1 Saline Water

First and foremost, it is important to understand the authentic meaning of “saline water.” Saline water implies that it is contaminated with a sufficient amount (referred to as “concentration”) of dissolved salts. Here, the concentration is an extent (by weight) of salt in water conveyed in “parts per million” (ppm); this is the mass of a chemical or contaminate per unit volume of water (1 ppm = 1 mg/l). For example, if the concentration of water is 5000 ppm dissolved salts, then the weight of the water that comes from dissolved salts is 0.5%.

A geological survey of the United States divides saline water into three salinity classes. As listed in Table 1.3, the salt concentration in low-saline water is in the range of 500–1500 ppm; the concentration in moderate- or medium-saline water is

Table 1.3 Classes of water salinity as per dissolved salt concentration (ppm or mg/l)

Water class	Salt concentration (mg/l or ppm)	Type of water	
Non-saline	<500	Fresh water or irrigation water	
Slightly saline	500–1500	Irrigation water	Brackish water
Moderately saline	1500–7000	Primary drainage water and groundwater	
Highly saline	7000–15,000	Secondary drainage water and groundwater	
Very highly saline	15,000–35,000	Very saline groundwater	
Brine	>45000	Sea water	

in the range of 1500–7000 ppm; and the concentration of in high-saline water is in the range of 7000–15,000 ppm. The salinity of seawater falls under the class of very high concentration, approximately 45,000 ppm, which is equivalent to 45 g salt/1 L (or kg) of water [14, 15]. Here, “saline water” is used as a common term to express brackish water as well as seawater.

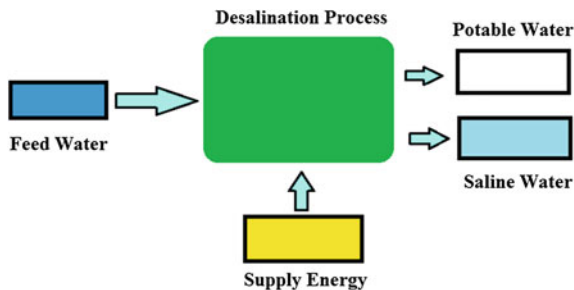
Thermal conductivity is inversely proportional to the degree of salinity or salt concentration (ppm or mg/l), and it increases with increase in temperature. The salt concentration is measured with an instrument called a “salinometer.”

1.7.2 Desalination

“Desalination” refers to the technique or processes of removing some concentration of salts and other minerals available in contaminated saline water. Usually, our need to desalinate saline water is to fulfill the demands of the population for potable water supply as explained previously. Thus, desalination technique is used to produce potable water of good quality for humans and for other purposes. Desalination is not a recent technique; it has been used for many years to meet the demand of living organisms on the Earth for safe drinking water. Even today, this process or technique is being used in many world nations for the treatment of saline or polluted water to produce potable water. This technique was used in ancient times on ships and boats for the treatment of seawater to make it suitable for drinking. Water pollution is growing at a fast pace over time, which forces many nations to use desalination technique worldwide. In general, desalination technology is one of the water-purification methods that almost completely removes contaminants from polluted or seawater and makes it safe and useful for humans.

Desalination process is a natural copy of the hydrological cycle (or water cycle). In the hydrological cycle, evaporation takes place from the surfaces of natural-water resources such as rivers, seas, oceans, waterways, and streams with the absorption of solar energy. In the next step, cooler air comes in contact with these water vapors

Fig. 1.8 Simple desalination process



and re-condensation takes place, which causes rain or forms dew. With including cooling and heating sources, this cycle can be produced artificially and faster than it occurs in nature. It is clearly understood that the amount of salt concentration extracted from the seawater increases with an increase in the supply of energy used for extraction.

Figure 1.8 shows that saline water (or feed water) is poured into the desalination system; after undergoing the process of desalination, potable water is taken out through one stream, whereas the wastewater or polluted water with a high content of salts flows through the other stream. Appropriate control of the appropriate disposal of wastewater is a significant issue regarding environmental health. The size and method of the distillation process is based on the following factors [14, 15]:

- (a) the availability of the water-source type such that there is a presence of concentration of salts or pollutants;
- (b) the requirement of potable water; and
- (c) the type of energy available on-site to run the desalination system.

The requirement for or the efficient use of an energy supply is a direct function of the following:

- (a) the dimensions of the desalination system; and
- (b) The amount of salt content (ppm or mg/l) available in the seawater.

An effective principle behind the process of desalination is that when water vapor condenses, it gives back the heat used to vaporize it. Several desalination technologies capture a portion of this heat and re-use it.

Unless water from available saline water is made potable, the battle against the scarcity of water will be lost. For many years, desalination industries have been focusing on decreasing the energy requirements for desalination. In recent times, the consumption of energy has been decreased almost by 50%, and it can be decreased further in future. The International Desalination Association (IDA) projected a task of global-energy decrease. IDA has set a goal for industry sectors in all nations to decrease the energy needed for desalination by 20% by the year 2025. Today, many technologies have been developed for cleaning polluted or saline water. These technologies are divided into the following three categories:

- (a) **High technologies:** These technologies require huge amount of energy as input and these are most successful either in cities or other central facilities.
- (b) **Medium technologies:** These technologies are normally used to adjust downward the cluster level (a group of similar contents available in water) in schools, community centers, apartment buildings, and villages.
- (c) **Low Technologies:** This includes one of the simplest techniques to obtain potable water, and it is commonly used for low-economic populations such as average developed villages, backward villages, slum dwellers, as well as in individual homes or during emergencies.

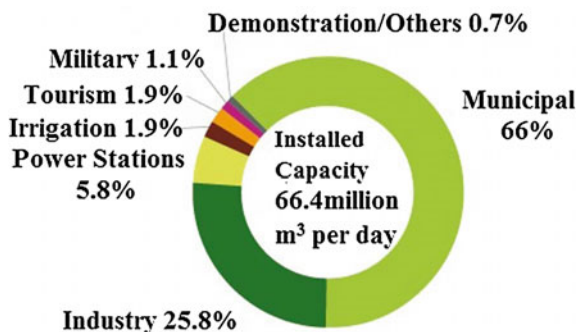
The main motive behind every desalination technology (either low, medium, or high) is to remove contaminants and other impurities in polluted water such that its quality is improved as much as possible so that it can be used for drinking purposes.

1.7.3 Some Global-Desalination Facts [5, 7, 16]

These global-desalination facts are as follows:

- (a) Approximately 30% of water-supply areas are affected by salinity-related problems worldwide, and of the solution to this problem appears to be very costly.
- (b) The overall capacity of producing necessary potable water exceeds 66.4 million m^3/day , which includes industry (25.8%), (municipal 63%), power stations (5.8%), irrigation (1.95%), tourism (1.9%), military (1.1%), and other (0.7% as shown in Fig. 1.9. Approximately 16 years ago in 2001, approximately 13,000 desalination plants were available in more the 100 nations worldwide. The production capacity (of potable water) of these plants was approximately 14 million m^3/day , which is <1% of the overall worldwide consumption of water.
- (c) Desalination of water is a helpful and simple technique for low-income populations. Statistically, many nations in the Middle East—such as Saudi Arabia,

Fig. 1.9 Total worldwide installed capacity by feed water (source <https://www.watertechnonline.com>)



Kuwait, U.A.E., and Bahrain—use approximately 65–75% of desalinated water of the overall capacity of desalinated water produced in the world. In contrast, some nations in North Africa, such as Libya and Algeria, use approximately 6–7% of the worldwide desalinated water capacity.

- (d) In addition to low-economic nations, some industrialized and developed nations, such as the United States of America (USA), are front users of desalinated water. Desalination plants have been installed in cities of California and some regions of Florida.

1.8 Desalination Techniques

With the advancement of technology, currently many industries and commercial companies are launching instruments or devices for water purification. These devices have the capability of generating two to three gallons of good-quality potable water/hour from any type of contaminated water. These devices are available in a variety of dimensions such that they can be suitable for a variety of locations, such as homes, apartments, and schools, etc., depending on the requirement for potable water. These water-purification devices have many advantages, e.g., they require less space due to variety in dimension, they consume less input energy, they have low maintenance cost, they have low filter-replacement requirements (e.g., just once in 2–3 years), etc. These types of devices are used heavily by middle- and upper-class populations. Various desalination techniques are shown in Fig. 1.10. “Desalination” refers to the technique or processes of removing some concentration of salts and other minerals available in saline water as explained previously in Sect. 1.7.2.

Water purification can be accomplished by many techniques. Basically, there are three techniques for generating potable water that involve the process of desalination, and these are as follows:

- (a) membrane technologies,
- (b) distillation process (thermal technologies), and
- (c) chemical approaches.

These techniques can be used together in water-purification plants.

1.8.1 Membrane Technologies [17, 18]

Membrane technology is a combination of various separate processes, in which a membrane is used in every part of the process. In modern science, membrane has been emerging rapidly over time. Industries and commercial companies are launching more advanced devices to enhance water quality as much as possible.

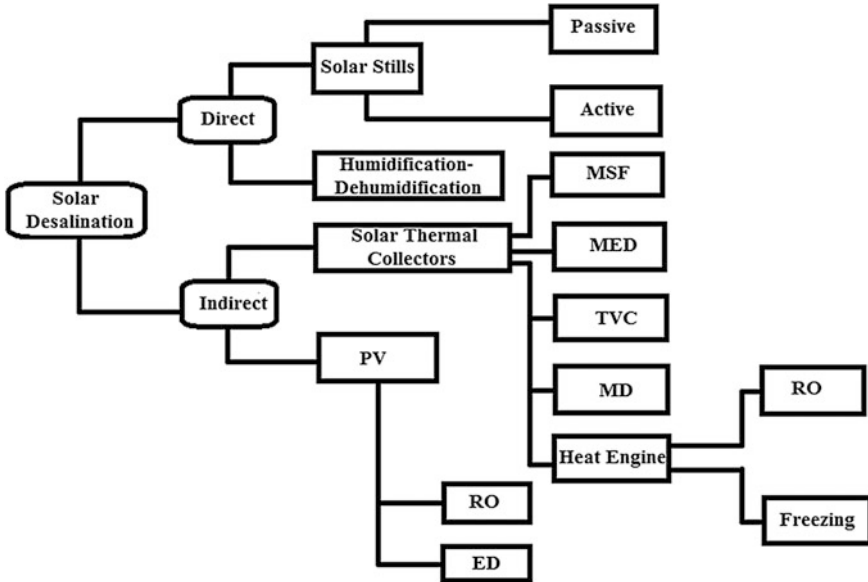


Fig. 1.10 Classification of solar desalination technologies

Use of membranes is very common for the filtration of raw water (polluted water) because it removes or filters all harmful agents. Membrane technique has the capability of filtering contaminated impurities of various sizes. This can be accomplished by using nano-, ultra-, or micro-filtration filters, which remove or filter particles, colloids, macromolecules, and other infection-causing agents. In general, polymeric materials are commonly used for the manufacturing of membranes that are made up of thin films (porous), which includes nylons, ceramics, acetate, and cellulose. These porous films do not allow contaminated agents and pollutants, such as bacteria, highly concentrated salts, toxic chemicals, metals, etc., through them. Membranes allow only water molecules to pass through them and thus produce potable safe drinking water.

In the desalination process, the uses of synthetic membranes are increasing at a very fast rate every year worldwide. Basically, there are two types of membrane technologies:

- (a) pressure driven and
- (b) electricity driven

The processes—which include reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) processes—come under the class of pressure-driven membrane technologies. Among these, nanofiltration process is more reliable and effective for the filtration of undesired contaminated agents such as bacteria, highly concentrated salts, toxic chemicals, metals, etc. In contrast,

Table 1.4 Applications of pressure-driven membrane processes

Membrane process	Applied pressure psi (kPa)	Minimum particle size removed	Application (type, average removal efficiency)
Microfiltration (MF)	4–70 (30–500)	0.1–0.3 μm	(i) Particle/turbidity removal (>99%) (ii) Bacteria/protozoa removal (>99.99%)
Ultrafiltration (UF)	4–70 (30–500)	0.01–0.1 μm	(i) Particle/turbidity removal (>99%) (ii) Bacteria/protozoa removal (>99.99%) (iii) Virus removal (partial credit only)
Nanofiltration (NF)	70–140 (500–1000)	200–400 daltons	(i) Turbidity removal (>99%) (ii) Color removal (>98%) (iii) Hardness removal softening (>90%) (iv) Synthetic organic contaminant (SOC) removal (500 daltons and up) (0–100%) (v) Sulfate removal (>97%) (vi) Virus removal (>95%)
Hyperfiltration (HF)	140–700 (1000–5000)	50–200 daltons	(i) Salinity removal (reverse osmosis) (>99%) (ii) Color and DOC removal (>97%) (iii) Radionuclide removal (not including radon) (>97%) (iv) Nitrate removal (85–95%) (v) Pesticide/SOC removal (0–100%) (vi) Virus removal (>95%) (vii) As, Cd, Cr, Pb, F removal (40 to >98%)

electrodialysis (ED) and electrodialysis reversal (EDR) come under the class of electricity-driven membrane technologies. Some membrane technologies for desalination are listed in Table 1.4.

I. Reverse osmosis

The mechanism of reverse Osmosis (RO) is established on the basis of the osmosis phenomenon, i.e., removing salt concentration (ppm or mg/l) from contaminated water by generating an osmotic pressure change between the salt and the potable water (Figs. 1.11 and 1.12).

In the process of reverse osmosis (RO), reverse flow plays a vital role. Therefore, to reverse the flow, some extra pressure (greater than the osmotic pressure) is applied so that potable-water molecules are filtered from the salt content through the synthetic membrane (thin-film) pores. The RO process has the ability to filter contaminated quantities/salts of concentrations $\leq 45,000$ ppm, which means that this process can easily desalinate the salt concentrations in brackish water as well as those of seawater. Usually reverse-osmosis process is used to remove/filter the salt content of brackish water and seawater having salt concentrations in the range approximately 1000–35,000 ppm. The amount of salt content present in the

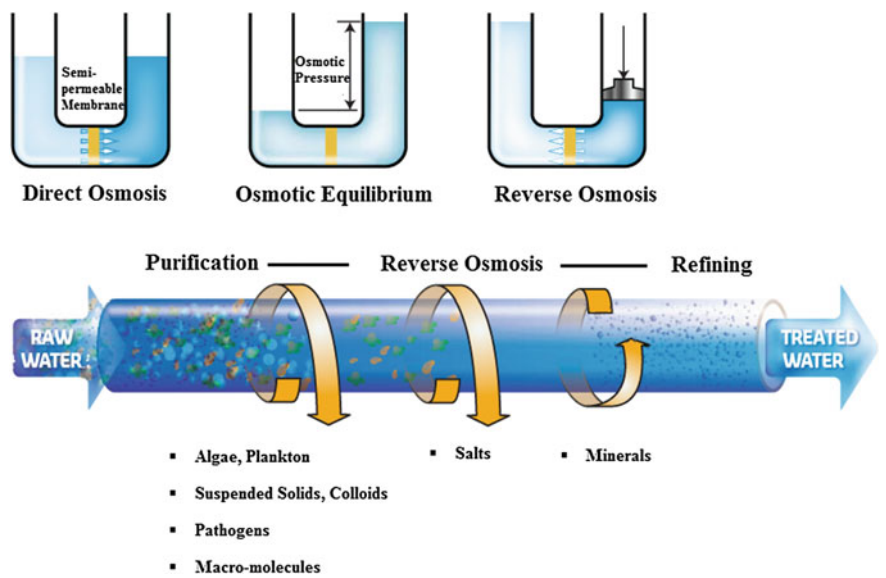


Fig. 1.11 Reverse osmosis phenomenon (source <https://www.degremont-technologies.com>)



Fig. 1.12 Plant of reverse osmosis (RO) desalination process (source <https://www.roplant.org>)

wastewater or polluted water is an important factor for estimating the overall cost of producing the potable water. The amount of energy required to produce potable water from any type of feed water is directly proportion to the amount of salt concentration present in it. Figure 1.12 shows the plant view of reverse osmosis (RO).

The recovery rate (RR) of a membrane process is an output-yield volume of potable water obtained as a percentage of the volume amount of contaminated water poured during the process. This is very significant factor which reveals the key role of the membrane. Depending on the pressure applied (greater than the osmotic pressure), the type of contaminated feed water, and other parameters, the recovery rates (RRs) for RO process can vary in the range of 35–85%. Therefore, industries and commercial companies are concentrating on designing RO membranes that can trigger desalination at minimum pressures and with high recovery rates. One example of this type of membrane is ultra-low pressure reverse-osmosis (ULPRO) membranes.

II. Nano-filtration (NF)

As explained previously, the quality of filtration or removal of contaminated agents from any type of feed water depends critically on the pore size of the membrane. In the case of nano-filtration technique, the range of pressure required has been in the range of 70–140 psi due to the large size of the membrane pores (usually in the range of 0.05–0.005 μm). Nano-filtration can filter high concentrations of salt or total dissolved solids (TDS) from feed water. Moreover, for low salt concentrations, only nano-filtration treatment may be applicable for producing potable water.

III. Electrodialysis

Electrodialysis (ED) is a membrane process, in which electric current is used to filter/remove the contaminated salt content (mg/l or ppm) or total dissolved salts through a thin-film porous membrane. Electromotive force is applied on adjacent electrodes of both sides of the membrane. Therefore, on applying an electric potential difference, salt ions from the contaminated water (feed water) are separated through the ion-filter membrane, and potable water is produced. The amount of energy required for generating potable water is directly proportional to the availability of contaminated salt in the feed water. Electrodialysis is more efficient for the desalination of brackish water.

Electrodialysis (ED) and electrodialysis reversal (EDR) are effective for desalinating brackish water contaminated with a salt concentration $\leq 35,000$ ppm. However, from a (high) cost point of view, usually neither ED nor EDR are considered for applications.

1.8.2 Thermal Technologies

Process in thermal technologies depends on modification of the physical state of water. The basic concept behind thermal technologies is the process of desalination and evaporation. These technologies are practical for the desalination of seawater. Classifications of thermal technologies are as follows:

- (a) multi-stage flash distillation,
- (b) multi-effect distillation, and
- (c) vapor-compression distillation.

I. Multi-Stage Flash (MSF) distillation

Multi-stage flash distillation (MSF) is an emerging technique for the desalination of seawater and its use is increasing quickly worldwide. Approximately 60–65% of desalinated water worldwide is being produced by multi-stage flash-distillation (MSF) plants.

This type of plant consists of a series of closed spaces or stages (cold end and hot end) that include a heat exchanger and condensate collectors divided by tube walls.

After the hot end, there is a container called a “brine heater.” The temperature and pressure of every stage is lower than the those of the previous stage, and the temperature of the tube walls remains in between the temperatures of the fluids. The pressure of each stage is different depending on the boiling point of heated salt water at stage temperature. In the beginning, only the first stage required (at high pressure) an external source for the heating and distillation process taking place by flashing (release of heat) some quantity of contaminated or seawater into multiple stages.

In the first stage of the process, the pressure is too low to trigger the evaporation process. The process of second stage is the reverse of the first stage, in which saline water is rapidly flashed and converted into vapor in a series of steps (stages). The total evaporation in all of the stages is up to approximately 15% of the water flowing through the system depending on the range of temperatures used. However, there are increasing difficulties with scale formation and corrosion with increases in temperature. The maximum temperature appears to be 120 °C, although scale avoidance may require temperatures <70 °C. During operation of the plant in steady state, the feed water at the cooler inlet flows and is pumped through the heat exchangers to increase its temperature in each stage. On the second end (hot end), the brine heater is placed as mentioned previously. When hot saline water reaches the brine container, its temperature has already achieved the maximum value. Some amount of extra heat is transferred to the heater. After this stage, the water recirculates through the valves into all of the stages (of low pressure and low temperature) again to separate it from the inlet water (feed water). The temperature of the brine water is always greater than the boiling point at stage pressure in every stage. Some amount of brine water is converted into flashes or vapor until an equilibrium state is attained. In the next step, the condensation of vapor takes place, and potable water is produced. Heat released during the condensation process is used to heat up the feed water (saline water). Figure 1.13 shows the systematic set-up for multi-stage flash (MSF) distillation.

An essential step in MSF distillation is to maintain the flashing process for a longer period of time without the addition of any external heat. Therefore, for this reason, the temperature and pressure of every stage are stabilized at a lower value than during the previous stage. In the final stage, the temperature of brine and condensate is same as the inlet temperature. The wastewater with a very high value of contaminated salts has not boiled and closes the process in the end. During exit, some amount of heat is carried away by the brine and lost from the system. The efficiency of MSF distillation depends on the number of stages, which requires more area, skilled operators, as well as maintenance cost and efforts.

II. Multi-effect distillation (MED)

Multi-effect distillation (MED) is a low-temperature thermal process of distillation that includes multiple stages of effects. Potable water is produced by collecting the vapor of contaminated salts or seawater on boiling it through a series of effects or vessels. Each of stage is maintained at a lower temperature than the

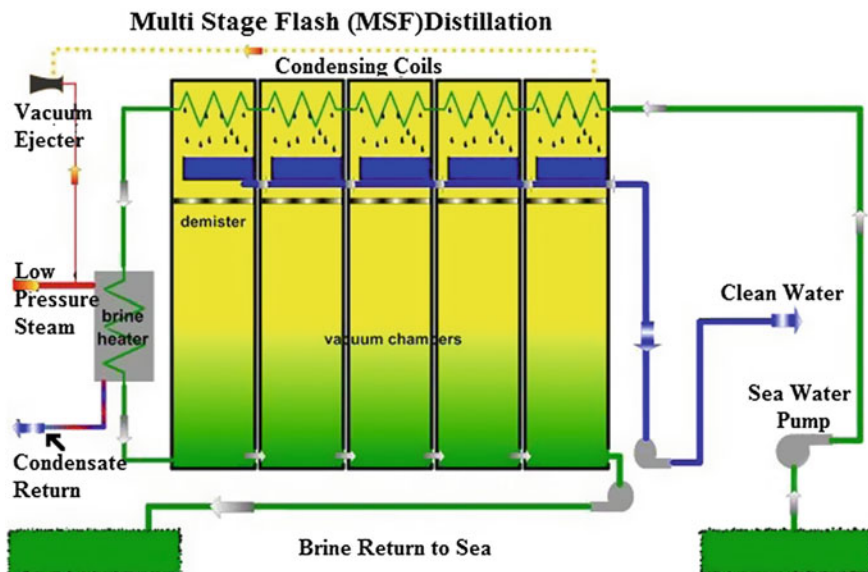


Fig. 1.13 Important steps in multi stage flash (MSF) distillation process (source <https://www.brighthubengineering.com>)

previous one. With the help of steam, saline water is heated, and evaporation takes place in tubes in all of the stages. Some quantity of water starts evaporating, and then steam enters into the tubes of the next stage to heat and evaporate more water content.

During evaporation in the MED process, when pressure decreases (i.e., boiling point decreases), the latent heat released by vapor in the first stage is used to heat the saline water in the next stage of distillation. The most basic fact is that both pressure and temperature are very high such that condensation of vapor takes place. Figure 1.14 shows the systematic set-up of the multi-effect distillation process.

The MED process has certain advantages: It requires low maintenance costs; it is simple to operate; and it triggers the desalination process at low temperature, i.e., $<70^\circ\text{C}$. This process consumes less energy as compared with other thermal processes such as multi-stage flash distillation (MSF). No pre-treatment of feed water is required, and it can be installed directly into the system for distillation.

III. Vapor-compression distillation (VCD)

Vapor-compression distillation (VCD) is a process, in which latent heat is released by the compressed vapors and used for the evaporation of contaminated saline water. In the vapor-compression distillation process, the function of the compressor is to compress the vapors, which enhances both the temperature as well as the pressure of the vapors. Thus, latent heat released during the condensation process can be reused to create more vapor. Vapor compression of feed water can

Fig. 1.14 Important steps in multi effect distillation (MED) process (source <https://www.ikcorp.biz>)

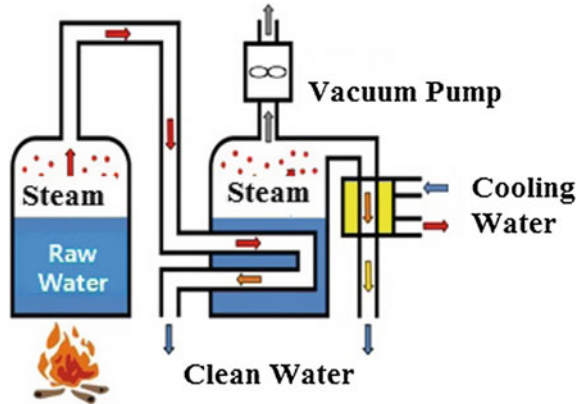
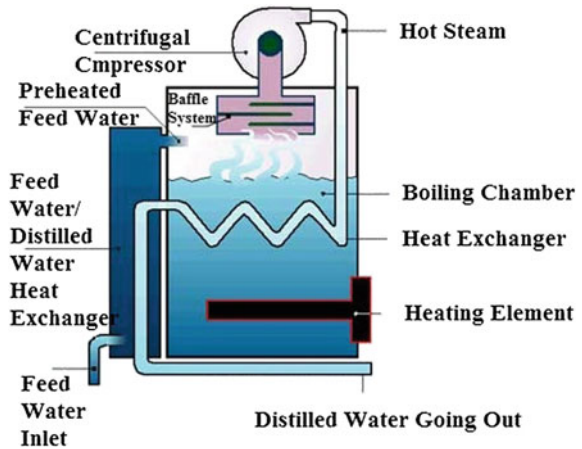


Fig. 1.15 Vapor compression distillation (VCD) process (source <https://www.aquatechnology.net>)



be attained by using a mechanical device that is electrically driven in most cases. The vapor compression–distillation (VCD) process is shown in Fig. 1.15.

The advantage of the VCD process is that it can trigger or start working only with the help of electrical or mechanical energy; thus, no external heat source is required. Its low energy consumption, low maintenance cost, high reliability, easier handling or operation, simple cleaning process, and high water-production efficiency had drawn the attention of marketing industries. Currently the vapor compression–distillation process is growing rapidly in the worldwide market.

1.8.3 Alternative Technologies

Following are alternative technologies for potable-water production:

I. Solar distillation (SD)

In very simple manner, solar distillation replicates the natural hydrological process or water cycle as mentioned previously. The only difference is that SD is a close-loop system, whereas the hydrological process is an open-loop system. In the SD process, saline water or feed water placed in a basin with a cover of transparent glass is heated using solar radiation. Condensation takes place at the inner surface of the top cover, and potable water is collected through a channel. In this process, human labor is required to feed the water. Many solar stills (solar-distillation systems) have been examined, and it is concluded that a single-basin design is the most efficient. It has been observed that a single-basin still can produce potable water at approximately $2\text{--}3 \text{ L/m}^2/\text{day}$ (annual average) under hot weather conditions. There are some advantages of using a solar still: They are easier to operate; they require no pre-treatment of feed water; they are cost-effective; they have no technical maintenance requirement; and they are adaptable for small-scale use, etc. [14].

II. Vacuum distillation (VD)

The basic principle behind vacuum distillation is that contaminated saline water or feed water starts boiling when the vapor pressure of the liquid increases the ambient pressure. An important fact in this process is that it works with or without heating. In general, when contaminated feed water is under a vacuum, then the boiling temperature of the feed water starts decreasing. Therefore, the saline water is vaporized at low temperatures, and one can harvest potable water during condensation. A plant for the vacuum-distillation process is shown in Fig. 1.16.



Fig. 1.16 Column of vacuum distillation system

III. Freezing

Much work has been performed in the past few years toward the development of a method of desalination by freezing. There are three important steps in freezing desalination:

- (a) ice formation,
- (b) cleaning the ice, and
- (c) ice melting.

The process of freezing desalination has been grown quickly in the past 50 years. This process has many advantages: It has low energy requirements, and it has no pre-treatment or immunity of fouling, etc. Desalination by freezing is being used in many plants through various processes to desalinate contaminated saline water. During the past few years, many plants have been built worldwide. From a chemistry point of view, the freezing process is based on the fact that impurities from ice crystals (made up of potable water) are removed with the growth of the crystal. Heat is released on decreasing the temperature of the contaminated saline water up to its freezing point. In general, desalination by freezing method passes through critical steps such as partitioning ice crystals from the brine, cleaning ice crystals to remove extra salts on the crystal surface, and melting ice to produce potable water [14, 19]. The important steps of a freezing-distillation system are shown in Fig. 1.17.

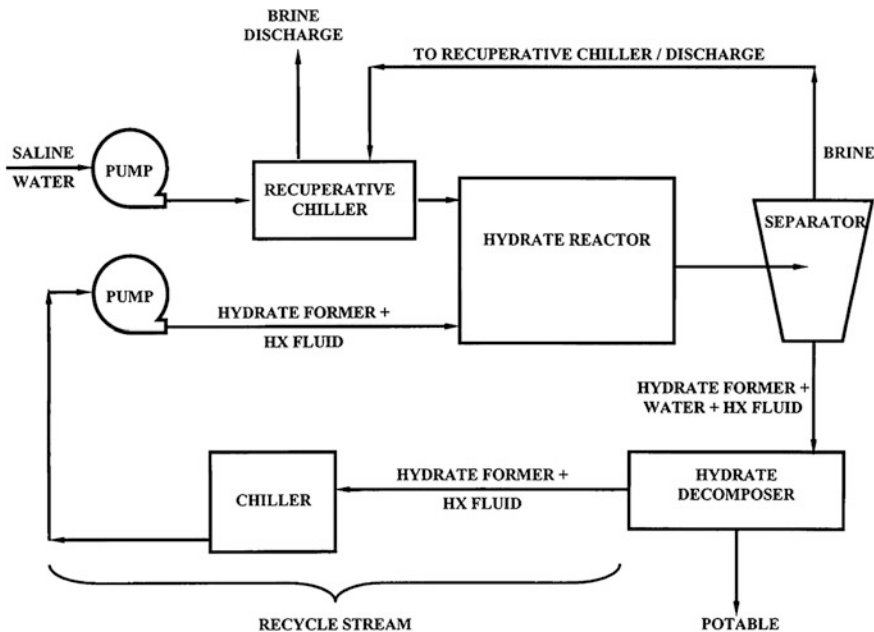


Fig. 1.17 Flow chart of freezing distillation system (source <https://www.strutpatent.com>)

The first step of desalination by freezing is the crystal formation under acquired conditions with cooling to desalinate the contaminated feed water. After preparing the crystal, it is washed in a perfect manner just to exclude the remaining impurities or adhering salts. In the next step, freezing takes place, and then finally potable water is produced on melting the ice. There are some advantages of freezing compared with distillation methods: It has a low input-energy requirement; it decreases the potential for corrosion; and very few problems related to precipitation exist. In contrast, there are some drawbacks of freezing distillation, which mainly include difficulty in treating mixtures of ice and water mixtures [14]. However, this process has not achieved any success commercially for obtaining a potable water for community purposes. However, this technology is superior compared with other techniques for the desalination of contaminated saltwater or wastewater for the production of safe drinking water.

All of the high-capacity desalination plants (based on physical changes) or methods—such as multi-stage flash distillation (MSF) and multi-effect distillation (MED)—are normally used worldwide. However, these requires enormous amount of energy for desalination process. In the freezing process, desalination of contaminated saline water is independent on the salt concentration. Therefore, desalination of brackish water which needs less energy for desalination is not suitable under this type of technology.

IV. Passive vacuum technique of distillation

The essential portion in the passive vacuum distillation technique is to evaporate liquid at minimum temperature with use of low energy as much as possible. Goswami and Al-Kharabsheh [20] have performed work on vacuum distillation and performed an experiment. The experimental set-up was assembled with some important parts—such as an evaporator, a heat exchanger, and a condenser—at a height of approximately 10 m above ground level including fin, injection and withdrawal pipes, etc. The condenser was connected through pipes to the contaminated saline-water (feed water) supply tank and the potable-water tank, respectively, as shown in Fig. 1.18.

Initially, by balancing the hydrostatic and atmospheric pressures, a vacuum is established inside the feed pipes as well as the discharge pipes. Inside the feed pipes, cold fluid is conveyed directly to the evaporation chamber. The chamber is allowed to receive the solar (or thermal) energy through a closed-loop heat exchanger (CLHE), and brine water is also extracted through the withdrawal pipes. Now, to use the maximum amount of heat from the hot brine, both cold fluid as well as withdrawn brine flows through the heat exchanger (tube-in-tube) as shown in Fig. 1.18. Moreover, for the ejection of condensation heat, the evaporator and condenser are connected together.

During this process, the vapor pressure of contaminated feed water must be kept greater than that of the potable water to continue distillation in a passive vacuum-distillation system. This can be achieved using solar energy to increase the temperature of contaminated saline water. The vacuum plays a vital role such that it

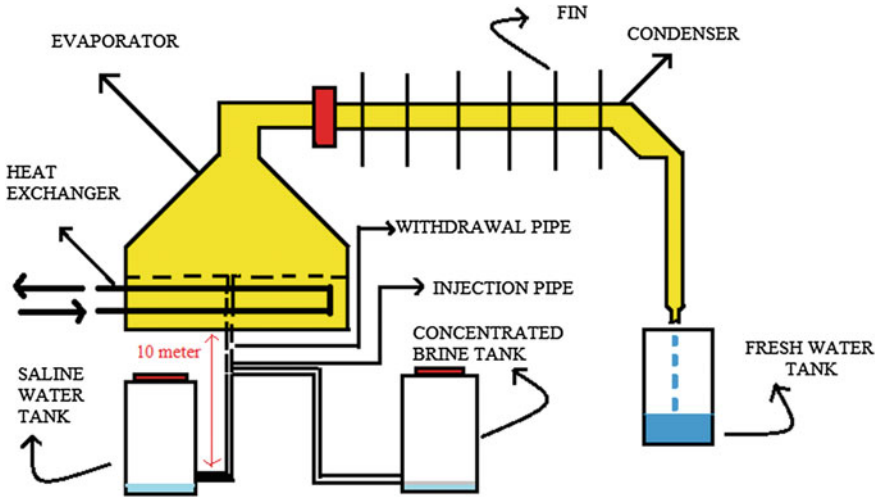


Fig. 1.18 Schematic of passive vacuum distillation system

maintains the distillation process at a lower temperature and therefore requires low thermal energy. The salinity of contaminated feed water increases with evaporation, which decreases its rate in the evaporation chamber. Thus, it is very important to extract the concentrated brine with some flow rate and at the same time pour contaminated feed water at the rate of extraction plus evaporation. This is regulated within a tube-in-tube heat exchanger [14, 20].

Such a system requires proper cleaning, flushing, and restarting on regular intervals to remove all of the non-condensing gasses from the system; otherwise, they can ruin the vacuum. Various desalination techniques are listed in Table 1.5.

1.9 Simple Technologies

In low-income countries, the lack of potable water is a serious problem, and many populations in these nations do not have access to potable water. As discussed in previous sections, every year, people in many world regions, especially children, suffer through water-related health problems. Contaminated water can be converted into potable water for drinking by using simple water filters: A few examples are discussed below, which explain the use of filters based on simple technology. One or more than one material can be used together to prepare the filters. It is not always essential that only a complicated technology or high-technology computer-based techniques can be successful and effective [21].

Table 1.5 Summarizing important desalination technologies

Technology	Brief description	Feed water
Solar distillation (SD)	A pond or river of contaminated salt water with a clean surface takes benefits of solar energy Solar energy is used raise the temperature of contaminated salt water and increases evaporation Energy supply: solar energy	SW/BW
Multiple stage flash distillation (MSF)	Pours heated water into small pressure vessel triggering Flash Distillation it to “flash” into vapor, which is condensed and collected as fresh water. Then takes heat from condensing vapor to deliver it for feed water. Saltwater drifting through the tubes is chiller than the vapor surrounding the tube. The vapor is condensed to form fresh water Energy supply: heat	SW
Multiple effect distillation (MED)	Vapors are collected as pure water on heating water to its boiling point and receives heat condensing vapor to deliver heat for upcoming stages (effects) Energy supply: heat	SW
Vapor compression distillation (VCD)	Compresses water vapor to origin condensation as fresh water. Utilizes heat from condensation to heat feed water and produce vapor Energy supply: electricity	SW/BW
Electrodialysis (ED)	Uses electric current to separate salt from feed water through membrane Energy supply: electricity	SW/BW

I. Simple filtration

In the process of simple filtration, contaminated water is injected into a tank consisting of multiple layers of different materials, e.g., sand, charcoal, gravel, etc. Because the feed water descends through several layers, the bacteria as well as dirt gets is removed as shown in Fig. 1.19. After filtration, potable water flows through a pipe that is safe for human health for drinking. Therefore, potable water obtained through this simple technology helps humans to live longer healthy lives.

II. Mud pot–filtering system

A mud pot–filtering system is commonly used in homes in many parts of South Asia. It consists of a clay pot that contains a clay mixture and burn-out materials such as sawdust (particles of wood and other materials). For its use as a filter, the clay pot is heated or fired to burn off materials, which are then removed from the clay pores. These pores do not allow the passage of other contaminants available in water. In general, the rate of filtration decreases with time due to a pore-blockage problem. A mud pot–filtering system is shown in Fig. 1.20 that consists of three pots one above the other. The contaminated water is poured in the top pot along

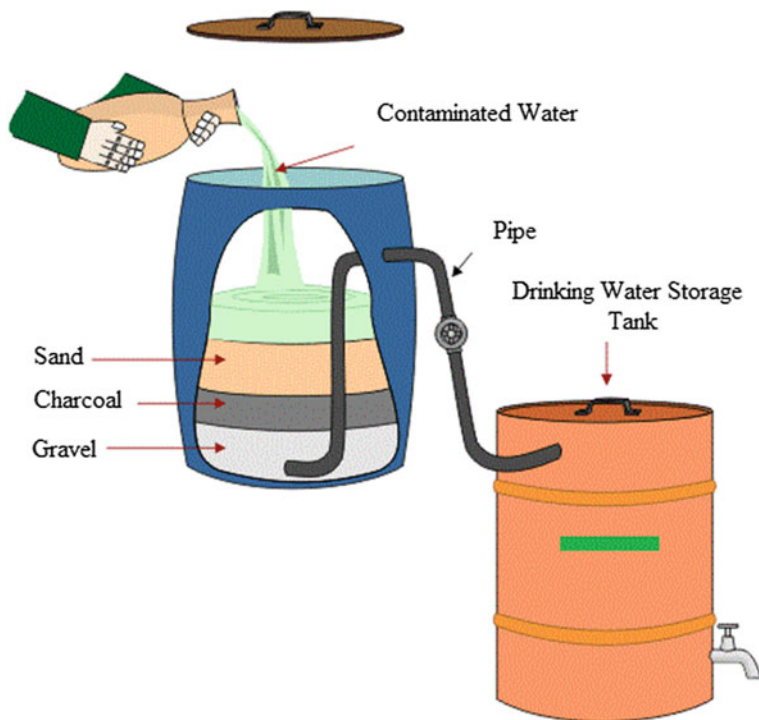


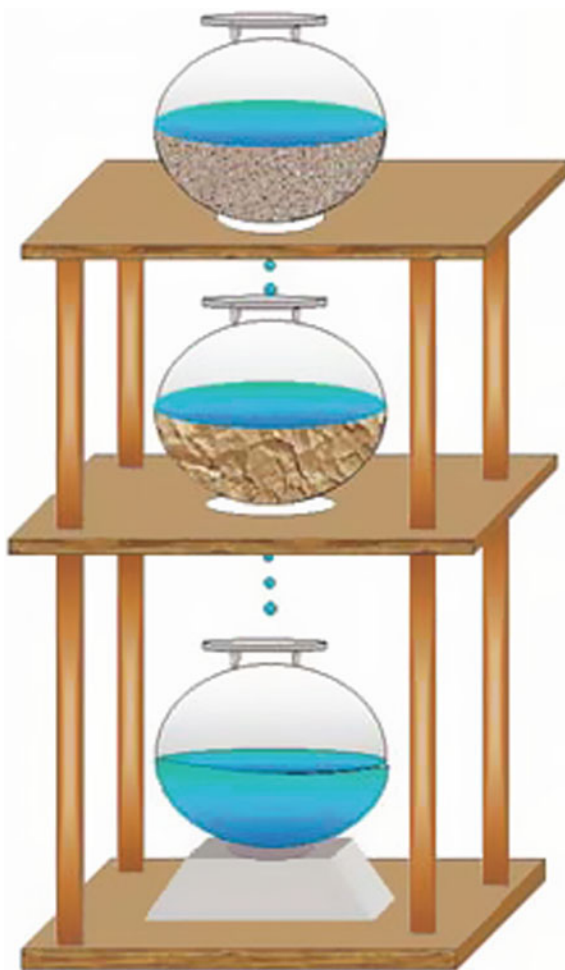
Fig. 1.19 Simple filtration process (source <http://www.technologystudent.com>)

with layers of pre-washed gravel and sand. The water enters the second pot through a cloth cover (acting as filter), and a layer of coal at the bottom of the second pot helps to remove all of the toxins and bacteria from the feed water. Therefore, the water escaped through the second pot is potable; it is collected in the third bottom pot to keep the second pot available for repeat use [14, 15, 22]. The production rate of potable water is very slow; however, it can be operated at home overnight and the water used for drinking and other purposes during the day. This method is totally independent of the use of electricity, the use of filters, and the use of other chemicals, etc., which also decreases the costs of energy consumption and maintenance.

III. Solar distillation

In this method, potable water is produced in a simple manner by using solar energy. The design or dimensions of solar stills depends on the requirement of potable water for drinking. Solar stills can produce approximately 2–3 L/m² potable water/day (annual average) under hot weather conditions for the needs of a single family or an entire village. In brief, a solar-distillation system, or simply a solar still, consists of a basin (black-painted surface) that acts as an absorber and top cover of transparent glass (as discussed previously). The contaminated basin water directly

Fig. 1.20 Mud pot filtering system



absorbs the incident solar radiation, and an evaporation mechanism takes place inside the still cavity. Vapors reach the inner surface of the top glass cover and become condensed there after releasing their latent heat [14]. Therefore, vapors of potable water drips down and is collected at lower end of the glass cover by way of a channel. This process eliminates contaminated salts, impurities, e.g., heavy metals, and other microscopic organisms (waterborne diseases) that can infect human health such as diarrhea, fever, and even death.

The advantages of the solar-distillation method include its easy operation, cost-effectiveness, pollution free, variety in design, suited to for small-scale use, low maintenance cost, etc. It is quite helpful for producing potable water for drinking for low-income populations. A conceptual diagram of the process of a solar still is shown in Fig. 1.21 [14, 15].

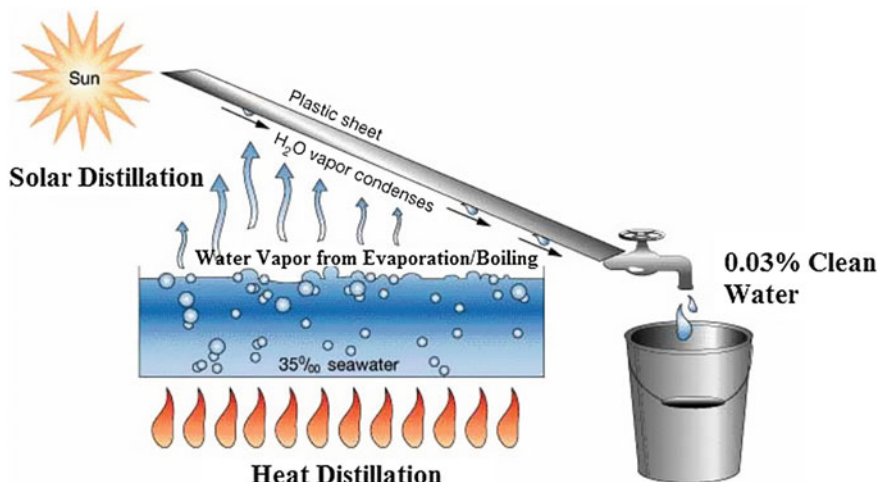


Fig. 1.21 Conceptual diagram explaining the process of solar distillation

Energy consumption (electrical or fossil energy) is one of the major issues in most conventional distillation plants. However, the solar-distillation method, which consumes solar energy to produce potable water from saline water, is a viable replacement of these high energy-consuming technologies. The technology involved in the distillation of saline water or brackish water using solar energy is relatively simple and can be operated and maintained by semiskilled/unskilled operators

Moreover, for the small-scale decentralized production of potable water from brackish or saline water with a salinity level $<10,000$ ppm, solar distillation is the best-suited method and also capable of removing bacteria. In the next section, the basic principle of solar distillation (based on the hydrological/water cycle) is discussed in detail. As shown in Fig. 1.22, the water cycle/hydrological cycle includes an exchange of heat, which further changes the temperature.

In the hydrological cycle, water evaporates by gaining energy from its surroundings (solar energy) and depresses the temperature of the environment. After this stage, during condensation it releases energy to the environment and makes it warmer [23]. These exchanges of heat during the process affect the climate conditions. Water becomes purified during the evaporation process and delivers potable water through rain on the Earth. A copy of this natural cycle is shown on a small scale in the design of a solar still as shown in Fig. 1.23.

1.10 Basic Principle of Solar Distillation

As discussed previously, solar distillation is the simplest way of producing potable water from contaminated saline water using harvesting solar energy. The body of the solar still is usually made of fiber-reinforced plastic (FRP) with a top cover of

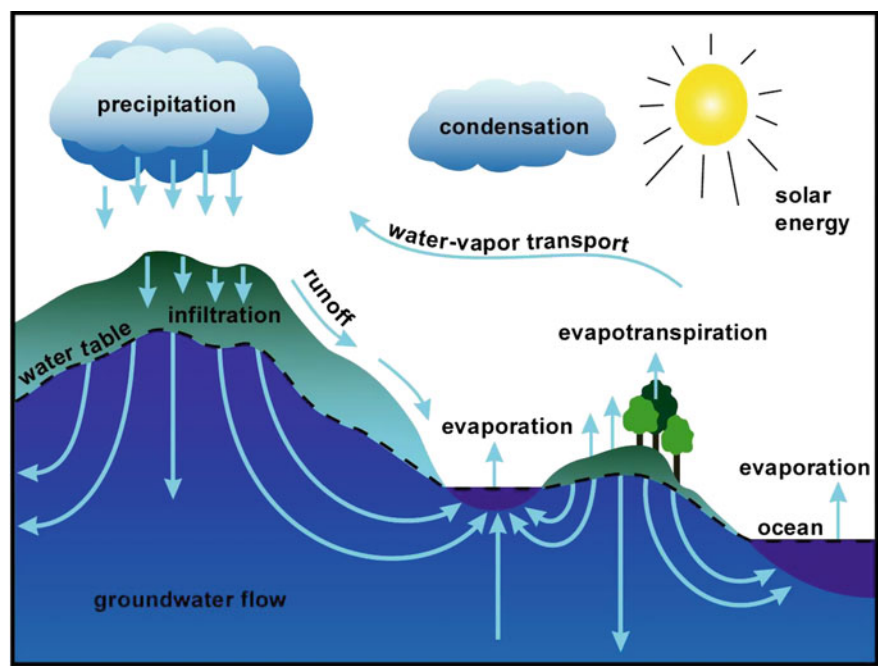


Fig. 1.22 Natural hydrological cycle (source <https://www.slideshow.net>)

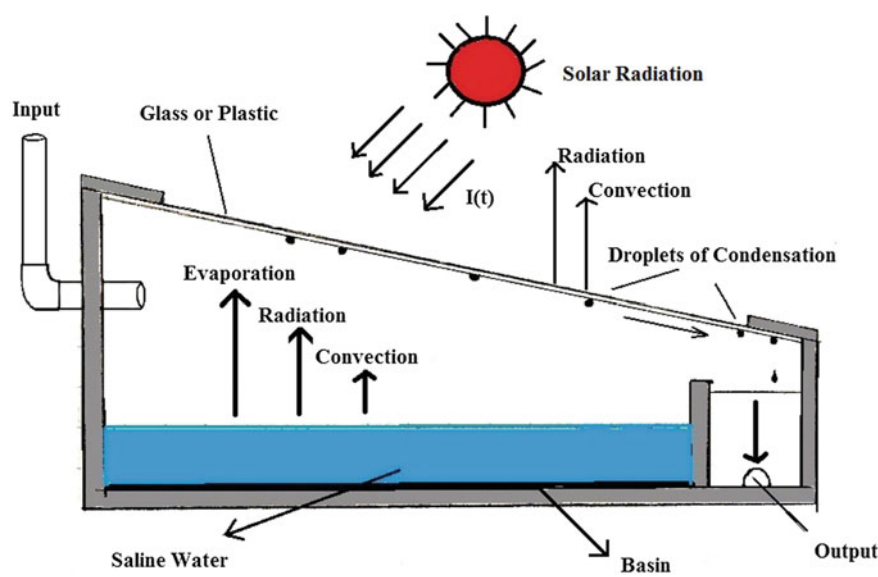


Fig. 1.23 Simple basin type single slope passive solar distillation system

transparent glass. It is essential to keep the solar still in such an orientation so that it can retrieve the maximum solar radiation (i.e., single-slope solar still should be south facing, and double-slope solar still should be in the east—west orientation in case of the Northern Hemisphere). The area of the inner surface (side walls and rectangular base) of the solar still is painted matte black to absorb the maximum solar radiation. The fraction of solar radiation is reflected from the outer surface of transparent glass cover and water surface, and the maximum solar radiation penetrates into the still cavity and is absorbed by the basin water (feed water) and blackened surface (basin liner). The attenuation of solar flux through the basin-water mass depends critically on its absorptivity and the quantity of water mass available in the still. The rest of the solar radiation reaches the blackened surface and is mostly absorbed. After absorption of the solar radiation at the blackened surface, stored thermal energy is convected to the basin water mass and increases its temperature in the basin (greenhouse effect). Thus, it leads to an enhanced difference of temperatures between the basin-water mass (evaporative surface) and the inner surface of the top glass cover. The mechanism of evaporative heat transfer takes place from the basin-water surface, and water vapor reaches the inner surface of the condensing cover; it is condensed there after releasing its latent heat to the cover. The condensed-water or potable-water droplets (free of contaminants such as bacteria, heavy metals, cancer-causing pollutants, pathogens, salts, and other microscopic organism) trickles into the channels provided at the lower ends of the glass cover under gravity [14, 15, 23–27]. A solar still is a more reliable, simpler, and easy-to-use water purifier that can be maintained at home. Figure 1.24 shows a simple structure of basin-type single-slope solar still.

Figure 1.25 systematically shows a basin-type double slope solar still, in which different energy-exchange processes takes place. The basic mechanism of potable-water production is similar to that of the basin-type single-slope solar still (discussed previously). In case of a double-slope solar still, it is important to mention that when the east side acts as a source of solar energy (input), the west side acts as a condensing surface (in morning hours in the Northern Hemisphere) and vice versa, whereas both glass covers (east and west side) act as a source during peak sunshine hours. In brief, energy is transferred from the evaporative surface (saline water or feed water) to the inner surface of the transparent glass cover in evaporation process by way of following mechanisms [14, 15]:

- (a) Vapor is condensed at the inner glass cover with the release of latent heat by condensation.
- (b) A small fraction of heat is also released to the inner surface of the transparent glass by free convection of the air in the double-slope still.
- (c) In the final step, a huge amount of heat is received by the condensing cover, which arrives from the heat radiated by the feed-water surface. The heat that is transferred to the inner surface of the transparent glass is not completely retained or absorbed such that a small fraction is lost to the ambient directly through it.

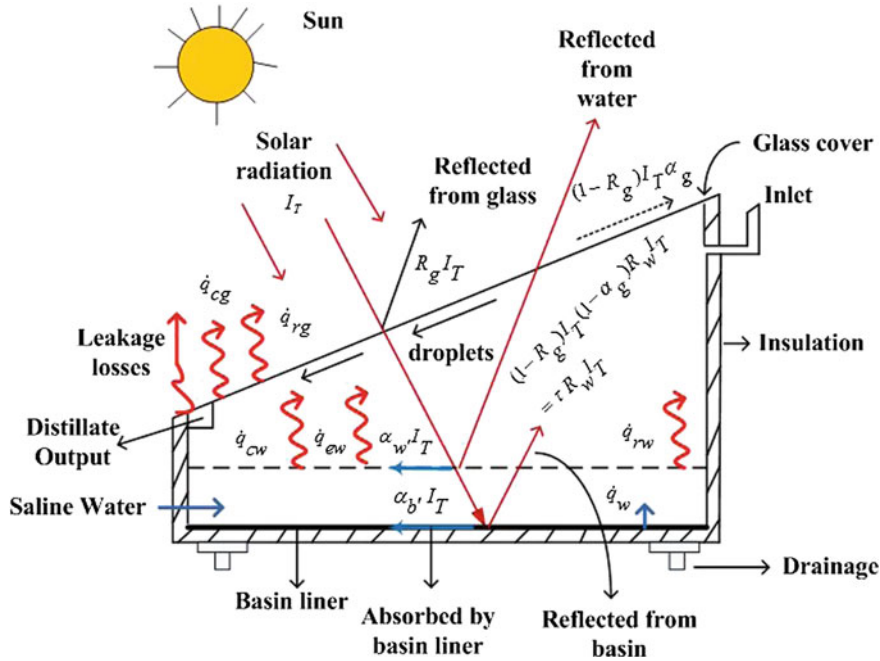


Fig. 1.24 Distillation process in basin type single slope solar distillation system (source <http://www.reddit.com>)

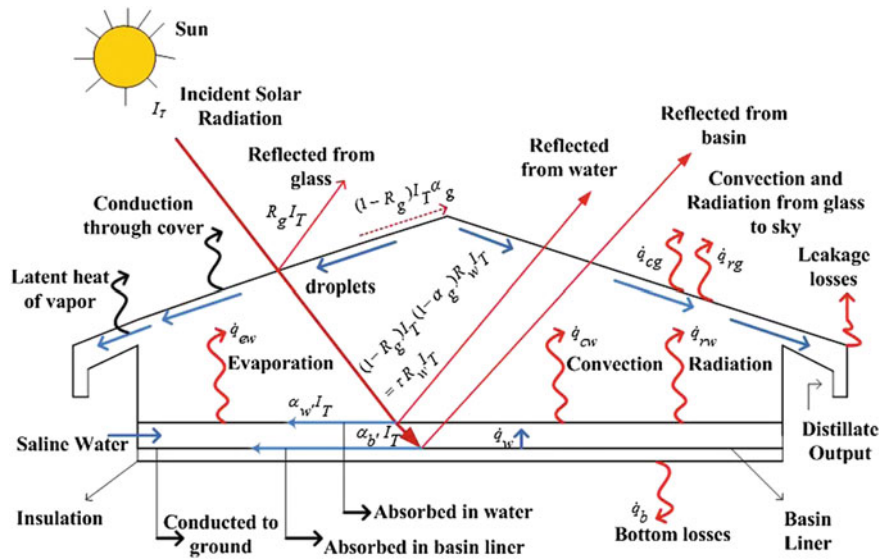


Fig. 1.25 Basin type solar distillation system (double slope) with energy flow

1.10.1 Difficulties in the Large-Scale Installation of Solar Stills

The design or size the dimensions of a solar still depends on the requirement of potable water for drinking. To produce huge amount of potable water (in liters), solar stills can be connected together in series or parallel combination as desired. Solar stills have some problems especially for large-scale production as follows [14, 15]:

- (a) There is the necessity for a larger area from which the distiller/still can receive as much solar radiation as possible.
- (b) There are risks of weather-related damage.

Generally, a solar still can produce approximately 2–3 L of potable water/m²/day (annual average) under hot weather conditions. Thus, the productivity of potable water critically depends on the area of the still and implies that it should occupy a huge area for larger production, which is not suitable where the cost of land is high (e.g., cities). This is a major problem regarding such solar stills in high-economic populations and also a reason behind the consideration of other more economic units, such as RO and VC, which occupy less space. Citizens of various nations may then deliberate whether it is economical to exchange such a solar still for a small RO or VC unit that occupies only a fraction of the space and their time. Apart from these, there are some for this type of solar still as follows:

- (a) There is a high initial cost to design a solar still.
- (b) There is a requirement of daily maintenance such as regular checking for leakage, cleaning glass to remove dust for the proper transmission of solar radiation, flushing water left in the basin after distillation of required amount of potable water, feeding water to the still regularly, etc.
- (c) As condensation and evaporation take place in one container (or still), the yield of potable water is very low and is also quickly affected with variation in solar radiation.

1.10.2 Constraints on the Use of a Solar Still

Under hot weather conditions, solar stills perform best to produce potable water for a requirement of $\leq 3\text{--}4$ L/day. Water-transportation as well as fuel-supply costs also inhibit the use of solar stills. Some constraints on solar stills that further inhibit their use are as follows:

- (a) Saline water is accessible, but other sources completely exploited.
- (b) Yield is low, e.g., a few cubic meters per day.
- (c) There is a requirement of hot weather.

- (d) It depends on an annual rain fall (should be <0.5).
- (e) Water-transportation charges are high (approximately Rs. 400/L).

In the next sub-sections, the following important facts are discussed in detail:

- Filling and maintenance of solar stills
- Water purity/quality from solar stills
- Safety of potable water for drinking?
- Understanding the energy requirement for distillation
- Main advantages and disadvantages of solar distillation
- Use of potable water
- Factors influencing solar distillation.

1.10.3 Filling and Maintenance of a Solar Still [14]

To obtain distillate water from the solar still, it is necessary to feed contaminated water inside the solar still on regular intervals. The solar still can produce potable water continuously until the water temperature becomes equivalent to an ambient temperature. Feeding of the water must be performed each day by the amount slightly more than the distillate produced for greater yield (productivity). This process of feeding of water every day consumes both effort and time. It is essential to clean the basin as well as to flush the contaminated saline water left inside the basin regularly because after some time of evaporation mechanism, salt contaminants saturate the basin of the still. Therefore, depending on the demand of potable water, cleaning and flushing of the still is required at least once a day to avoid the problem of saturated salts. The proper operation of a solar still requires overall approximately 1 h/day to obtain potable water.

1.10.4 Water Purity and Quality from a Solar Still

The pH value of potable water is 7, and the pH value of potable water is in the range of 5.6–7. A solar still moderates the impact of natural pH, which yields and smooth and good-tasting water compared with steam distillation. Potable water produced from solar stills is sufficient for families to fulfill their requirements of clean drinking water as well as for other needs such as cooking.

As discussed previously, solar stills produce potable water from poor-quality contaminated saline water; moreover, it removes all of the microbiological organisms, arsenics, metals, and other waterborne diseases that affect the health of humans [14, 28]. In general, solar stills can produce good-quality potable water for drinking by removing $>99\%$ bacteria from it.

1.10.5 Potable Water for Drinking

Some people have a misconception regarding the drinking of potable water and think that it is inimical to health. Many people in some regions around the world have used potable water for drinking during the past 50 years without reporting any health-related problems.

Following are the benefits of potable water:

- (a) It is 99.9% free of impurities.
- (b) It sharpens mental performance.
- (c) It improve skin appearance.
- (d) It promotes weight loss.
- (e) It decreases stress anxiety and depression.
- (f) It improves oxygen delivery.
- (g) It aids in proper digestion.
- (h) It alleviates asthma, allergy, and arthritis symptoms.
- (i) It remove toxins and waste products.
- (j) It transports nutrients and increases nutrient absorption.
- (k) It regulates body temperature and improves immune function.
- (l) It generates cellular energy.

1.10.6 Understanding the Energy Requirement for Distillation

In solar stills, latent heat released by the water vapor is used or reused to evaporate more water. The numerical value of latent heat is 2260 kJ/kg at atmospheric pressure. This numerical value implies that an input heat of 2260 kJ is needed to produce a 1 L of potable water from contaminated water by the process of distillation.

The main point is that although 2260 kJ/kg is needed for the evaporation of 1 kg of contaminated water to confirm that its contaminants have been removed, for pumping 1 kg of contaminated water through a 20-m head requires only 0.2 kJ/kg. Thus, the energy requirement is 11,300 times more if the distillation option is chosen for potable water compared with the pumping potable water from ground [14]. Hence, distillation is normally considered only when a source of easily-pumped potable water is not available but brackish water is available. Second, the use of fossil fuel and electricity would be very costly means for the distillation.

1.10.7 Main Advantages and Disadvantages of Solar Distillation

Following are the main advantages of solar stills compared with other conventional distillation systems.

- (a) It produces potable water.
- (b) There is no requirement of skilled or trained operators for maintaining and handling the unit.
- (c) It provides independent drinking-water supplies for families.
- (d) No conventional source of energy is required.
- (e) There is the feasibility of local manufacturing and repairing.
- (f) No high-technology exchange parts—such as batteries, filters, or membranes—are needed.
- (g) It can purify highly saline water (even seawater).

Disadvantages

Following are some disadvantages of solar stills:

- (a) There is requirement of greater area so the still can retrieve the maximum solar radiation.
- (b) There is high initial-investment cost.
- (c) There are risks of climate-related damage.
- (d) Because condensation and evaporation takes place in a single container or distiller (or still cavity), the yield of the produced potable water is very low and is also quickly by variations in solar radiation.
- (e) During low-temperature conditions, evaporation suffers from the contamination of microbiological organisms.
- (f) A solar still is a sensitive mechanism re (transportation, operation, glass parts)
- (g) A solar still continuously decreases in effectiveness over time.

1.10.8 Use of Potable Water

Following are the main popular uses of the potable water:

- (a) industries for industrial processes,
- (b) hospitals and dispensaries for sterilization,
- (c) garages and automobile workshop for radiator and battery maintenance,
- (d) telephone exchanges for battery maintenance,
- (e) laboratories for analytic work, and
- (f) people living in marshy and costal areas to obtain fresh potable water.

1.10.9 Factors Influencing Solar Distillation

The performance of a solar still can be efficiently improved as follows:

- (a) if the temperature of feed (undistilled) water to the still is high;
- (b) by attaining a sufficiently high temperature difference between the contaminated water (feed water) and inner surface of the top transparent glass cover (this can be achieved (1) if the transparent glass cover allows the maximum solar radiation to pass through (very high transmissivity of the cover) and (2) if the heat dissipated by condensed water (vapors) on the inner surface of the glass cover is removed rapidly; and
- (c) when very low vapor leakage can be attained.

The high water temperature can be achieved if:

- (a) the water absorbs a high proportion of incoming solar radiation (this can be attained by increasing absorptivity of the basin liner);
- (b) low heat losses through the base as well as side walls are attained; and
- (c) the water depth is low so that the heat is not used merely for heating the water.

1.11 Distillation-Related Terms

Scientific terms related to distillation and their definitions are as follows:

- (a) **Less brackish water:** Water having a concentration of contaminated salts in the range of 500–3000 ppm may not demand any desalination depending on the purpose for use.
- (b) **Brackish water:** Availability of the concentration (mg/L or ppm) of contaminated salts in brackish water is greater than that of the seawater. Generally, water having a concentration of contaminated salts at considerable levels (>500 ppm) but lower than the availability in seawater (approximately 35,000 ppm) is considered brackish water.
- (c) **Moderately brackish water:** Water having concentration of contaminated salt in the range of 3000–10,000 ppm would generally require desalination before use equivalent to seawater.
- (d) **Highly brackish water:** Water having a concentration of contaminated salts in the range of 10,000–35,000 ppm would generally need treatment corresponding to that of seawater.
- (e) **Desalination:** “Desalination” refers to techniques or processes of removing some concentration of salts and other minerals available in saline water. In general, it removes the contaminants from any type of poured water (brackish water or sea water) during the process and produces potable water for drinking and other uses.

- (f) **Pure water:** Water having a low concentration of dissolved salts, generally <500 ppm, is considered potable water, and it is normally available in the natural resources of water on the Earth, e.g., ice caps, glaciers, ponds, rivers, groundwater, lakes, steams, and oceans.
- (g) **Seawater:** Seawater contains 96.5% water, 2.5% salts, a few atmospheric gases, and other microbiological organisms. The concentration of contaminated salts in seawater is near approximately 35,000 ppm.
- (h) **Potable water:** Water suitable for drinking that generally has salt and dissolved solids <500 ppm.
- (i) **Product water:** Potable water obtained from the desalination process.
- (j) **Waste concentrate:** Completely salty water that is a byproduct of the desalination process; the concentration of contaminated salts in wastewater might be >50,000 ppm.

1.12 Historical Background [14, 29–34]

The deficiency of potable water has always been a problem in terms of the population growth on Earth. Constructing equipment to exploit solar energy for the desalination of seawater was the first step in obtaining potable water. In historical review on the desalination of water, Nebbia and Menozzi [35] mention the historical background of solar distillation and first documented work of scientist Giovanni Batista Del Porta (1535–1615) in solar distillation. Until medieval times, no application of desalination by solar energy existed. During this period, solar energy was used for some purposes, e.g., fire alembics to concentrate dilute alcoholic solutions or herbal extracts for medical applications as well as to produce wine and various perfume oils. Mouchot [36], the famous French scientist who experimented with solar energy, in one of his numerous books mentions that in the 15th century, Arab alchemists used polished Damascus concave mirrors to focus solar radiation onto glass vessels containing saline water to produce potable water. He also reports his own solar-energy experiments to distill alcohol and developed an apparatus with a metal mirror having a linear focus in which a boiler was located along its focal line.

Later on during the Renaissance, Giovanni Batista Del Porta (1535–1615), one of the most important scientists of his time, wrote many books. In 1558, he wrote a book, *Magiae Natuealis* (first edition) [37], in which he included three systems for desalination. The second edition of his book came out in 1589 and comprised 20 volumes. Volume 19 is a vital volume in which he describes an piece of equipment for solar desalination that converted brackish water into potable water from the air. Figure 1.26 shows the Delta Porta system. In volume 20 (second chapter), he also mentions a method to produce potable water from the air; currently this method is known as “the method of humidification and dehumidification.” An explanation of the experiment is discussed as follows [14, 32].

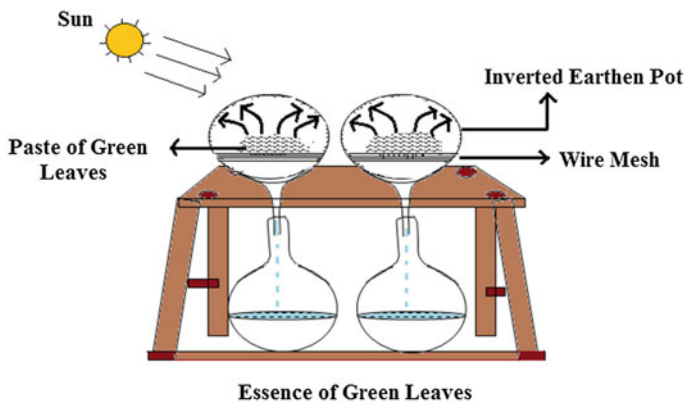


Fig. 1.26 Solar distillation (solar still) apparatus of Della Porta (1589)

Place a paste of green leaves (herbs) on mesh of wires inside of the large earthen pots, which are filled with water). During sunshine hours, the top of the earthen pot is heated from inside, and there is convective and radiative heat losses to the paste of green leaves, which becomes heated. After sunset, the earthen pot is cooled; evaporation takes place from the paste to the inner hot surface (top) of the port; and condensed droplets fall into the vases kept just underneath the earthen pots as shown in Fig. 1.26. After sunset, replace these herbs with new ones.

Delyannis [32] mentions that during the period of Della Porta until the 19th century, no useful application of solar distillation was established. The first large distillation plant was designed and developed in 1872 in Las Chile by an engineer named Carlos Wilson from Sweden. The essential purpose of the plant was to fulfill the demands of the workers and their families of a saltpeter mine for potable water. The salt concentration of the feed water was approximately 40,000 ppm. Manufacturing of the plant was very simple: A rigid structure was made of wood and timber and then covered with a glass sheet. The plant was composed of 64 bays with a total surface area of 4450 m² and an overall surface area of 7896 m². The plant was capable of producing potable water in the amount of approximately 70 m³/day. It was in working mode almost for approximately 40 years.

A few references were available about the latest solar distillation plants, e.g., the work of Abbot [38] for constructing solar distillation equipment, which is similar to that of Mouchot [36] up until World War II. During the same period, some work on solar distillation was undertaken in the USSR. In the meantime (1930–1940), a situation of dryness compelled California to solve the problem of water shortage, and this stimulated a new interest in the desalination of contaminated saline water. However, some projects on distillation were initiated during that period, but no application was found due to the slow economy. During World War II, in some regions of North Africa, the Pacific Ocean Islands, and other isolated places, hundreds of soldiers suffered through a deficiency of drinking potable water. This scenario drew much attention to the problem of water shortage.

In 1943, Maria's team at MIT had already begun experiments with solar stills. At the same time, for military needs research was sponsored by the US National Research Defense Committee (NRDC) to construct solar stills at sea. Some patents for solar-distillation apparatuses that were adaptable to lifeboats and rafts were granted. During World War II, these apparatuses were heavily used by the US Navy and saved thousand lives. Telkes [39] developed and investigated many different configurations of the solar stills such as glass-covered and multiple-effect solar stills.

After World War II, the worst economic conditions compelled to the US to expand the urban population as well as industries, which pushed the demand for potable water into the newspaper headlines. In 1950, the president of U.S.A (H. S. Truman) in his budget message remarked that (OSW 1961): "Experience in recent years has been that it is not possible to meet the shortage of water, which is a threat in some areas, through our extensive water resources programs. I recommended, therefore, that the Congress enact legislation authorizing the initiation of research to find the means for transferring saline water into freshwater in large volumes at economical costs." In July 1952, the Office of Saline Water (OSW) was established by the US Secretary of the Interior. The motive of the OSW was to finance research to various institutes and other research-oriented organizations on solar distillation.

Many small-capacity solar-distillation plants were established by McGill University in some Caribbean Islands. Howe [40] was another pioneer in solar stills. Howe and his collaborators performed much research on solar distillation (UC/Davis, 1970–1985) at the Sea Water Conversion Laboratory of the University of California, Berkeley. In India, much research was performed on solar distillation i.e., experimental work on solar distillation was performed at the National Physical Laboratory (NPL), New Delhi, as well as in the Central Salt and Marine Chemical Research Institute (CSMCRI), Bhavnagar. The Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia, Melbourne (1963), performed numerous works on solar distillation, and they constructed a bay-type still covered with a glass and having a base surface made of a black polythene sheet. With the help of these bay-type stills, they developed solar-distillation plants in the deserts of Australia, which produced potable water from concentrated saline water.

At the same time, one of the plants of these bay-type solar stills was constructed in Coober Pedy. On March 17, 1954, the Association for Applied Solar Energy (AASE), now called the International Solar Energy Society (ISES), was established in Phoenix, Arizona, and it focused on the use of solar energy. In 1956, Telkes explained the Las Salinas solar-distillation plant at the First World Symposium organized by AASE in collaboration with the University of Arizona and the Stanford Research Institute. It was reported that the plant was in working mode for approximately 36 continuous years. At the same symposium, two articles were delivered that were devoted to the background and evolution of solar-energy machines. The first article by Abbot—"Weather and Solar Variations—was published in the *Journal of Solar Energy Science and Engineering*, which was published by the AASE in January 1957. During the period of 1965–1970,

solar-distillation plants were established on four Greek Islands to produce potable water for small communities [30, 31, 41, 42]. Stills were constructed at the Technical University of Athens; the stills produced potable water from the concentrated saline water using a single glass cover; and the capacity of the plant was in the range of 2044–8640 m³ potable water/day.

Apart from the common basin-type solar stills, several other types of stills have also been recently proposed and studied. These include the following:

- (a) multiple-effect stills [43, 44],
- (b) tilted-tray or inclined-stepped solar stills [45, 46],
- (c) tilted, wick-type, and multiple wick-type solar stills [47–49],
- (d) solar film-covered and wiping spherical stills [50],
- (e) solar still–greenhouse combination [48, 51], and
- (f) indirectly heated solar stills [36, 52].

Depending on their expected life span and application, solar stills are classified into three types: permanent (glass-covered stills)-type, semi-permanent (plastic stills)- type, and expandable (double-cube and floating stills)- type solar stills. It is expected that the third variety would prove to be economical and comfortable to handle and transport. Currently most of these plants are not in working condition. In recent years, many research works have been performed worldwide, especially for the construction of high-capacity solar-distillation plants, on solar stills in many research institutes. Tables 1.6 and 1.7 list some interesting data on several major solar-distillation plants in both non-working and working condition, respectively, which had been installed both earlier and presently.

1.12.1 Solar-Distillation Plants

As discussed earlier in previous sections, there are many advantages of the solar-distillation process. The conventional solar-distillation process is simpler and more economical than other seawater-distillation processes due to following reasons:

- (a) available cost-free energy,
- (b) decreased operating cost,
- (c) local manufacturing/repairing is possible,
- (d) no need for high-technology exchange parts such as batteries, filters, or membranes,
- (e) simplicity of design; and
- (f) skilled manpower not required for construction and maintenance.

Choice of distillation-unit design

The choice of distillation-unit design depends on the available land in the region. For example, conventional symmetrical and non-symmetrical solar-distillation units

Table 1.6 Earlier installed distillation plants in various countries (in non-working mode now) [31]

Country	Location	Year	Basin Area (m ²)	Feed	Cover	Status
Australia	Muresk	1963	372	BW	Glass	Rebuilt
	Muresk II	1966	372	BW	Glass	Operating
	Goober Pedy	1966	3160	BW	Glass	Operating
	Hamelin Pool	1966	557	BW	Glass	Operating
	Griffith	1966	413	BW	Glass	Operating
Cape Verde	Santa Maria	1965	743	SW	Plastic	Abandoned
Chile	Las Salinas	1872	4460	BW	Glass	Abandoned
	Quillagua	1968	100	SW	Glass	Operating
China	Wuzhi	1976	385	SW	Glass	Operating
	Zhungjian	1979	50	SW	Glass	Operating
Greece	Symi I	1964	2686	SW	Plastic	Rebuilt
	Symi II	1968	2600	SW	Rg. Pls	Dismantled
	Aegina I	1965	1490	SW	Plastic	Rebuilt
	Aegina II	1968	1486	SW	Rg. Pls	Abandoned
	Salamis	1965	388	SW	Plastic	Abandoned
	Patmos	1967	8600	SW	Glass	Operating
	Kimolos	1968	2508	SW	Glass	Operating
	Nisyros	1969	2005	SW	Glass	Operating
	Fiskardo	1971	2200	SW	Glass	Operating
	Kionion	1971	2400	SW	Glass	Operating
	Megisti	1973	2528	SW	Glass	Operating
India	Bhavnagar	1965	377	SW	Glass	Operating
	Awania	1978	1866	SW	Glass	Operating
	Bitran	1980	–	SW	Glass	Operating
	Kulmis	1980	–	SW	Glass	Operating
Island	Santa Maria	1968	–	–	–	–
Mexico	Natividad	1969	95	SW	Glass	Operating
Pakistan	Gwadar I	1969	306	SW	Glass	Operating
	Gwadar II	1969	9072	SW	Glass	Operating
Spain	Las Marinas	1966	868	SW	Glass	Operating
Tunusia	Chakmou	1967	440	BW	Glass	Operating
	Mahdia	1968	1300	BW	Glass	Operating
USA	Daytona	1959	228	SW	Glass	Rebuilt
	Daytona	1961	246	SW	Glass	Dismantled
	Daytona	1961	246	SW	Plastic	Dismantled
	Daytona	1963	148	SW	Plastic	Dismantled
USSR	Bakharden	1969	600	BW	Glass	Operating
West Indies	Potit	1967	1710	SW	Plastic	Operating
	Haiti	1969	223	SW	Glass	Operating

Rg. Pls. rigid plastic, *SW* sea water, *BW* brackish water

Table 1.7 Distillation plants in working condition till 1990 [57]

Country	Year	Location	Design	Capacity	References
Haiti	1984	Grande Saline	Single Slope	400	Lawand and Alward [58]
India	1968	Gulf of kutch	Symmetrical	130	Gomkale [27]
	1977	Awania	Symmetrical	5000	
	1979	Bhaleri	Symmetrical	8000	
	1983	Lakshadweep	Symmetrical	2000	
	1985	Delhi	Symmetrical	150	
Israel	1984	Sade Boger	Single Slope	125	Kudish [59]
Mexico	1987	ITLP		80	Fernandez and Chargoy [60]
Papua New Guinea (PNG)	1987	Port Morsby	Double Slope	25	Lawrence and Tiwari [53]
Saudi Arabia	1989	Jeddah	Symmetrical	50,000	Madani and Zaki [61]
Thailand	1984	Bangkok	Single Slope	90	KMIIT report (1984)

are most suitable for regions where cost-free non-agricultural land is available for providing drinking water. Moreover, an arrangement to collect rain water should be made in the design as suggested by Lawrence and Tiwari [53]. The design can also be established on the roof of a building in urban areas because it decreases the cost of land (provided the roof is strong enough to bear the load of the distillation plant). The multi-wick solar-distillation system can be appropriate for urban areas because the load of this unit is less than that of the conventional distillation system.

The choice of distillation-unit design is significant because the main factor that influences the annual yield (per m^2) is the location where the plant is installed. The annual yield (per m^2) of a conventional distillation plant mainly depends on the insolation level and other climatic conditions of the plant location. The capacity of the plant (yield/ m^2) is directly proportional to the surface area for evaporation. The capital cost and payback period vary proportionally with the capacity of the plant for a given design at a given location.

Solar distillation was considered the most desirable option for producing drinking water for small requirements at remote geographic locations till the end of 1980. In recent times, advanced systems, such as reverse osmosis (RO) and electrodialysis (ED), have grown rapidly. Thus, due to increased payback cost, most of the solar-distillation plants installed by developed countries, such as Australia, Japan, USA, and the Soviet Union, were abandoned. However, solar distillation always remains an attractive desalination process in less developed countries such as India, Thailand, South Pacific Island countries, and Arab countries, etc., due to unsophisticated maintenance facilities. The experience in installation and operation of solar-distillation systems in different countries is reviewed as follows [14, 15, 35]:

I. India

Educational institutions and industrial units have been trying to improve the development work on solar-distillation units from many years: including Central Salt Marine and Chemical Research Institute (CSMCRI), Bhavnagar; Centre for Energy Studies, I.I.T. Delh; CAZRI, Jodhpur; and M/S. Jyoti Ltd., Vadodra. FRP modular solar stills are commercially available. Most of the early distillation plants in India, particularly in the states of Gujarat, Rajasthan, and coastal areas, were installed under the supervision of Central Salt Marine and Chemical Research Institute (CSMCRI), Bhavnagar. A report on the functioning of various distillation plants in the country was prepared by CSMCRI, Bhavnagar, in 1987. Based on this report, it was believed that the solar-distillation plants should be installed under supervision of an R & D organization with grants from the central government and later handed over to an appropriate state government department for operation and maintenance [14, 15].

The Government of India decided to install distillation plants in areas where drinking water availability is low or not available. The decision in favor of the installation of distillation plants as a solution to supply drinking water at a particular site is determined by the following factors:

- (a) No drinking water should be available within a distance of 15–20 km from the site, and no other alternate conventional water supply scheme is feasible.
- (b) The site should not have any other source of energy except solar energy and should have saline water with salinity >10,000 ppm.
- (c) The beneficiaries should be willing to adopt the technology without pressure and be committed to look after its operation and maintenance.
- (d) The site should be free from natural calamities such as heavy rains, storms, cyclones, and tides, etc.

In addition to the previous points, it was believed that a solar-distillation plant should be installed only after confirming the interest of the user and their commitment to maintaining the unit. The first pilot plant with a capacity 1000 L/day was installed in 1965 by CSMCRI, Bhavnagar, to supply drinking water to laborers in salt mines; however, they were damaged due to heavy rains in 1968. Later in 1968, another plant with a capacity of 130 L/day was installed at the Gulf of Kutch, and it is still supplying drinking water to staff members. After a decade, due to an importance using renewable-energy sources, a major distillation plant with a capacity of 5000 L/day was installed for supplying water to villagers of Amania in Gujarat (1977/78) for drinking and other uses. The windmill and photovoltaic pumps were also used for water pumping. This plant was extensively damaged by a cyclone in November 1982; however, it was repaired and re-commissioned in October 1984. The details about designs and performance can be seen in Appendix A in Malik et al. [15].

It has been reported that that installed plants have been abandoned either due to lack of raw water at the site or due to cyclone/heavy rains. Hence, these points should be taken into account seriously before recommending the installation of a

solar-distillation plant in any area. Moreover, it may be emphasized that the output of the plant decreases very rapidly in cases of poor maintenance.

Research and Development (R&D) Progress on Solar Desalination in India [54]

Development work on solar-distillation units has been performed in a number of educational institutions and industrial units. In an overview of desalination and water reuse in India, Mishra and Sadhukhan (BARC) explained the research and development work on desalination. In 1960, at the Central Salt and Marine Chemical Research Institute (CSMCRI), Bhavnagar, research and development work on the desalination of water was started in the laboratory under the Council of Scientific and Industrial Research (CSIR) of the Government of India. The motive of the research work was to enhance the technology for conversion of contaminated saline water or seawater into potable water. After some experiences in several phases of seawater application, this laboratory achieved some success in solar desalination and erected a small desalination unit that was based on the multi-stage flash (MSF) process. This research institute had also accomplished a successful work on electrodialysis (ED) and reverse-osmosis (RO) technology for the desalination of brackish water, and the institute still performs research work in this area. At Bhabha Atomic Research Centre (BARC), the work on desalination was started in the late 1960s as part of a study on a Nuclear Powered Agro Industrial Complex (BARC 1970); later, in late 1970s, work on RO (reverse osmosis) was also accomplished in this programme. Pilot plants using both MSF and RO process were mounted and shown effectively at BARC for the desalination of seawater and brackish water, respectively. During the same period, work on desalination was also engaged at the Defense Laboratory, Jodhpur, on electrodialysis process. The National Environmental Engineering Research Institute (NEERI), Nagpur, took up R&D on membrane processes for waste treatment. Moreover, the basic theoretical studies on methods of mass transfer in membranes were performed by a number of academic and research institutes. Eventually, RO technology was adapted by numerous private companies trading in water treatment as a supplement for the production of potable water from filthy water or raw water containing contaminated salts with salinity of approximately 1000–1500 ppm. During the 1980s, which was approved as the International Decade for Water Supply and Sanitation by the UN (United Nations), three research laboratories that had established reverse-osmosis and electrodialysis technology set up a number of demonstration plants in the villages. The main objective behind this step was to produce potable drinking water from accessible underground sources of brackish water.

II. Haiti

A single-slope conventional solar-distillation plant consisting of 32 units was installed at Grand Saline, located 100 km north-west of Port-au-Prince at the mouth of the Artibonite River. Each unit has an evaporation area of $1\text{ m} \times 3.5\text{ m}$ with a capacity 400 L/day. An arrangement for rainwater collection has also been built

Table 1.8 Distillation yield (L/m^2) from four distillation basins on Grande Saline [58]

Date (May)	Solar radiation (kWh/m^2) (maximum)	Ambient temperature ($^{\circ}\text{C}$) (maximum)	Distillation production (L/m^2)
10	5.11	38	3.27
11	5.40	35	2.32
12	2.64	28	0.75
13	5.38	32	1.63
14	6.63	–	2.67
15	5.85	–	3.25
16	6.40	32	3.19
17	6.45	36	3.17
18	6.30	33	3.11
19	6.49	–	2.08
20	6.14	–	–
21	6.38	–	2.73
22	6.56	–	2.99
23	5.97	34	2.88
24	5.83	–	2.05
25	6.93	–	2.00
26	5.94	–	2.11
27	4.90	–	1.63
28	6.24	–	2.36
29	5.37	33	2.47
30	5.22	–	1.04
		Average	2.271

into the design. The typical outputs in liters per m^2 from four solar distillation units are listed in Table 1.8. On the basis of experience during construction and operation, the following recommendations were made for better performance:

- Close and expert supervision throughout the period of construction is required.
- The local community should be trained in maintenance and operation.
- The reservoir for distillate output and rain water should be sunk into the ground for maximum head difference, which decreases the overall cost of the system.
- The individual basin area can be decreased to prevent fracturing inherent in greater basin area in the sandy soil.
- The leakage should be regularly checked.

III. Mexico

The scarcity of potable water is a very sensitive problem in many areas on this planet. The acute scarcity of freshwater, and even of poor-quality water, affects the living standard of the people of Southern Baja California, Mexico. In some villages, water is carted for approximately 50 km to reach the consumers, fishermen, and

farmers; this costs approximately US \$10 m³. Initially, some conventional solar-distillation plants were installed to purify the brackish water. Even with satisfactory performance of the system, the plants were abandoned due to poor craftsmanship, improper operating practices, and poor maintenance. The functioning of old stills in Puerto Chals was stopped due to cumbersome cleaning.

To alleviate these problems, a multi-stage indirectly heated solar-distillation plant was installed. During the operation of this distillation plant, the following observations were made:

- (a) The collector performance remained the same after operation of the system for approximately 18 months.
- (b) During the collector process, water leakages were observed at joints; this was corrected with proper interconnects.
- (c) The rate of corrosion inside the tube, storage tank, and heat exchanger due to use of brackish water was acceptable; however, it may be high with seawater.
- (d) Some of the plastic hoses (a flexible tube for conveying a liquid, e.g., water, to a desired point) had to be replaced.
- (e) One of the pumps required repair due to the burning of the electric winding.

There were no other problems, and the system seems to be capable of working with little maintenance as per expectation.

IV. Thailand

In two educational institutions—the Asian Institute of Technology (AIT), Bangkok, and King Mongkuts Institute of Technology (KMUT), Thonburi—the research on solar-distillation systems started in 1977. During the period of research, 16 single-slope solar stills were manufactured with FRP body and transparent glass cover. The field test was taken at the following locations:

- (a) Buddha Buja Temple, Bangkok
- (b) Health Centre, Lad Sawai, Patumthane
- (c) Banglamung Hospital, Chonburi
- (d) Sawangnivas Health Recovery Centre, Samutprakam.

Each still had a plastic basin area of 1.8 m × 0.6 m. The front wall of each basin was 0.1 m high. Styrofoam of 0.25-mm thickness was inserted between the inner and outer walls of the still. Black paint was added to the resin coated on the floor of the basin to provide good absorptivity of solar radiation on the surface of the still. A glass cover of 3-mm thickness with inclination of 14° was used.

Four stills were tested at each location for approximately 7 months, and it was observed that the potable water obtained from each solar still was unacceptably acidic with a pH value of 4 to. To improve the distillation output, these solar stills were withdrawn, and aluminum foil with black paint was applied as the inner surface. Small pieces of charcoal were used in the basin to increase the evaporating surface area. With these improvements, the stills were tested again for approximately 1 month. Twenty additional improved stills were subsequently installed at different locations in the country for long-term field tests.

V. Papua New Guinea (PNG)

Water scarcity originates due to a deficiency of essential freshwater resources to fulfill the demands of populations on the Earth as discussed previously. Many regions face this problem everyday. In Papua New Guinea (PNG), approximately 100 FRP single-basin solar stills were supplied through an exchange programme of commonwealth countries, and these solar stills were manufactured by Jyoti Ltd., Baroda, India. These solar stills were meant to be commissioned at various organizations including educational, thermal power plant, and city council water supply, etc. However, during the process of solar distillation, it was observed that the design of the FRP solar stills were found not suitable due to low depth of basin and vapor leakage from the inferior end of the transparent glass cover.

To amend these problems and for better performance, conventional solar stills were designed, (with available local materials), fabricated, and tested using local technical assistance. It was observed that the double-slope FRP and the concrete solar still with large basin depth are most appropriate for this country. After completing the project, a survey of drinking-water demand was performed in different coastal villages. It was observed that these villages were not serviced by any central water supply and were totally depended on rain water collected in large metallic drums from the roof of the house; there was acute water shortage during the dry season. During the lean periods, the demand for drinking water has been generally met by coconut water. One double-slope solar still was donated to Goba-Goba village located 80 km from Port Marshy; the population was satisfied with the results. The government may provide more units under a United Nations Development Program (UNDP).

1.12.2 Multi-wick Desalination Plant [55, 56]

The multi-wick solar distillation plant was constructed of 28 multi-wick solar stills with 4 stills in each of 7 rows. It was first installed at IIT Delhi to meet the potable water needs of the Chemistry Department in January 1981. The plant was constructed with 4 stills in each of 7 rows, and each still with effective area of 1 m². This design of this multi-wick solar-distillation plant made of galvanized iron sheet had a capacity of 85 L/day. Each row of stills had independent water-feeding pipes connected to small storage tank. The level of water in the still-reservoir and the storage tank was maintained the same. This small storage tank was connected to a large tank of 1000-L capacity to supply water in the absence of the supply from the mains. The various problems faced during the operation of this plant were as follows:

- (a) There was difficulty in maintaining the same water level in the still-reservoir and the storage tank because of irregular roof surface.

- (b) Due to independent water-feeding pipes, each still had different rates of water feeding resulting in frequent overflow of water, which usually caused leakage from the sides of the still.
- (c) Algae formation in pipes was seen to be blocking the water flow.
- (d) On account of power shortage/failures, etc., the main storage tank was found inadequate in supplying the required amount of water to the small tank.
- (e) Sometimes very high wind speed resulted in the fracture of glass as well as knock-outs of polyvinyl chloride (PVC) pipes joining the still with the storage tank.

In June 1982, the plant was disassembled due to the previously mentioned problems and reinstalled in October 1982 with the following changes for better performance [55]:

- (a) To solve the first problem, the stills were fixed on brick pillars, which was performed especially for this purpose.
- (b) The water pressure was balanced constant by supplying it in both of the two rows from the minor storage tank.
- (c) To decrease the formation of algae, colorful plastic pipes and copper sulphate were used.
- (d) Overflow also creates leakage; therefore, the design of the stills was marginally changed. Hence, an extra little side wall of 1-inch thickness provided drainage for spare water at the base.
- (e) Aluminum was used for manufacturing to avoid drainage corrosion.

With the execution of the above-mentioned precautionary procedures, observations were re-taken, and the redesigned stills were found to perform satisfactorily. This plant consisted of 24 units of GI sheet multi-wick solar stills. A rectangular storage tank of with 1000-L capacity and cylindrical tanks with 50-L capacity were made of GI sheet, (24 gauge) and enclosed to eradicate the formation of algae. The storage tank was situated on a stand at height 1 m above ground level, and it was linked to the mains through a float valve. The 3 cylindrical tanks were linked in series. The middle tank connected to the main tank through PVC colored pipe was also provided with a float valve to sustain a uniform level of water as that in the still reservoir. The spare water from the stills was collected in a tank and served to the main tank.

Problems and descriptive questions

- 1.1 What factors indicate the increasing demand of pure water on the Earth?
- 1.2 What are the reasons behind the origin of the scarcity of pure water? Explain the facts about the global water crisis.
- 1.3 What is meant by the term “water pollution”? Explain various types of water pollution.
- 1.4 How are wastewater and sewage are responsible for water pollution?
- 1.5 What are the effects of water pollution on human health?

- 1.6 What is meant by the terms “saline water” and “desalination”? Explain.
- 1.7 What is membrane technology? Explain the phenomenon of reverse osmosis (RO).
- 1.8 Briefly explain the working principles of multi-stage flash (MSF) distillation and multi-effect distillation (MED).
- 1.9 Explain the freezing process with a flow chart.
- 1.10 Explain the working principal of the passive-vacuum technique of distillation.
- 1.11 What is solar distillation? Explain the basic principle of solar distillation with a suitable diagram.
- 1.12 What is a solar still or solar distiller? What are its advantages and disadvantages?
- 1.13 What is multi-wick desalination plant? Explain.

Objective Questions

- 1.1 Water available in the human body is in the range of:
 - (a) 50–75%
 - (b) 90–95%
 - (c) 30–40%
 - (d) 70–90%
- 1.2 The percentage of freshwater available on the Earth for drinking is:
 - (a) 10%
 - (b) 1%
 - (c) 5%
 - (d) 50%
- 1.3 Most of the fresh water available on the Earth is in the form of:
 - (a) Aquifers
 - (b) Ice caps and glaciers
 - (c) Surface water
 - (d) Oceans
- 1.4 Potable water is also known as:
 - (a) Drinking water
 - (b) Surface water
 - (c) Seawater
 - (d) Irrigation water
- 1.5 According to the World Health Organization (WHO), how many people do not have access to clean potable drinking water on this planet?
 - (a) 1 of 10
 - (b) 1 out 500
 - (c) 1 of 50
 - (d) 1 out 6

- 1.6 The approximate pH (hydrogen-ion concentration) values of potable water and rain are, respectively:
- (a) 6 and 2.5
 - (b) 7 and 5.6
 - (c) 6 and 6.5
 - (d) 7 and 6.5
- 1.7 The pH (hydrogen-ion concentration) value of potable water lies in the range of:
- (a) 3.5–5
 - (b) 2.4–5
 - (c) 5.6–6
 - (d) 6–7.5
- 1.8 The solution for water scarcity as substitute sources of water is/are:
- (a) Rainwater harvesting
 - (b) Storage of aquifer and recovery
 - (c) Domestic recycling
 - (d) All of these
- 1.9 Which of the following is a point source of water pollution?
- (a) City streets in urban areas
 - (b) Lawns and gardens in a suburban area
 - (c) A sewage-treatment plant
 - (d) An area of farmlands
- 1.10 Which of the following is an example of a non-point source of pollution?
- (a) A sewage-treatment plant
 - (b) Agricultural fertilizers from cropland
 - (c) Industrial drainage through pipes
 - (d) City sewage
- 1.11 Thermal pollution is the largest problem in which of the following locations:
- (a) Groundwater
 - (b) Air
 - (c) Surface water
 - (d) None of these
- 1.12 The amount of energy required producing potable water from any type of feed water is:
- (a) Inversely proportional to salt concentration
 - (b) Independent of salt concentration
 - (c) Directly proportional to salt concentration
 - (d) None of these

1.13 The correct salinity (salt concentration in ppm) of potable water is:

- (a) 0–500
- (b) 500–1000
- (c) 1000–5000
- (d) 30,000–40,000

1.14 The correct salinity (salt concentration in ppm) of brine water is:

- (a) >500
- (b) <5000
- (c) >20,000
- (d) >45,000

1.15 The design of a reverse-osmosis (RO) membrane is based on:

- (a) High pressure and low recovery rates
- (b) Low pressure and low recovery rates
- (c) Low pressure and high recovery rates
- (d) High pressure and high recovery rates

1.16 The method of water purification using the membrane technique is known as:

- (a) Distillation
- (b) Boiling
- (c) Semi-distillation
- (d) Reverse osmosis

1.17 Which of the following process takes place during hydrological cycle for the production of clean or pure water?

- (a) Distillation
- (b) Evaporation
- (c) Condensation
- (d) None of these

1.18 A limitation to the use of the distillation process for the production of potable or drinking-water is:

- (a) Risks of climate-related damages
- (b) Cost effective
- (c) Can purify highly saline water
- (d) No conventional source of energy needed

- 1.19 The yield of a solar still can be enhanced by increasing the temperature difference between:
- (a) The basin and feed water
 - (b) The feed water and inner glass of the cover
 - (c) The basin and ambient
 - (d) All of these
- 1.20 The yield of a solar-distillation unit is a function of following:
- (a) Depth of feed water
 - (b) Climate and area of the unit
 - (c) Facing of the unit
 - (d) All of these

Answers

- 1.1 (a) 1.2 (b) 1.3 (b) 1.4 (a) 1.5 (d) 1.6 (b) 1.7 (c) 1.8 (d) 1.9 (c) 1.10 (b) 1.11 (c) 1.12 (c) 1.13 (a) 1.14 (d) 1.15 (c) 1.16 (d) 1.17 (b) 1.18 (a) 1.19 (b) 1.20 (d)

References

1. R.P. Schwarzenbach, T. Egli, T.B. Hofstetter, U.V. Gunteen, B. Wehrli, Global water pollution and human health. *Annu. Rev. Environ. Resour* **35**, 109–136 (2010)
2. DESWARE, in *Encyclopedia of Desalination and Water Resources*. Retrieved from, <http://www.desware.net>
3. A UN Water analytic Brief. in *Wastewater Management*. Retrieved from, <http://www.unwater.org>
4. W.J. Cosgrove, F.R. Rijsberman, in *World Water Vision. Making Water Everybody's Business* (World Water Council, London, 2000)
5. World Health Organ. (WHO)/UN Child. Fund (UNICEF). in *Progress on Drinking-Water and Sanitation: Special Focus on Sanitation* (WHO/UNICEF, Geneva, Swaziland/New York, 2008), p. 58
6. World Health Organization (WHO)/UN Child. Fund (UNICEF), in *Meeting the MDG Drinking Water and Sanitation Target: The Urban and Rural Challenge of the Decade* (WHO/UNICEF, Geneva, Swaziland/New York, 2006)
7. The United Nations and World Water Development, in *Managing Water under Uncertainty and Risk*. Report 4, 1 (2012)
8. I. Ashmad, S.M.K. Hameed, Solar sterilization of water. *Renew. Energy* **12**, 321 (1997)
9. C. Woodford, in *Water Pollution: an Introduction*. Retrieved from <http://www.explainthatstuff.com>
10. United States Environmental Protection Agency, in *The Facts about Nutrient Pollution*. Retrieved from <http://midwestadvocates.org>
11. K. Kummere, in *Pharmaceuticals in Environment; with Sources, Fate, Effects, and Risks*, 2nd edn. (Springer publication, 2004)
12. International Atomic Agency, in *Disposal of Radioactive Wastes*. Specific Safety Requirements SSR No. **5**, (2011). Retrieved from <http://www-pub.iaea.org/MTCD/publications>

13. A. Fenwick, Waterborne infectious diseases- could they be consigned to history? *Science* **313**, 1077–1081 (2006)
14. G.N. Tiwari, A.K. Tiwari, in *Solar Distillation Practice for Water Desalination Systems* (Anamaya Publishers, 2008)
15. M.A.S. Malik, G.N. Tiwari, A. Kumar, M.S. Sodha, *Solar Distillation* (Pergamon Press, Oxford, UK, 1982)
16. USGS-Science for a changing world, Retrieved from <http://water.usgs.gov>
17. S. K. Sharma, R. Sanghi, in *Advances in Water Treatment and Pollution Prevention* (Springer publication, 2012)
18. T. Younos, K.E. Tulou, Overview of desalination techniques. *Universities council on water resources. J. Contemp. Water Res. Edu.* **132**, 3 (2005)
19. Z. Lu, L. Xu, Freezing desalination process. *J. Therm. Desalin. Process* **2**, 275 (2010)
20. G.D. Yogi, S. Al-Kharabsheh, Experimental study of an innovative solar water desalination system using a passive vacuum technique. *Sol. Energy* **75**, 395 (2003)
21. V. Ryan, in *World Association of Technology Teachers (2001–2009). Water Purification and Simple Technology*. Retrieved from www.technologystudent.com
22. M.M. Naima, M.A.A. El- Kawi, in *Non-conventional Solar Stills with Charcoal Particles as Absorber Medium*. *J. Desalin.* **153**, 55 (2002a)
23. T. Oki, S. Kanae, Global hydrological cycles and world water resources. *Science* **313**, 1068–1072 (2006)
24. P.I. Cooper, The absorption of solar energy radiation in solar stills. *Sol. Energy* **12**, 333 (1969)
25. K.V. Baibut aev, B.M. Achilov, G. Kamaeva, in *Effect of Salt Concentration on Evaporation Process in Solar Stills*. *Geliotekhnika* **6**, 83 (1970)
26. J.W. Bloemer, J.R. Irwin, J.A. Eibling, G.O.G. Lof, A practical basin type solar still. *J. Solar Energy* **9**, 197 (1965)
27. S.D. Gomkale, Solar distillation as a means to provide Indian villages with drinking water. *J. Desalin* **69**, 171 (1988)
28. A. Hanson, W. Zachritz, K. Stevens, L. Mimbela, R. Polka, L. Cisneros, Distillate water quality of a single-basin solar still: laboratory and field studies. *Sol. Energy* **76**, 635 (2004)
29. A. Delyannis, E. Delyannis, in *Solar Distillation Plant of High Capacity*. *Proceedings of 4th International Symposium on Fresh Water from Sea*, vol. 4 (1973), p. 487
30. A. Delyannis, E. Delyannis, Recent solar distillation development. *J. Desalin* **45**, 361 (1983)
31. E. Delyannis, Status of solar assisted desalination: a review. *Desalination* **67**, 3 (1987)
32. E. Delyannis, Historical background of desalination and renewable energies. *J. Solar Energy* **5**, 357 (2003)
33. P.I. Cooper, in *Solar Distillation: State of Art and Future Prospects*. *Solar Energy and Arab World*, *Proceedings of 1st Arab International Solar Energy Conference*, Kuwait (1983), p. 311
34. T.A. Lawand, H. Boutiere, in *Solar Distillation, Its Application in Arid Zone*. *Proceedings of the First Water Symposium on Arid Zone*, Mexico (1970)
35. G. Nebbia, G. Mennozi, in *A Short History of Water Desalination*. *Acque Dolce Dal Mare*, II Inchiasta Internazionale, *Proceedings of Int. Symposium*, Milano (1966), p. 129
36. A. Mouchot, in *La Chaleur Solavie et ses Applications Industrielles* Gauthier- Villars, Paris (1869), p. 1
37. G.B.D. Porta, in *Magiae naturalis libri XX*, Napoli (1589)
38. C.G. Abbot. in *Smithsonian Inst. Ser.*, 2, U.S. Patent No. 2, vol. 141 (1938), p. 330
39. M. Telkes, in *Solar Distiller for Life Rafts*. *United States Office of Science, R&D*, Report No. 5225, P.B. 21120 (1945)
40. E.D. Howe, *Solar Distillation Research at the University of California*. *U.N. Conference on New Source of Energy*, Rome (1961), p. 1
41. A.A. Delyannis, Solar stills provide an Island's inhabitants with water. *Sun at Work* **10**, 6 (1965)
42. A. Delyannis, E. Piperoglou, The patmos solar distillation plant: technical note. *J. Solar Energy* **12**, 113 (1968)

43. F. Oltra, in *Saline Water Conversion and Its Stage of Development in Spain* (Publication of J.E.M., Madrid, 1972)
44. Bartali, in *Chimney and Heated Head Solar Still*, Heliotechnique and Development **11**, p. 431 (1976)
45. E.D. Howe, in *Solar Distillation Research at the University of California*. U.N. Conference on New Source of Energy, Rome, p. 1. References 259 (1961)
46. R.A. Akhtamov, Study of regenerative inclined-stepped solar still. *Geliotekhnika* **14**, 51 (1978)
47. G. Frick, J.V. Sommerfeld, Solar stills of inclined evaporating cloth. *J. Solar Energy* **14**, 427 (1973)
48. M.S. Sodha, J.K. Nayak, G.N. Tiwari, A. Kumar, in Double basin solar still. *J. Energy Convers.* **20**, 23 (1980b)
49. S.M.A. Moustafa, Bruswitz, Direct use of solar energy for water desalination. *Sol. Energy* **22**, 141 (1979)
50. EZh Norov, Results of tests on solar film-covered stills. *Geliotekhnika* **11**, 130 (1975)
51. M.K. Selcuk, in *Analysis, Design and Performance Evaluation of Controlled Environment Greenhouse*. Trans ASHRAE, No. 2172 (1971)
52. M.A.S. Malik, V.V. Tran, A simplified mathematical model for predicting the nocturnal output of a solar still. *Sol. Energy* **14**, 371 (1973)
53. S.A. Lawrence, G.N. Tiwari, Parametric studies of various solar still under PNG climatic conditions. *Int. J. Solar Energy* **7**, 215 (1989)
54. B.M. Mishra, H.K. Sadhukhan, in *Desalination and water reuse in india-an overview*. History Development and Management of Water Resources, 2, BARC, India
55. M.S. Sodha, A. Kumar, G.N. Tiwari, R.C. Tyagi, Simple multiple-wick solar still: analysis and performance. *J. Solar Energy* **26**, 127 (1981)
56. G.N. Tiwari, S.A. Lawrence, Experimental evaluation of solar distiller units with FRP lining under PNG climatic conditions. *Int. J. Solar Energy* **9**, 241 (1991)
57. G.N. Tiwari, in *Recent Advances in Solar Distillation*. Chapter II, Contemporary Physics: Solar Energy and Energy Conversion (Wiley Eastern Ltd., New Delhi, India, 1992)
58. T.A. Lawand, E. Alward, in *A Community Solar Still in Haiti*. Intersol-85, **2**, 1346 (1985)
59. A.I. Kudish, J. Gale, M. Zarmi, A Low Cost Design Solar Desalination Unit. *Energy Conversion and Management* **22**, 269 (1982)
60. J. Fernandez, N. Chargo, Multistage, indirectly Heated Solar Still. *J. Solar Energy* **44**, 215 (1990)
61. A.A. Madani, G.M. Zaki, Performance of Solar Still with Intermittent Flow of West Hot Water in the Basin. *Desalination* **73**, 167 (1989)

Chapter 2

Solar Radiation and Heat Transfer

2.1 Introduction

The Sun (with a diameter of 1.39×10^6 km) comprises intensely hot gaseous matter and is the most abundant source of solar energy in the universe. The Sun is a continuous fusion reactor, and it comprises 75% hydrogen, 24% helium, and 1% other elements. The surface temperature of the Sun is 5777 K. Various thermonuclear processes take place at the interior of the Sun with the most important being hydrogen protons ($n = 4$) combining to form helium (helium nucleus), and the formed final mass is found to be less than the mass of the four protons (the initial mass). This conveys that the lost mass in the reaction has been converted to energy. This energy is produced at temperatures on the order of millions of degrees and is transferred outward at the outer surface of the Sun and further radiates into space [1]. On average, the Sun–Earth distance is 1.5×10^8 km. One half of the Earth is ignited by solar radiation at a time, and it reflects approximately one third of the solar radiation falling on it. This is known as the “albedo” of the Earth.

Heat-transfer mechanism plays an important role in renewable-energy technologies and practical applications. Heat transfer between any two systems takes place as a result of driving force called “temperature difference.” In general, heat is a form of energy that can be transferred from one system to another as a consequence of a difference of temperatures (ΔT) among the two systems. The energy transfer by way of mode of heat transfer occurs through electrical and mechanical processes. It is essential to understand and determine the rates of such heat transfer. In any particular direction, the rate of heat transfer depends on the temperature gradient in that direction, and it increases with an increase in the temperature gradient. Basically, heat is transferred through three modes: conduction, convection, and radiation. These modes of heat transfer are governed by different laws and differ profoundly in nature. Heat transfer through these modes always takes place from the higher surface temperature to the lower one [1, 2] in the modes of transfer of a

solar-distillation system (i.e., conduction, convection, radiation, and evaporation) are discussed in detail in this chapter.

2.2 Solar Radiation

Any object can emit electromagnetic radiation provided that its temperature is >0 K. Solar radiation is a part of electromagnetic radiation that is emitted by the Sun in large amounts through thermonuclear processes. The spectral radiance depends on the emitting properties of the surface and the temperature of an object. The green portion of the visible spectrum gives the maximum solar intensity at a wavelength of $0.48\text{ }\mu\text{m}$. The ultraviolet ($\lambda < 0.4\text{ }\mu\text{m}$) and visible region ($0.4\text{ }\mu\text{m} < \lambda < 0.7\text{ }\mu\text{m}$) of the spectrum consists of approximately 8.73 and 38.15%, respectively. The remaining 52.12% of the total energy is present in the infrared region ($\lambda > 0.70\text{ }\mu\text{m}$). The mechanism of absorption and scattering of solar radiation takes place during the propagation of energy through the atmosphere. Nitrogen, oxygen, and other atmospheric gasses in the ionosphere highly absorb the X-ray and extreme ultraviolet rays of the Sun. The ultraviolet ($\lambda < 0.7\text{ }\mu\text{m}$) and infrared radiations ($\lambda > 2.3\text{ }\mu\text{m}$) are extensively absorbed by the ozone layer. There is almost comprehensive absorption of short-wavelength radiation ($\lambda < 0.29\text{ }\mu\text{m}$). Consequently, there is negligible solar energy available below and above the range of $0.29\text{ }\mu\text{m} < \lambda < 2.3\text{ }\mu\text{m}$ of the spectrum of solar radiation incident on the surface of the Earth [2].

In general, the atmosphere of the Earth has two unique properties:

- (i) It allows short-wavelength radiation having wavelength in the range of $0.29\text{ }\mu\text{m} < \lambda < 2.3\text{ }\mu\text{m}$, and it absorbs ultraviolet and far infrared radiations.
- (ii) It does not allow radiation having wavelength, $\lambda \geq 2.3\text{ }\mu\text{m}$ which is known as “long-wavelength radiation.”

The Earth receives approximately 180×10^8 GW of solar radiation at any one point at a given geographical site. The amount differs between night and day due to the rotation of the Earth as well as between seasons due to the Earth’s orbit. In addition, in space it varies due to the change in obliquity of solar rays with latitude and longitude at any given time. In general, the amount of power received by the Earth at a given location and time depends on the relative Sun–Earth position. Due to this reason, time and Sun–Earth geometry plays a vital role for solar-energy conversion. Therefore, it is essential to understand the Sun–Earth angles, which are discussed later in the text.

The determination of solar flux either on a horizontal surface or on a surface perpendicular to the solar radiation gives the energy flux of the beam radiation on an arbitrarily oriented surface. If the beam flux (I) on a plane surface is incident at an angle θ_i , then the flux incident on the plane surface becomes $I \cos \theta_i$.

Table 2.1 Different orientations of solar distillation system (Northern hemisphere)

Solar distillation system	Orientation	Inclination in different weather condition				
		Solar still		FPC ^a		Annual
		Summer	Winter	Summer	Winter	
Passive single slope	Due South	$\phi - 15^\circ$	$\phi + 15^\circ$	–		ϕ
Passive double slope	East–West	$\phi - 15^\circ$	$\phi + 15^\circ$	–		ϕ
Active single slope (FPC)	Due South	$\phi - 15^\circ$	$\phi + 15^\circ$	$\phi - 15^\circ$	$\phi + 15^\circ$	ϕ
Active double slope (FPC)	East–West	$\phi - 15^\circ$	$\phi + 15^\circ$	$\phi - 15^\circ$	$\phi + 15^\circ$	ϕ

Note ^aOrientated only due south

Latitude (ϕ): The latitude of a location is the angle made by the radial line joining the given location to the center of the Earth with its projection on the equatorial plane. For the Northern Hemisphere, the latitude is positive, and it is negative for the Southern Hemisphere. The different orientations of solar distillation systems for Northern Hemisphere are given in Table 2.1.

Declination (δ): Declination is defined as the angle between the line joining the centers of the Sun and the Earth and its projection on the equatorial plane, and it is due to the rotation of the Earth on its own axis. It makes an angle of 660.5° with the plane of its rotation around the Sun. The range of the declination angle varies from 230.45° on June 21 (maximum value) to -230.45° on December 21 (minimum value). It is expressed as follows:

$$\delta = (23.45) \sin \left[\left(\frac{360}{365} \right) (284 + n) \right] \quad (2.2.1)$$

Hour angle (ω): This is the angle through which the Earth must rotate to bring the meridian of the plane directly under the Sun. In other words, it is the angular displacement of the Sun east or west of the local meridian due to the rotation of the Earth on its axis at 15° per hour. The hour angle is zero at solar noon, negative in the morning, and positive in the afternoon. The expression for the hour angle is given by the following:

$$\omega = (ST - 12)15^\circ \quad (2.2.2)$$

where ST is local solar time.

Zenith (θ_z): This is defined as the angle between the Sun's rays and a perpendicular line to the horizontal plane.

Altitude or solar-altitude angle (β): This is defined as the angle between the Sun's rays and a horizontal plane. In addition, $\alpha = 90^\circ - \theta_z$.

Slope (β): This is the angle between the plane surface under consideration and the horizontal. It is taken to be positive for surfaces sloping toward the south and negative for surfaces sloping toward the north.

Table 2.2 Surface azimuth angle (γ) for various orientations in Northern hemisphere [2]

Surface orientation	γ
Sloped towards South	0°
Sloped towards North	180°
Sloped towards East	-90°
Sloped towards West	$+90^\circ$
Sloped towards South-East	-45°
Sloped towards South-West	$+45^\circ$

Surface-azimuth angle (γ): This is the angle in the horizontal plane between the line due south and the projection of the normal to the surface (inclined plane) on the horizontal plane. By convention, the angle will be taken to be negative for the Northern Hemisphere (India) and positive for the Southern hemisphere (Australia) if the projection is east of south and positive if it is west of south. The values of γ for some orientations are listed in Table 2.2.

Solar-azimuth angle (γ_s): This is the angle in a horizontal plane between the line due south and the projection of beam radiation on the horizontal plane. By convention, the angle is taken to be positive and negative, respectively, if the projection is east of south and west of south for the Northern Hemisphere (India) and vice versa for the Southern Hemisphere.

Angle of incidence (θ_i): This is the angle between beam radiation on a surface and normal to that surface. In general, the angle of incidence (θ_i) can be expressed as follows:

$$\cos \theta_i = (\cos \varphi \cos \beta + \sin \varphi \sin \beta \cos \gamma) \cos \delta \cos \omega + \cos \delta \sin \omega \sin \beta \sin \gamma + \sin \delta (\sin \varphi \cos \beta - \cos \varphi \sin \beta \cos \gamma) \quad (2.2.3)$$

For a horizontal plane facing due south, $\gamma = 0$, $\beta = 0$, $\theta = \theta_z$ (zenith angle)

$$\cos \theta_z = \cos \varphi \cos \delta \cos \omega + \sin \delta \sin \varphi. \quad (2.2.4)$$

There is only 1.7% variation between the Sun and Earth during the orbital motion of the Earth around the Sun. The solar radiation outside the Earth's atmosphere remains at nearly fixed intensities. The surface of unit area receives the radiant energy flux per second outside the atmosphere. Moreover, the unit surface area, which held normal to the direction of the solar radiations at the mean Sun–Earth distance, basically remains constant all year long. This is known as the “solar constant” (I_{sc}) and has a numerical value of 1367 W/m^2 . Extraterrestrial radiation (I_{ext}) varies due to the elliptical path of the Earth around the Sun (at one of the foci). The solar intensity of extraterrestrial radiation, in terms of solar constant I_{sc} measured on the n th day of the year on a plane normal to the radiation, is given as follows

$$I_{ext} = I_{sc} \left[1 + 0.033 \cos \left(\frac{360n}{365} \right) \right] \quad (2.2.5)$$

2.3 Solar Radiation on an Inclined Surface

The total solar radiation incident on a surface is a combination of the following:

- (a) Beam radiation (I_b) or direct radiation: The solar radiation propagating along the line joining receiving surface and the Sun;
- (b) Diffuse radiation (I_d): The solar radiation scattered by dust, aerosols, and molecules etc.; it does not have any particular direction of propagation; and
- (c) Solar radiation reflected from the ground and surroundings.

After knowing beam and diffuse radiation on horizontal surface, the total radiation or global radiation on a surface of any arbitrary orientation (β) of solar thermal device (for east, south, north, and west) for $\gamma = \pm 90^\circ, \pm 180^\circ$ and 0° (Table 2.2) can be obtained from the formulae given by Liu and Jordan [3]:

$$I_T = I_b R_b + I_d R_d + \rho R_r (I_b + I_d) \quad (2.3.6)$$

where R_b , R_d and R_r are known as conversion factors for the beam, diffuse, and reflected components, respectively; and ρ is the reflection coefficient of the ground (0.6 and 0.2 for snow and ordinary covered ground, respectively). The expressions for R_b , R_d and R_r are given below:

- (i) R_b : This is defined as the ratio of the flux of beam radiation incident on an inclined surface to that on a horizontal surface. Therefore, R_b for beam radiation can be obtained as follows:

$$R_b = \frac{I'_b}{I_b} = \frac{\cos \theta_i}{\cos \theta_z}$$

- (ii) R_d : This is defined as the ratio of the flux of diffuse radiation falling on the tilted surface to that on the horizontal surface.

The distribution of diffuse radiation over the sky as well, as portion of the sky exposed to the surface, defines the value of R_d . No reasonable method has been developed for the evaluation of diffuse radiation distribution over the sky.

However, it is widely considered that the sky is an isotropic source of diffuse radiation. If the radiation shape factor for a tilted surface with respect to sky is $(1 + \cos \beta)/2$, then

$$R_d = \frac{1 + \cos \beta}{2}$$

- (iii) R_r : The ground and other surrounding objects are responsible for the origin of the reflected component. Considering the reflected radiation as diffuse and isotropic (the situation opposite to the above case), then

$$R_r = \frac{1 - \cos \beta}{2}$$

It may be mentioned here that both R_b and R_d undergo reflection from the ground and surroundings. The effective ratio of incident solar energy on a surface to that on a horizontal surface is given as follows:

$$R' = \frac{I_T}{I_b + I_d} = \frac{I_b R_b + I_d R_d}{I_b + I_d} + \rho R_r$$

To obtain the total radiation from Eq. (2.3.6), the beam and diffused radiation can be calculated from the following methods.

2.3.1 First Method

According to Singh and Tiwari [4] (by knowing the experimental values of beam and diffused radiation), the rate of beam (direct) radiation reaching the terrestrial region can be expressed as

$$I_N = I_{\text{ext}} \exp[-(m\varepsilon T_R + \alpha')] \quad (2.3.7)$$

The expression of I_{ext} is given in Eq. (2.2.5).

Where m is air mass; T_R is the turbidity factor; ε is the atmosphere's optical thickness of an integrated Rayleigh scattering; and α' is the lumped atmospheric parameter for the beam radiation. The parameters m and ε are given as [5, 6] follows:

$$m = \frac{1}{\left[\cos \theta_z + 0.15(93.88 - \theta_z)^{-1.25} \right]} \quad (2.3.8)$$

and

$$\varepsilon = (4.53 \times 10^{-4})m^2 - (9.67 \times 10^{-3})m + 0.1080 \quad (2.3.9)$$

Therefore, the terrestrial beam radiation is expressed by classical equation as follows:

$$I_b = I_N \cos \theta_z = I_{\text{ext}} \exp[-(m\varepsilon T_R + \alpha')] \cos \theta_z \quad (2.3.10)$$

where α' determines an additional reduction of the direct normal radiation in the terrestrial region due to different climatic conditions such as cloudiness/haziness as well as transient and unpredictable changes.

On the horizontal surface, the diffused radiation can be rewritten as follows:

$$I_d = K_1(I_{\text{ext}} - I_N)\cos\theta_z + K_2 \quad (2.3.11)$$

where K_1 (dimensionless) and K_2 (W/m^2) are constants of lumped atmospheric parameters for diffuse radiation. Furthermore, the constant K_1 can be inferred as a *perturbation factor* for describing the scattering out of a beam traversing the lumped atmosphere, and K_2 can be expressed as background diffuse radiation.

2.3.2 Second Method

The following expression for the beam and diffuse radiation on the horizontal surface can be used (case of non-availability of data for the beam and diffuse radiation):

$$I_b = I_N \cos\theta_z \quad (2.3.12)$$

$$I_d = \frac{1}{3}[I_{\text{ext}} - I_N]\cos\theta_z \quad (2.3.13)$$

and

$$I_N = I_{\text{ext}} \exp\left[\frac{-T_R}{(0.9 + 9.4 \sin \alpha)}\right] \quad (2.3.14)$$

The expression of I_{ext} is given in Eq. (2.2.5). T_R is the turbidity factor, and it depends on the sky conditions (clear, cloudy, and hazy) as well as different regions (mountain, flat land, city, desert, or forest etc.). The turbidity factors for different months and locations are listed in Table 2.4.

After knowing the beam and diffuse radiation on a horizontal surface, total radiation on a surface of arbitrary orientation (east, south, west and north $\gamma = -90^\circ, 0, +90^\circ$ and $\pm 180^\circ$ for a given latitude (ϕ)) can be evaluated from the Liu and Jordan formulae as given in Eq. (2.3.6).

Example 2.1 Calculate the total solar radiation from (a) the first method and (b) the second method for an inclined surface having an inclination of 10° facing east at 11 am for New Delhi on 23 September 2015 ($T_R = 4.75$ and $\rho = 0.2$). Use the parameters listed in Table 2.3 for the first method (Table 2.4).

Solution

$$\varphi = 28.58^\circ; \beta = 28.58^\circ; \gamma = -90^\circ (\text{East surface}); n = 266; \text{ST} = 11 \text{ a.m.}$$

$$\delta = 23.45 \sin \left[\left(\frac{360}{365} \right) (284 + n) \right] = -1.0088^\circ; \omega = (11 - 12) \times 15^\circ = -15^\circ$$

Table 2.3 Evaluated parameters (T_R , α' , K_1 , K_2) for average weather conditions for New Delhi climatic conditions New Delhi climatic conditions

Month factor	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
T_R	2.65	2.94	3.39	3.49	4.58	7.33	4.49	3.77	4.75	4.33	3.60	4.28
α'	0.33	0.28	0.25	0.38	0.35	0.39	1.03	1.02	0.35	0.03	0.04	-0.04
K_1	0.40	0.41	0.43	0.44	0.46	0.49	0.40	0.37	0.39	0.28	0.16	0.34
K_2	-12.12	-14.51	-12.08	-08.62	-15.56	-49.59	-39.26	-24.69	-19.53	+29.68	+65.18	+4.66

Table 2.4 The turbidity factor (T_R) for different months and locations

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mountain	1.8	1.9	2.1	2.2	2.4	2.7	2.7	2.7	2.5	2.1	1.9	1.8
Flat land	2.2	2.2	2.5	2.9	3.2	3.4	3.5	3.3	2.9	2.6	2.3	2.2
City	3.1	3.2	3.5	3.9	4.1	4.2	4.3	4.2	3.9	3.6	3.3	3.1

Note For cloudy condition $T_R = 10.0$

From Eqs. (2.2.3) and (2.2.4),

$$\begin{aligned}\cos(\theta_i) &= 0.872 \quad \text{or} \quad \theta_i = \cos^{-1}(0.872) = 29.33^\circ \\ \cos(\theta_z) &= 0.8396 \quad \text{or} \quad \theta_z = \cos^{-1}(0.8396) = 32.9^\circ\end{aligned}$$

Conversion factors:

$$R_b = \frac{0.872}{0.8396} = 1.038; R_d = \frac{1 + \cos(10)}{2} = 0.9924; R_r = \frac{1 - \cos(10)}{2} = 0.0076$$

$$I_{\text{ext}} = 1367 \times \left[1 + 0.033 \cos\left(\frac{360 \times 266}{365}\right) \right] = 1361 \text{ W/m}^2$$

(a) **First method**

$$\begin{aligned}m &= \frac{1}{\left[\cos \theta_z + 0.15(93.88 - \theta_z)^{-1.25} \right]} = 1.190 \\ \varepsilon &= (4.53 \times 10^{-4})m^2 - (9.67 \times 10^{-3})m + 0.1080 = 0.0965\end{aligned}$$

From Table 2.3, $T_R = 4.75$, $\alpha' = 0.35$, $K_1 = 0.39$, $K_2 = -19.53$

$$\begin{aligned}I_N &= I_{\text{ext}} \exp[-(m\varepsilon T_R + \alpha')] = 558.90 \text{ W/m}^2 \\ I_b &= I_N \cos \theta_z = I_{\text{ext}} \exp[-(m\varepsilon T_R + \alpha')] \cos \theta_z = 469.27 \text{ W/m}^2 \\ I_d &= K_1(I_{\text{ext}} - I_N) \cos \theta_z + K_2 = 243 \text{ W/m}^2\end{aligned}$$

From Eq. (2.3.6)

$$I_T = I_b R_b + I_d R_d + \rho R_r (I_b + I_d) = 1082 \text{ W/m}^2$$

(b) **Second method**

$$I_N = 1361 \times \exp \left[\frac{-4.75}{(00.9 + 9.4 \sin(90 - 32.9))} \right] = 793.12 \text{ W/m}^2$$

$$I_b = I_N \cos \theta_z = 665.92 \text{ W/m}^2$$

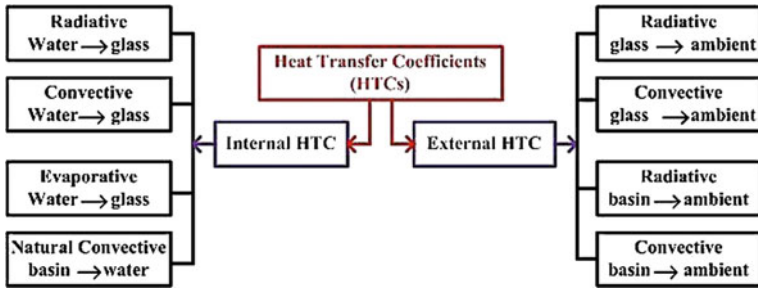
$$I_d = \frac{1}{3} [I_{\text{ext}} - I_N] \cos \theta_z = 158.93 \text{ W/m}^2$$

From Eq. (2.3.6),

$$I_T = I_b R_b + I_d R_d + \rho R_r (I_b + I_d) = 691.22 + 157.7 + 1.25 = 850.1 \text{ W/m}^2$$

2.4 Heat Transfer

The heat transfer in a solar-distillation system can be broadly categorized as (i) internal heat transfer and (ii) external heat transfer as described in the flow chart. These are the most desired heat transfers in a solar-distillation system.



The mechanism of internal heat transfer takes place through the modes of evaporation, convection, and radiation. In contrast, external heat transfer involves conduction, convection, and radiation processes. In the solar-distiller cavity, heat transfer is accomplished by transport of the vapor formed above the water surface through an air–vapor mixture. The internal heat-transfer mechanism is accountable for the conveyance of pure or potable water in vapor form leaving behind all of the impurities remains in the basin of the distillation system. The external heat transferring through the condensing cover is accountable for the condensation of pure vapor as distillate [2, 7, 8].

External heat transfer takes place from the glass cover, the sides of the insulation, and the bottom to the ambient air. The side and bottom losses (external heat transfers) of the distillation system are undesirable. Therefore, it is essential to

minimize heat transfer from the sides and bottom as much as possible for the better performance of the system. The different modes of heat transfer in a solar-distillation system are as discussed in detail later in the text.

2.4.1 Conduction

The process of conduction takes place in solids, liquids, or gases, in which the high energetic particles of the substance transfers energy to adjacent low energetic ones as a consequence of interaction between the particles.

The collision and diffusion of molecules occurs in gases and liquids due to their random motion, which is responsible for the conduction. In solids, it is due to the energy transfer by free electrons and the combination of vibrations of the molecules in a lattice.

Geometry of the medium plays an essential role for the heat-conduction rate, i.e., the temperature difference across the medium as well as thickness and material of the medium. For example, the rate of heat loss from a hot-water tank can be reduced by wrapping it with glass wool, which is an insulating material. Heat loss is less with greater thickness of the insulation. Moreover, the quick heat loss by a hot water tank with a lower surrounding temperature is a well-known fact.

Let us consider a steady-state heat condition through a large plane wall with thickness $\Delta x = L$, surface area A (always normal to the direction of heat transfer); and temperature difference across the wall ΔT . According to Fourier's law of heat conduction, the rate of heat transfer ($\dot{Q}$) through the wall is

$$\dot{Q} = -KA \frac{dT}{dx} \quad (2.4.15)$$

where constant K is the normal conductivity of the material, which determines the material's ability to conduct heat. The above-mentioned relation specifies that the rate of heat conduction in any arbitrary direction increases with an increase in temperature gradient in that direction. This implies that heat conduction occurs in the direction of low temperature such that the temperature gradient becomes negative when temperature decreases with increasing x . Therefore, a negative sign is added in Eq. (2.4.15) to indicate heat transfer in the positive direction.

2.4.2 Convection

The temperature gradient is the driving force for all of the modes of heat transfer. The temperature difference between the fluid and any hot surface in contact with the fluid causes the density gradient in between the layers of fluid above the surface, thus resulting in buoyancy. Consequently, the developed motion of fluid above the surface is called "free convection" or "natural convection." However, the

convection is called “forced convection” if forces arise from an externally imposed pressure difference. The natural- and forced-convection processes may sometimes occur simultaneously.

Mathematically, the rate of heat transfer by convection within the boundary layer of a cooled fluid that is in contact with a hot surface is described by a general equation:

$$\dot{Q} = h_{cw} A \Delta T \quad (2.4.16)$$

where h_{cw} convective heat-transfer coefficient ($\text{W/m}^2 \text{ } ^\circ\text{C}$), A area responsible for heat transfer (m^2); and ΔT temperature difference between the fluid and surface of the body.

In Eq. (2.4.16), the crux of the problem is to evaluate the convective heat-transfer coefficient (h_{cw}). It is a convoluted function of the parameters (a) the geometry of the surface, (b) the flow characteristics of the fluid, (c) the physical properties of the fluid at operating temperature, and (d) the operating-temperature range.

Heat-transfer coefficients are evaluated from empirical relations in most of the practical cases. These empirical relations have been developed by correlating experimental outcomes with the help of the dimensional-analysis method. The thermo-physical properties and heat-transfer correlations of different nanofluids are also given in Appendix E.

Dimensionless heat-convection parameters

Nusselt number (Nu): The *Nusselt* number illustrates the process of heat transfer at the solid–fluid boundary, and it is the ratio of convective heat transfer to heat transfer by conduction in the fluid. It is usually unknown in problems of convection because it includes the heat-transfer coefficient (h_{cw}), which is an unknown parameter.

Let us consider a fluid layer of thickness d and temperature difference, (T). Heat transfer through the fluid layer could take place by way of the mode of conduction when the fluid layer is motionless, and it occurs by way of the mode of convection when the fluid involves some motion (natural or forced). The rate of heat transfer per unit time per unit surface area (heat flux) in either case will be as follows:

$$\dot{q}_{\text{conv}} = h_{cw} \Delta T \quad (2.4.17)$$

$$\dot{q}_{\text{cond}} = \left(\frac{k}{d} \right) \Delta T \quad (2.4.18)$$

From the above-mentioned two equations, according to the definition of the *Nusselt* number (Nu):

$$Nu = \frac{h_{cw}}{(k/d)} \quad (2.4.19)$$

This represents the enhancement of heat transfer through a fluid layer as a result of convection relative to conduction across the same fluid layer. For the larger value of *Nusselt* number, the convection is more effective. It is unity for a fluid layer, in which heat transfer takes place through the mode of pure conduction only.

Reynold's number (Re): This is the ratio of the fluid dynamic force (ρv_0^2) to the viscous drag force ($\mu v_0/X$):

$$Re = \frac{\rho v_0 X}{\mu} \quad (2.4.20)$$

where μ . the dynamic viscosity; ρ is the density; and X is the characteristic length. *Reynold's* number describes the flow behavior in forced convection. Furthermore, it serves as a criterion for the stability of laminar flow.

Prandtl number (Pr): This is the ratio of momentum diffusivity (μ/ρ) to the thermal diffusivity ($K/\rho C_p$):

$$Pr = \frac{\mu C_p}{K} \quad (2.4.21)$$

Through the diffusion mechanism, the specific heat (C_p) gives the relative effectiveness of momentum transport in the velocity boundary layer over the thermal-energy transport in the thermal boundary layer. It is unity for gasses.

Grashof number (Gr): This is the ratio of the buoyancy force to the viscous force.

$$Gr = \frac{g \beta d^3 \rho^2 \Delta T}{\mu^2} \quad (2.4.22)$$

where g is the gravitational acceleration; β is the coefficient of volumetric thermal expansion; and ΔT is the temperature gradient. It signifies the flow regime in natural convection. Low *Grashof* number corresponds to the laminar flow, whereas its large value indicates the turbulent flow in natural convection.

Rayleigh number (Ra): This is the ratio of thermal buoyancy to viscous inertia. The *Rayleigh* number (Ra) for a fluid is related with buoyancy-driven flow, and it is a dimensionless number, also known as “free convection” or “natural convection.” If the *Rayleigh* number is below a critical value for a particular fluid, then heat transfer primarily occurs in the form of conduction, whereas it takes place in the form of convection when it exceeds the critical value. In general, the transition in a boundary layer of the fluid in natural convection depends on the relative magnitude of the viscous and buoyancy forces. It is correlated in terms of the *Rayleigh's* number, which is the product of *Grashof* number (Gr) and *Prandtl* number (Pr).

$$Ra = Gr Pr \quad (2.4.23)$$

The *Reynold* (Re), *Prandtl* (Pr), and *Grashof* (Gr) numbers are evaluated by using the physical properties at the average temperatures (T_f) of two surfaces. The thermo-physical properties of water vapor; water vapor and air mixture; and water (basefluid) are given in Tables 2.5, 2.6, and 2.7 respectively. For the other shape, the characteristic dimension (X) is given by the following:

$$X = \frac{A}{P} \quad (2.4.24)$$

where A and P is area and perimeter of the surface, respectively, which is generally used for the irregular shape. For a rectangular horizontal surface ($L_0 \times B_0$), it can be evaluated by (Table 2.8)

$$X = \frac{L_0 + B_0}{2} \quad (2.4.25)$$

Example 2.2 For a passive double-slope solar still, calculate the convective heat-transfer coefficient from the blackened surface (basin liner) to (a) the water (basefluid) and (b) the nanofluid (Al_2O_3 nanoparticles) for the following parameters:

Water mass (M_w) = 40 kg, solar still area (A_b) = $2 \text{ m} \times 1 \text{ m}$, ambient temperature (T_a) = 35°C , average glass temperature (T_{gi}) = 50.7°C , solar intensity ($I(t)$) = 940 W/m^2 , wind velocity (v) = 1.5 m/s , $C = 0.54$, $n = 0.25$, inclination angle (θ) = 30° , characteristic length (d) = 1.5 m , absorptivity of glass (α_g) = 0.85 , absorptivity of water (α_w) = 0.65 , absorptivity of basin (α_b) = 0.8 , $\epsilon_{\text{eff}} = 0.741$, and thermal conductivity of glass (K_g) = $0.004 \text{ (W/m}^\circ\text{C)}$.

Properties of Al_2O_3 nanoparticles: $C_{pp} = 880 \text{ (J/kg K)}$, $\beta_p = 8.1 \times 10^{-6} \text{ (K}^{-1}\text{)}$, $\phi_p = 0.004\%$, $\rho_p = 3.89 \times 10^3 \text{ (kg/m}^3\text{)}$, thermal conductivity of particle $k_p = 39.5 \text{ (W/m}^\circ\text{C)}$, diameter of nanoparticle (d_p) = 15 nm .

Take temperature of water (T_w) = 72.25°C , Temperature of nanofluid (T_{nf}) = 74.45°C .

Solution

- (a) From Table 2.7, all of the thermo-physical properties of water can be obtained as

$$\rho_w = 9.7716 \times 10^3 \text{ (kg/m}^3\text{)}, \mu_w = 0.3984 \times 10^{-3} \text{ (kg/ms)}, k_w = 0.661 \text{ (W/m}^\circ\text{C)}, C_w = 4.190 \times 10^3 \text{ (J/kg K)}, \beta_w = 0.0029 \text{ K}^{-1}$$

$$Nu = C(GrPr)^n = 2.289 \times 10^2; \text{ where, } Gr = \frac{g\beta d^3 \rho^2 \Delta T}{\mu^2} \text{ and } Pr = \frac{\mu C_p}{k}$$

$$\text{Convective heat-transfer coefficient } (h_{cw}) = Nu \times \left(\frac{k_w}{d}\right) = 100.9 \text{ (W/m}^2 \text{ }^\circ\text{C)}$$

Table 2.5 Thermo physical properties of vapor [2]

Quantity	Symbol	Expression
Specific heat	C_v	$999.2 + 0.1434 \times (T_v) + 1.101 \times (T_v^2) - 6.7581 \times 10^{-8} \times (T_v^3)$
Density	ρ_v	$353.44 / (T_v + 273.15)$
Thermal conductivity	k_v	$0.0244 + 0.7673 \times 10^{-4} \times (T_v)$
Viscosity	μ_v	$1.718 \times 10^{-5} + 4.620 \times 10^{-8} \times (T_v)$
Latent heat of vaporization of fluid	L	$3.1625 \times 10^6 + [1 - (7.616 \times 10^{-4} \times (T_v))]; \text{ for } T_v > 70^\circ\text{C}$
		$2.4935 \times 10^6 [1 - (9.4779 \times 10^{-4} \times (T_v) + 1.3132 \times 10^{-7} \times (T_v^2) - 4.7974 \times 10^{-3} \times (T_v^3))]; \text{ for } T_v < 70^\circ\text{C}$
Partial vapor pressure at condensing cover and fluid temperature	P_{gi}	$P(\text{gi}) = \exp \left[25.317 - \left(\frac{5144}{T(\text{gi}) + 273} \right) \right]$
		$P(\text{fluid}) = \exp \left[25.317 - \left(\frac{5144}{T(\text{fluid}) + 273} \right) \right]$
Thermal expansion coefficient	β_v	$1 / (T_v + 273.15)$

Table 2.6 Thermo physical properties of water vapor and air mixture [28]

Quantity	Expression
Specific heat	$C_{pm} = \frac{C_{pu}(P_0 - P_v)M_u + C_{pv}P_vM_v}{M_u(P_0 - P_v) + P_vM_v} \quad (\text{kJ/kg K})$
	Correlations of dry air and water vapor specific heat capacity;
	$C_{pa} = CA_0 + CA_1(T) + CA_2(T^2) + CA_3(T^3) + CA_4(T^4)$
	250 K < T < 1050 K
	$CA_0 = 1.034, CA_1 = -0.284 \times 10^{-3}, CA_2 = 0.781 \times 10^{-6},$
	$CA_3 = -0.497 \times 10^{-9}, CA_4 = 0.1077 \times 10^{-12}$
	$C_{pv} = CV_0 + CV_1(T) + CV_2(T^2) \quad 0^\circ\text{C} < T < 120^\circ\text{C}$
	$CV_0 = 1.869, CV_1 = -2.578 \times 10^{-4}, CV_2 = 1.941 \times 10^{-5}$
	Specific heat capacity of the saturated mixture (kJ/kg K) is fitted by the following fourth order polynomial;
	$C_{pm} = CP_0 + CP_1(T) + CP_2(T^2) + CP_3(T^3) + CP_4(T^4)$
Density	$CP_0 = 1.0880, CP_1 = -0.010577, CP_2 = 4.7691 \times 10^{-4},$
	$CP_3 = -7.898 \times 10^{-6}, CP_4 = 5.122 \times 10^{-8}$
	$\rho_m = \left(\frac{P_0}{RT}\right) \left\{ M_a \left[1 - RH \left(\frac{P_v}{P_0} \right) \right] + M_v RH \left(\frac{P_v}{P_0} \right) \right\} \quad (\text{kg/m}^3)$
	$\bar{R} = 8.314 (\text{kJ/k mol}^\circ\text{K}); RH = \frac{P_v}{P_{sv}}$
	$P_{sv} = A_0 + A_1(T) + A_2(T^2) + A_3(T^3) + A_4(T^4)$
	$10^\circ\text{C} < T < 110^\circ\text{C}$
	$A_0 = 1.132, A_1 = -3.75 \times 10^{-2}, A_2 = 5.591 \times 10^{-3},$
	$A_3 = -6.6220 \times 10^{-5}, A_4 = 1.105 \times 10^{-6}$
	The saturated humid air mixture density (kg/m ³) is fitted by the following third order polynomial function;
	$\rho_m = RO_0 + RO_1(T) + RO_2(T^2) + RO_3(T^3)$
	$RO_0 = 1.299, RO_1 = -6.0436 \times 10^{-3}, RO_2 = 4.697 \times 10^{-5},$
	$RO_3 = -5.760 \times 10^{-7}$
(continued)	

Table 2.6 (continued)

Quantity	Expression
Thermal conductivity	$k_m = k_a(1 - x_v) + k_v x_v \quad (\text{W/m K})$
	Correlations of dry air and water vapor thermal conductivity;
	$k_a = \text{KA}_0 + \text{KA}_1(T) + \text{KA}_2(T^2) + \text{KA}_3(T^3) + \text{KA}_4(T^4) + \text{KA}_5(T^5); \quad (\text{W/mK})$
	250 K < T < 1050 K
	$\text{KA}_0 = -2.276 \times 10^{-3}, \text{KA}_1 = 1.260 \times 10^{-4}, \text{KA}_2 = -1.481 \times 10^{-7},$
	$\text{KA}_3 = 1.735 \times 10^{-10}, \text{KA}_4 = -1.0660 \times 10^{-13}, \text{KA}_5 = 2.476 \times 10^{-17}$
	$k_v = \text{KV}_0 + \text{KV}_1(T) + \text{KV}_2(T^2); \quad (\text{W/m K}) \times 10^{-3}$
	$0 < T < 120^\circ \text{C}$
	$\text{KV}_0 = 17.617; \text{KV}_1 = 0.0555, \text{KV}_2 = 0.000166$
	Thermal conductivity of the saturated mixture (W/m K) is fitted by the following third order polynomial function;
Viscosity	$k_m = \text{K}_0 + \text{K}_1(T) + \text{K}_2(T^2) + \text{K}_3(T^3)$
	$\text{K}_0 = 0.0241; \text{K}_1 = 5.526 \times 10^{-5}; \text{K}_2 = 4.631 \times 10^{-7};$
	$\text{K}_3 = -9.438 \times 10^{-9}$
	$\mu_m = \frac{\mu_a(P_0 - P_v)\sqrt{M_a} + \mu_v P_v \sqrt{M_v}}{(P_0 - P_v)\sqrt{M_a} + P_v \sqrt{M_v}} \quad (\text{Ns/m}^2)$
	Correlations of dry air and water vapor viscosity;
	$\mu_a = \text{MA}_0 + \text{MA}_1(T) + \text{MA}_2(T^2) + \text{MA}_3(T^3) + \text{MA}_4(T^4)$
	$(\text{Ns/m}^2) \times 10^{-6} \quad -23^\circ \text{C} \ll T \ll 327^\circ \text{C}$
	$\text{MA}_0 = -0.986, \text{MA}_1 = 9.08 \times 10^{-2}, \text{MA}_2 = -1.176 \times 10^{-4},$
	$\text{MA}_3 = 1.123 \times 10^{-7}, \text{MA}_4 = -5.797 \times 10^{-11}$
	$\mu_v = \text{MV}_0 + \text{MV}_1(T); \quad (\text{Ns/m}^2) \times 10^{-6} \quad 0^\circ \text{C} \ll T \ll 120^\circ \text{C}$
	$\text{MV}_0 = 80.58, \text{MV}_1 = 0.400$
	Viscosity of the saturated humid air (Ns/m ²) is fitted by the fourth order polynomial function;
	$\mu_m = \text{MU}_0 + \text{MU}_1(T) + \text{MU}_2(T^2) + \text{MU}_3(T^3) + \text{MU}_4(T^4)$
	$\text{MU}_0 = 1.685 \times 10^{-5}, \text{MU}_1 = 9.151 \times 10^{-8},$
	$\text{MU}_2 = -2.16 \times 10^{-9}, \text{MU}_3 = 3.413 \times 10^{-11}, \text{MU}_4 = -2.645 \times 10^{-13}$

(continued)

Table 2.6 (continued)

Quantity	Expression
Thermal diffusivity	$\alpha_m = \frac{k_{m-}}{\rho_m c_m} \quad (\text{m}^2/\text{s})$
	Thermal diffusivity of saturated air mixture (m^2/s) at the temperature range of interest, is fitted by the following fourth order polynomial expression;
	$\alpha_m = \text{TD}_0 + \text{TD}_1(T) + \text{TD}_2(T^2) + \text{TD}_3(T^3)$
	$\text{TD}_0 = 1.88 \times 10^{-5}, \text{TD}_1 = 8.0276 \times 10^{-8}, \text{TD}_2 = 1.496 \times 10^{-9},$
	$\text{TD}_3 = -2.1124 \times 10^{-11}$

a dry air, *m* mixture, *v* water vapor, *M* molar mass of humid air, *T* temperature, *w* water

(b) From Appendix E,

$$\begin{aligned} C_{nf} &= \frac{[(\varphi_p \rho_p C_p + (1 - \varphi_p) \rho_w C_w)]}{\rho_w} = 4164.2 \text{ (J/kg K)}; \rho_{nf} = \varphi_p \rho_p + (1 - \varphi_p) \rho_w \\ &= 1.0954 \times 10^3 \text{ (kg/m}^3\text{)}; \mu_{nf} = \mu_w [1 + 2.5(\varphi_p) + 6.2\varphi_p^2] \\ &= 0.4327 \times 10^{-3} \text{ (kg/ms)} \end{aligned}$$

$$\begin{aligned} k_{nf} &= k_w \left[1 + (1.0112)\varphi_p + (2.4375)\varphi_p \left(\frac{47}{d_p(\text{nm})} \right) - (0.0248)\varphi_p \left(\frac{k_p}{0.613} \right) \right] \\ &= 0.7544 \text{ (W/m}^\circ\text{C)}; \beta_{nf} = (1 - \varphi_p)\beta_w + \varphi_p\beta_p = 0.0028 \text{ K}^{-1}. \end{aligned}$$

$$Nu = C(GrPr)^n = 7.1848 \times 10^2; \text{ where, } Gr = \frac{g\beta d^3 \rho^2 \Delta T}{\mu^2} \text{ and } Pr = \frac{\mu C_p}{k}$$

$$\text{Convective heat transfer coefficient } (h_{cw}) = Nu \times \left(\frac{k_{nf}}{d} \right) = 361.3 \text{ (W/m}^2\text{ }^\circ\text{C)}$$

Free convection

In free or natural flow, the homogeneity of mass forces acting on the considered volume of the fluid is responsible for the origin of motion of the volume. If this natural flow has not been distributed within a space by solid boundaries, then it is referred to as “free convection.” Consequently, the temperature gradient among the fluid and the contacting surface originates the fluid motion for free convection. This occurs due to the terrestrial gravitational field acting on the fluid with a non-uniform density distribution. Particularly in rotating systems, free convective heat transfer is influenced through centrifugal and Coriolis forces.

Depending on type of the flow (laminar or turbulent, free or forced), the heat-transfer coefficient is usually incorporated with the *Nusselt* number.

For free convection:

$$Nu = C(GrPr)^n K' \quad (2.4.26)$$

where C and n are the constants. The above-mentioned relation is derived from the dimensionless-analysis method. The values of the constants C and n depend on the geometry of similar bodies and can be obtained by correlation of experimental data of the bodies. Free convective heat transfer of various geometries is listed in Table 2.8. The correlation factor K' in the relation is introduced to signify the entire physical behavior of the problem. Moreover, some empirical relations used for free convection are listed in Table 2.9.

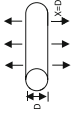
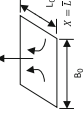
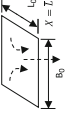
Forced convection

In the process of forced convection, a pump or a fan is incorporated for forcing the fluid flow over the surface to create fluid motion artificially. For this purpose, an

Table 2.7 Thermo physical properties of water (basefluid) [29]

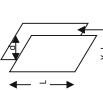
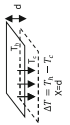
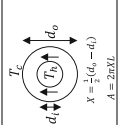
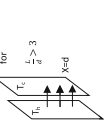
Quantity	Symbol	Expression
Density	ρ_{bf}	$999.79 + 0.0683 \times T_{bf} - 0.0107 \times T_{bf}^2 + 0.00082 \times T_{bf}^{2.5} - 2.303 \times 10^{-5} \times T_{bf}^3$
Specific heat	C_{bf}	$4.217 - 0.00561 \times T_{bf} + 0.00129 \times T_{bf}^{1.5} - 0.000115 \times T_{bf}^2 + 4.149 \times 10^{-6} \times T_{bf}^{2.5}$
Viscosity	μ_{bf}	$\frac{(557.82 - 19.408 \times T_{bf} + 0.136 \times T_{bf}^2 - 3.116 \times 10^{-4} \times T_{bf}^3)}{1}$
Thermal conductivity	k_{bf}	$0.565 + 0.00263 \times T_{bf} - 0.000125 \times T_{bf}^{1.5} - 1.515 \times 10^{-6} \times T_{bf}^2 - 0.000941 \times T_{bf}^{0.5}$

Table 2.8 Free convective heat transfer of various systems [2]

System	Schematic	C'	n	k'	Operating conditions
Horizontal cylinder		0.47	0.25	1	Laminar flow condition
		0.1	–	1	Turbulent flow condition
		0.0246	0.4	$[Pr^{-1/6}/((1+0.496Pr^{2/3})^{1/2})]^{2/3}$	Turbulent flow condition; to obtain local Nu use $C' = 0.0296$, $X = x$
Vertical cylinder with small diameter		0.686	0.25	$[Pr/(1+1.05Pr)]^{1/4}$	Laminar flow condition $Nu_{local} = \overline{Nu} + 0.52(L/D)$
Heated horizontal plate facing upward		0.54	0.25	1	Laminar flow condition ($10^5 < GrPr < 2 \times 10^7$) $X = (L_0 + B_0)/2$ Laminar flow condition ($10^7 < GrPr < 10^{11}$), $X = A/P$ for circular disc of diameter D , use $X = 0.9D$
		0.14	0.33	1	Turbulent flow condition ($2 \times 10^7 < GrPr < 3 \times 10^7$), $X = (L_0 + B_0)/2$
		0.15	0.33	1	Turbulent flow condition ($10^7 < GrPr < 10^{11}$), $X = A/P$
Heated horizontal plate facing downward		0.27	0.25	1	Laminar flow condition only

(continued)

Table 2.8 (continued)

System	Schematic	C'	n	k'	Operating conditions
Moderately inclined plane		0.8	0.25	$\left[\frac{\cos \theta}{1 + \left(\frac{1}{\sqrt{Pr}} \right)^2} \right]^{1/4}$	Laminar flow condition (multiply Gr by $\cos \theta$ in the formula for vertical plate)
Two vertical parallel plates at the same temperature		0.04	1	$(d/L)^3$	Air layer
Hollow vertical cylinder with open ends		0.01	1	$(d/L)^3$	Air column
Two horizontal parallel plates hot plate uppermost		0.27	0.25	1	Pure conduction $\dot{q} = K(T_h - T_c)/d$ Laminar flow condition (air) ($3 \times 10^5 < GrPr < 3 \times 10^{10}$)
Two concentric cylinders		0.317	0.25	$\left[X^3 \left(\frac{1}{d_1^{3/5}} + \frac{1}{d_2^{3/5}} \right) \right]^{-1/4}$	Laminar flow condition
Two vertical parallel plates of different temperatures (h for both surfaces)		0.18	0.25	$\left(\frac{L}{d} \right)^{-1/9} (Pr)^{-1/4}$	Laminar flow condition (air) ($2 \times 10^4 < Gr < 2 \times 10^5$)
		0.065	–	$\left(\frac{L}{d} \right)^{-1/9} (Pr)^{-1/3}$	Turbulent flow condition (air) ($2 \times 10^5 < Gr < 2 \times 10^7$)

(continued)

Table 2.8 (continued)

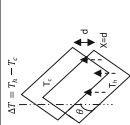
System	Schematic	C'	n	k'	Operating conditions
Two inclined parallel plates				$\overline{Nu} = \frac{[\overline{Nu}_{vert} \cos \theta + \overline{Nu}_{horiz} \sin \theta]}{2}$	
Two horizontal parallel plates cold plate uppermost		0.195	0.25	$P_r^{1/4}$	Laminar flow condition (air) ($10^4 < Gr < 4 \times 10^5$)
		0.068	–	$P_r^{1/3}$	Turbulent flow condition (air) $Gr > 4 \times 10^5$

Table 2.9 Simplified equations for free convection from various surfaces to air at atmospheric pressure

Cases	Surface	Laminar $10^4 < Gr_f Pr_f < 10^9$	Turbulent $Gr_f Pr_f > 10^9$
1	Horizontal hot plate facing upward	$h = 1.32(\Delta T/L)^{1/4}$	$h = 1.52(\Delta T)^{1/3}$
2	Hot plate facing downward	$h = 0.59(\Delta T/L)^{1/4}$	
3	Vertical plane and cylinder	$h = 1.42(\Delta T/L)^{1/4}$	$h = 1.31(\Delta T)^{1/3}$
4	Horizontal cylinder	$h = 1.32(\Delta T/d)^{1/4}$	$h = 1.24(\Delta T)^{1/3}$

external energy is provided to balance the process, which includes two types of forces viz. (a) the frictional force produced by viscosity $\left(\mu \frac{dv}{dy}\right)$ and (b) the fluid pressure related to flow velocity $\left(\frac{1}{2} \rho v^2\right)$. The non-dimensional *Reynold* number signifies their relative importance in heat transfer. Furthermore, it directs the flow (laminar or turbulent) in the boundary layer, and the rate of heat transfer is closely connected to it.

Forced convection:

$$Nu = C(RePr)^n K' \quad (2.4.27)$$

Forced convective heat transfer by way of cylindrical tubes can be expressed by the following empirical relation:

$$\overline{Nu} = \frac{hD}{K_{th}} = CRe^m Pr^n K' \quad (2.4.28)$$

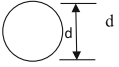
where $D = 4\left(\frac{A}{P}\right)$ is the hydraulic diameter (m); A is the area (m^2); P is the perimeter of the section (m); and K_{th} is the thermal conductivity (W/mK). For various conditions, the values of C , m , n and K are given in Table 2.10.

In the case of fully developed laminar flow in the tubes at constant wall temperature gives the following relation:

$$Nu_d = 0.36 + \left[0.0668 \left(\frac{d}{L}\right) RePr\right] \left\{1 + 0.04 \left[\left(\frac{d}{L}\right) RePr\right]^{\frac{2}{3}}\right\}^{-1} \quad (2.4.29)$$

The obtained heat-transfer coefficient from the above-mentioned relation is an average value over the entire length of the tube. The *Nusselt* number approaches a constant value of 3.66 for sufficient length of the tube. The *Nusselt* number for the heated plate over its entire length can be calculated by integrating the following equation over the plate length:

Table 2.10 The value of constants for forced convection

Cross-section	D	C	m	n	K	Operating conditions
	d	3.66	0	0	1	Laminar flow case long tube $Re < 2000$, $Gz < 10$
	d	1.86	0.33	0.33	$(d/l)^{1/3}(\mu/\mu_w)^{0.14}$	Laminar flow case short tube for $Re < 2000$, $Gz > 10$
	d	0.027	0.8	0.33	$(\mu/\mu_w)^{0.14}$	Turbulent flow case of highly viscous liquids for $0.6 < Pr < 100$
	d	0.023	0.8	0.4	1	Turbulent flow case of gases $Re > 2000$

$$Nu_x = 0.332(Pr)^{1/3}(Re_x)^{1/2} \quad (2.4.30)$$

$$\bar{h} = \frac{1}{L} \int_0^L \frac{K}{x} (0.332)(Pr)^{1/3}(Re_x)^{1/2} dx = \frac{K}{L} (0.332)(Pr)^{1/3} \int_0^L \frac{1}{x} \left(\frac{v_0 x}{\vartheta} \right) dx$$

$$\frac{K}{L} (0.332)(Pr)^{1/3} (2) \left(\frac{v_0 L}{\vartheta} \right)^{1/2} = \frac{K}{L} (0.664)(Pr)^{1/3} (Re_L)^{1/2}$$

Therefore,

$$\overline{Nu}_L = 0.664(Pr)^{1/3}(Re_L)^{1/2} \quad (2.4.31)$$

In a solar-distillation system, the internal heat-transfer coefficient of convection from the blackened (basin) horizontal surface to the fluid mass, and vice versa, is evaluated from Eqs. (2.4.26) and (2.4.27) for free convection and forced convection, respectively. The numerical values of C and n for different cases are given as follows:

Direction of heat flow	C	n
Upward (hot surface facing upward)	0.54	1/4
Downward (hot surface facing downward)	0.27	1/4

In contrast, the internal heat-transfer coefficient of convection from a fluid surface to the inner surface of a condensing cover can be evaluated from the famous Dunkle's relation:

$$h_{cw} = 0.844 \left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})(T_w + 273)}{(268.9 \times 10^3 - P_w)} \right]^{\frac{1}{3}} \quad (2.4.32)$$

where

$$P(T) = \exp \left[25.317 - \left(\frac{5144}{273 + T} \right) \right] \quad (2.4.33)$$

The Dunkle's relation was discussed in detail in Sect. 2.6. The variation of saturation vapor pressure (Eq. 2.4.33) with temperature is shown in Fig. 2.1.

Example 2.3 Calculate (a) the *Grashof* number (*Gr*), the *Prandtl* number (*Pr*), and the *Rayleigh* number (*Ra*) for temperature difference 20 °C and fluid-layer thickness 0.30 m and (b) the *Nusselt* number for free convection for a hot surface facing upward ($C = 0.54, n = 0.25$). Use $X_0 = 1.5$.

Solution

- (a) From the thermo-physical properties of vapor listed in Table 2.5
Specific heat,

$$\begin{aligned} C_p &= 999.2 + 0.1434 \times (40) + 1.101 \times (40)^2 - 6.7581 \times 10^{-8} \times (40)^3 \\ &= 1005.11 \text{ J/kg } ^\circ\text{C} \end{aligned}$$

$$\text{Density, } \rho = \frac{353.44}{(40 + 273.15)} = 1.128 \text{ kg/m}^3$$

$$\text{Thermal conductivity, } k = 0.0244 + 0.7673 \times 10^{-4} \times (40) = 0.0275 \text{ W/m K}$$

$$\text{Viscosity, } \mu = 1.718 \times 10^{-5} + 4.620 \times 10^{-8} \times (40) = 1.9028 \times 10^{-5} \text{ kg/ms}$$

$$\text{Thermal-expansion coefficient, } \beta = \frac{1}{(40 + 273.15)} = 0.00319 \text{ K}^{-1}$$

$$\begin{aligned} \text{(i)} \quad Gr &= \frac{g\beta d^3 \rho^2 \Delta T}{\mu^2} = \frac{9.8 \times 0.00319 \times (0.30)^3 \times (1.128)^2 \times 20}{(1.9028 \times 10^{-5})^2} \\ &= 0.29 \times 10^7 \cong 3 \times 10^6 \end{aligned}$$

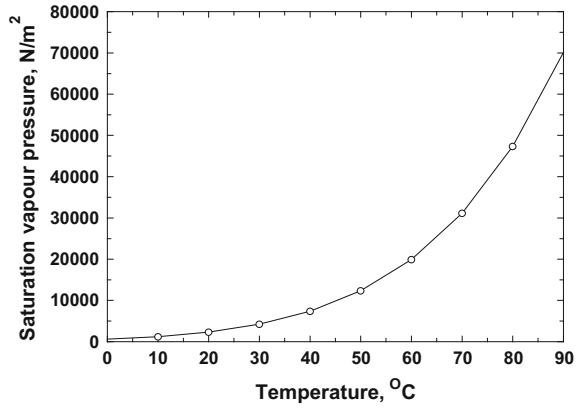
$$\text{(ii)} \quad Pr = \frac{(1.9028 \times 10^{-5}) \times (1005.11)}{0.0275} = 0.695$$

$$\text{(iii)} \quad Ra = (3 \times 10^6) \times 0.695 = 2.095 \times 10^6$$

$$\text{(b) Nusselt number: } Nu = C(GrPr)^n = 0.54 \times (2.085 \times 10^6)^{0.25} = 37.9$$

Example 2.4 Estimate the rate of heat loss from a horizontal rectangular surface (1.0 m × 0.8 m) maintained at 134 °C and exposed in the upward direction to an environment at 22 °C. Use $\frac{\mu}{\rho} = 2.08 \times 10^{-5} \text{ m}^2/\text{s}$, $Pr = 0.697$.

Fig. 2.1 Variation of saturation vapor pressure with temperature



Solution

The average film temperature, $T_f = (134 + 20)/2 = 77^\circ\text{C}$

$$\beta = \frac{1}{(77 + 273.15)} = \frac{1}{(293.15)} \text{ K}^{-1}$$

For the characteristic dimension of

$$(a) \quad L = \frac{A}{P} = \frac{0.8}{3.6} = 0.222 \text{ m}$$

$$GrPr = \left[\frac{9.8 \times 0.00319 \times (0.222)^3 \times 114}{(293.15) \times (2.08 \times 10^{-5})^2} \right] (0.679) = 6.72 \times 10^7$$

For the condition of the hot surface facing upward and the turbulent flow, the heat-transfer coefficient can be evaluated as follows:

$$\begin{aligned} h &= \left(\frac{K}{L} \right) (0.15) (GrLPr)^{0.333} = \left(\frac{0.03}{0.222} \right) (0.15) (6.72 \times 10^7)^{0.333} \\ &= 8.23 \text{ W/m}^2 \text{ } ^\circ\text{C} \end{aligned}$$

Hence, the rate of heat loss from the hot plate to the surrounding ambient air is:

$$\dot{Q} = hA(T_1 - T_2) = 8.23(1.0 \times 0.8)(134 - 20) = 751 \text{ W}$$

$$(b) \quad X = \frac{(L_0 + B_0)}{2} = 0.9$$

$$GrPr = 4.47 \times 10^7 \text{ and } h = \left(\frac{0.03}{0.9}\right)(0.14)(4.47 \times 10^7)^{1/3} = 7.74 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Hence, the rate of heat loss from the hot plate to the surrounding ambient air is:

$$\dot{Q} = hA(T_1 - T_2) = 7.742(1.0 \times 0.8)(134 - 20) = 706 \text{ W}$$

Example 2.5 Calculate the convective heat-transfer coefficient from the Dunkle's model for a passive single-slope solar-distillation system having a temperature of water surface and inner surface of the condensing cover of 50 and 30 °C, respectively.

Solution

From Eq. (2.4.33),

$$P_w = \exp \left[25.317 - \left(\frac{5144}{273 + 50} \right) \right] = 11983.71$$

$$P_{gi} = \exp \left[25.317 - \left(\frac{5144}{273 + 30} \right) \right] = 4188.5$$

Hence,

from

Eq. (2.4.32),

$$h_{cw} = 0.844 \left[(20) + \frac{(11983.71 - 4188.5)(50 + 273)}{(0.269 - 11983.71)} \right]^{\frac{1}{3}} = 2.74 \text{ W/m}^2 \text{ K}$$

2.4.3 Radiation

Thermal radiation comes from a source and propagates through some material or medium. It is the transfer of heat by electromagnetic waves ($0.1 \mu\text{m} \leq \lambda \leq 100 \mu\text{m}$) from a body at greater temperature to another one at lower temperature. Thermal radiation follows the same rules as that of light, and it lies in the infrared range. The collision of thermal radiation with any object is absorbed by that object and is converted into the heat form.

Radiation involving real surfaces

When a body is exposed to radiant energy, a part of it is reflected; another part of it is absorbed; and the rest is transmitted through that body. According to the law of conservation, the total sum must be equal to the incident radiation as follows:

$$I_T = I_r + I_a + I_t \quad \text{and} \quad \rho' + \alpha' + \tau' = 1$$

where ρ' , α' , and τ are the reflectivity, absorptivity, and transmissivity of the intercepting body, respectively. For an opaque surface, $\tau = 0$; therefore, $\rho' + \beta' =$

1. However, when $\rho' = \tau' = 0$, $\alpha' = 1$, that is, the substance absorbs the entire energy incident on it, and such a substance is called a “black body.” Similarly, $\alpha' = \tau' = 0$ and $\rho' = 1$ for a white body, which reflects the total radiation falling on it.

The absorbed energy is transformed into heat, and this heated body emits radiation by virtue of its temperature. Therefore, the radiant energy emitted per unit area of a surface in unit time is referred to as the “emissive power.”

Sky radiation

A certain equivalent black-body sky temperature is established in order to determine the radiation exchange between the sky and a body. It accounts for the fact of non-uniformity of the atmospheric temperature and radiates only in particular wavelength sections. Accordingly, the net radiation to a surface with emittance ϵ and temperature T is as follows:

$$\dot{Q} = A\epsilon\sigma(T_{\text{sky}}^4 - T^4) \quad (2.4.34)$$

Various expressions have been given by many researchers and engineers to express the equivalent sky temperature (T_{sky}). These relations are only approximations, although they are simple to use. The relation between the sky temperature and the local air temperature can be given by the following relation:

$$T_{\text{sky}} = 0.0552T_a^{1.5} \quad (2.4.35)$$

where T_{sky} and T_a are both in degrees Kelvin. Another commonly used relation is given as [8]

$$T_{\text{sky}} = T_a - 6 \quad (2.4.36)$$

or

$$T_{\text{sky}} = T_a - 12 \quad (2.4.37)$$

Radiative heat-transfer coefficient

The water surface and the surface of the condensing cover of a solar-distillation system are treated as the case of infinite parallel planes for understanding radiation. Justification of the validity of this consideration is due to the larger width and smaller inclination angle of the transparent top glass cover of the system. The rate of radiative heat transfer ($\dot{q}_{\text{rw}}$) among the evaporative and the condensing cover, which are considered infinite parallel planes, is given as follows:

$$\dot{q}_{\text{rw}} = \sigma\epsilon_{\text{eff}}F_{12} \left[(T_w + 273)^4 - (T_{\text{gi}} + 273)^4 \right] \quad (2.4.38)$$

or

$$\dot{q}_{rw} = h_{rw} F_{12} (T_w + T_{gi}) \quad (2.4.39)$$

where F_{12} is view factor, which is considered unity only for a small inclination of the condensing cover. Therefore, the radiative heat-transfer coefficient (h_{rw}) from the evaporative surface to the inner surface of the condensing cover can be expressed as follows:

$$h_{rw} = \sigma \epsilon_{\text{eff}} \left[(T_w + 273)^2 + (T_{gi} + 273)^2 \right] (T_w + T_{gis} + 546) \quad (2.4.40)$$

where $\frac{1}{\epsilon_{\text{eff}}} = \frac{1}{\epsilon_w} + \frac{1}{\epsilon_g} - 1$

The value of the radiative heat-transfer coefficient (h_{rw}) varies between 7–10 W/m² °C, and it is almost independent of temperature for a normal operating range of the temperature <80 °C.

Example 2.6 Calculate the radiative heat-transfer coefficient between the water surface ($T_w = 50$ °C) and the inner surface of a condensing cover ($T_{gi} = 30$ °C) of a passive solar-distillation system. Use $\epsilon_w = \epsilon_g = 0.9$ and $F_{12} = 1$.

Solution

$$\epsilon_{\text{eff}} = \left[\frac{1}{0.9} + \frac{1}{0.9} - 1 \right]^{-1} = 0.82$$

$$h_{rw} = 0.82 \times 5.64 \times 10^{-8} \left[(50 + 273)^2 + (30 + 273)^2 \right] (80 + 546) = 5.66 \text{ W/m}^2 \text{ K}$$

Example 2.7 Calculate the rate of long wavelength–radiation exchange (R) between the ambient air and the sky temperature for $T_a = 15$ °C.

Solution

By using $\Delta R = [(T_a + 273)^4 - (T_{\text{sky}} + 273)^4]$

$$T_{\text{sky}} = 0.0552(15)^{1.5} = 3.2 \text{ °C}; T_{\text{sky}} = 15 - 6 = 9 \text{ °C}; T_{\text{sky}} = 15 - 12 = 3 \text{ °C}$$

Now,

$$\begin{aligned} \Delta R &= 5.64 \times 10^{-8} [(15 + 273)^4 - (3.2 + 273)^4] = 59.58 \text{ W/m}^2 \\ &= 5.64 \times 10^{-8} [(15 + 273)^4 - (9 + 273)^4] = 31.22 \text{ W/m}^2 \\ &= 5.64 \times 10^{-8} [(15 + 273)^4 - (3 + 273)^4] = 60.52 \text{ W/m}^2 \end{aligned}$$

It is essential to mention here that the value of T_{sky} is nearly same for both the cases; thus, the numerical value of ΔR should be considered as 60 W/m².

2.4.4 Evaporation

Internal heat transfer is responsible for transporting the pure water in the form of vapor leaving behind impurities in the basin of the distillation system. Evaporative and convective heat transfer are the most desired types of internal heat transfer in a solar-distillation system. Heat transfer by way of the mode of evaporation takes place from the water surface to the inner surface of the condensing cover, and convective heat transfer occurs simultaneously with the evaporative heat transfer. These two mechanisms of heat transfer are independent of radiative heat transfer. The temperature difference among the evaporative surface and the inner surface of the condensing cover acts as a driving force for a solar-distillation system. The rate of evaporative heat transfer, or productivity (yield) of the system, increases with increasing temperature difference between these two surfaces in the distiller cavity. The transfer of heat per unit area per unit time by the mode of evaporation in a solar-distillation system and is given by the *Cooper and Dunkle* model, which is discussed in detail later in the text.

Cooper and Dunkle model The mass of air per unit area per unit time by free convection is given by the following:

$$M_a = \frac{\dot{q}_{cw}}{C_{pa}(T_w - T_{gi})} = \frac{h_{cw}}{C_{pa}} \quad (2.4.41)$$

It is assumed that the air next to the evaporative surface is saturated at the water temperature. Consequently, the specific humidity or water mass per mass of the dry air can be expressed as follows:

$$\left(\frac{M_w}{M_a}\right) \left(\frac{P_w}{P_T - P_w}\right) \quad (2.4.42)$$

Thus, the mass of water vapor transferred per unit area per unit time from the water surface is:

$$M_{v,ws} = \left(\frac{M_w}{M_a}\right) \left(\frac{P_w}{P_T - P_w}\right) \left(\frac{h_{cw}}{C_{pa}}\right) \quad (2.4.43)$$

Similarly, the mass of water vapor transferred per unit area per unit time from the glass surface is given by the following:

$$M_{v,gs} = \left(\frac{M_w}{M_a}\right) \left(\frac{P_{gi}}{P_T - P_{gi}}\right) \left(\frac{h_{cw}}{C_{pa}}\right). \quad (2.4.44)$$

Baum and Bairamov [9] found that the bulk of the air has an insignificant rate of exchange of water vapor with the interface layers between the water and the glass

surface. The net mass of water vapor transferred per unit area per unit time is given by the difference of expression of Eqs. (2.4.43) and (2.4.44) as follows:

$$\Delta M = \left(\frac{M_w}{M_a} \right) \left(\frac{h_{cw}}{C_{pa}} \right) \left[\frac{P_w}{P_T - P_w} - \frac{P_{gi}}{P_T - P_{gi}} \right] \quad (2.4.45)$$

The rate at which heat is transferred from the water surface to the glass cover on account of the mass transfer of the water vapor is:

$$\dot{q}_{ew} = L \left(\frac{M_w}{M_a} \right) \left(\frac{h_{cw}}{C_{pa}} \right) \left[\frac{P_T}{(P_T - P_w)(P_T - P_{gi})} \right] (P_w - P_{gi}) \quad (2.4.46)$$

or

$$\dot{q}_{ew} = h_{ew} (P_w - P_{gi}) \quad (2.4.47)$$

The values of P_w and P_g are significantly low than the values of P_T in a practical situation. Consequently, it is justified to assume that $(P_T - P_w)(P_T - P_{gi})$ is approximately equal to P_T^2 . Hence, from Eq. (2.4.46), the evaporative or equivalent mass transfer coefficient (h_{ew}) may then be written in terms of the convective heat-transfer coefficient (h_{cw}) as follows:

$$\frac{h_{ew}}{h_{cw}} = \left(\frac{L}{C_{pa}} \right) \left(\frac{M_w}{M_a} \right) \left(\frac{1}{P_T} \right) \quad (2.4.47)$$

The above-mentioned equation can also be obtained by using the Lewis' relation (1922, 1933):

$$\frac{h_{cw}}{h_D \rho_a C_{pa}} = 1 \quad (2.4.48)$$

where h_D is the mass-transfer coefficient (m/h); and ρ is the partial mass density of water vapor (kg/m^3). At a constant pressure of the mixture, the specific heat per unit volume is equal to the ratio of the heat-transfer coefficient to the mass-transfer coefficient.

h_D is defined as the mass-transfer rate ($\dot{m}$) per unit area from the water surface as follows:

$$\frac{\dot{m}}{A} = h_D (P_w - P_a) \quad (2.4.49)$$

On substituting h_D from Eq. (2.4.48) in the perfect gas equation ($PV = RT'$, for water vapor), one can obtain:

$$\frac{\dot{m}}{A} = \left(\frac{h_{cw}}{\rho_a C_{pa}} \right) \left(\frac{M_w}{RT'} \right) (P_w - P_a) \quad (2.4.50)$$

The reasonable approximation $T' \approx T'_w \approx T'_a$ is assumed. Therefore, the quantity of evaporative heat transferred on account of the mass transfer of the water vapor per unit area per unit time is as follows:

$$\dot{q}_{ew} = L \left(\frac{\dot{m}}{A} \right) = L \left(\frac{h_{cw}}{\rho_a C_{pa}} \right) \left(\frac{M_w}{RT'} \right) (P_w - P_a) = h_{ew} (P_w - P_a) \quad (2.4.51)$$

where

$$h_{ew} = L \left(\frac{h_{cw}}{\rho_a C_{pa}} \right) \left(\frac{M_w}{RT'} \right) \quad \text{Or} \quad \frac{h_{ew}}{h_{cw}} = \left(\frac{L}{\rho_a C_{pa}} \right) \left(\frac{M_w}{RT'} \right) \quad (2.4.52)$$

Using the perfect gas equation for air, one obtains:

$$RT' = \frac{M_a P_a}{\rho_a} \quad (P_a = \text{atmospheric pressure})$$

With above consideration, Eq. (2.4.52) can be expressed as follows:

$$\frac{h_{ew}}{h_{cw}} = \left(\frac{L}{C_{pa}} \right) \left(\frac{M_w}{M_a} \right) \left(\frac{1}{P_T} \right) \quad (2.4.53)$$

Since $P_T = P_a$ for small P_w as discussed previously, Eq. (2.4.53) is similar to Eq. (2.4.47). On substituting the suitable values of different parameter, the evaporative heat-transfer coefficient can be obtained as follows:

$$h_{ew} = 0.013(h_{cw}) \quad (2.4.54)$$

The value of $\left(\frac{h_{ew}}{h_{cw}} \right)$, obtained in the above-mentioned equation, is smaller than the value obtained by Bowen [10] and Dunkle [11]. This is due to the approximation made previously to neglect the terms P_w and P_{gi} on expanding the factor $(P_T - P_w)(P_T - P_{gi})$. It has been studied that the most significant depiction of the evaporative or mass heat-transfer phenomena is obtained for the value 16.273×10^{-3} of $\left(\frac{h_{ew}}{h_{cw}} \right)$. Thus; the evaporative heat transferred per unit area per unit time can be given by:

$$\dot{q}_{ew} = 16.273 \times 10^{-3} (h_{cw}) (P_w - P_{gi}) \quad (2.4.55)$$

Or the evaporative heat-transfer coefficient can be expressed as follows:

$$h_{ew} = 16.273 \times 10^{-3} (h_{cw}) \left(\frac{P_w - P_{gi}}{T_w - T_{gi}} \right) \quad (2.4.56)$$

The generalized expression of pressure, which is a function of temperature, is given as follows:

$$P(T) = \exp \left[25.317 - \left(\frac{5144}{273 + T} \right) \right] \quad (2.4.57)$$

Equation (2.4.55) can also be re-expressed as follows:

$$\dot{q}_{ew} = h_{ew} (T_w - T_{gi}) \quad (2.4.58)$$

The rate of mass transfer ($\dot{m}_{ew}$) is given by:

$$\dot{m}_{ew} = \frac{\dot{q}_{ew}}{L} \quad (2.4.59)$$

Example 2.8 Evaluate the evaporative heat-transfer coefficient for Example 2.5.

Solution

From example 2.5, $h_{cw} = 2.74 \text{ W/m}^2 \text{ K}$

Thus, $h_{ew} = 16.273 \times 10^{-3} (2.74) \left(\frac{7795.21}{20} \right) = 17.378 \text{ W/m}^2 \text{ K}$

Total internal heat transfer

As discussed in Chap. 1, internal heat transfer from the evaporative surface to the inner surface of the condensing cover takes place by three modes viz. evaporation, convection, and radiation. The rate of total internal heat transfer ($\dot{q}_{lw}$) is the combination of these three modes of heat transfer. The rate of total internal heat transfer can be expressed as follows:

$$\dot{q}_{lw} = \dot{q}_{cw} + \dot{q}_{rw} + \dot{q}_{ew} \quad (\text{W/m}^2) \quad (2.4.60)$$

and the total internal heat-transfer coefficient is:

$$h_{lw} = h_{cw} + h_{rw} + h_{ew} \quad (\text{W/m}^2 \text{ } ^\circ\text{C}) \quad (2.4.61)$$

where the convective (h_{cw}), radiative (h_{rw}), and evaporative (h_{ew}) heat-transfer coefficients are given in Eqs. (2.4.32), (2.4.40), and (2.4.56) respectively.

The energy fraction of each mode gives a superior understanding of all three modes of internal heat transfers. Heat transfer by way of each mode is expressed as a fraction of the total heat transfer in order to understand the relative significance or

contribution of the magnitudes of each mode of heat transfer [2, 7]. Thus, the evaporative, convective, and radiative energy fractions can be obtained as follows:

$$F_c = \frac{\dot{Q}_{cw}}{\dot{Q}_1}; F_e = \frac{\dot{Q}_{ew}}{\dot{Q}_1} \text{ and } F_r = \frac{\dot{Q}_{rw}}{\dot{Q}_1} \quad (2.4.62)$$

where

$$\dot{Q}_1 = \dot{Q}_{cw} + \dot{Q}_{rw} + \dot{Q}_{ew} (W) \quad (2.4.63)$$

Figure 2.2 shows the variation of these three energy fractions with respect to water temperature for indoor simulation as determined by Cooper [12, 13].

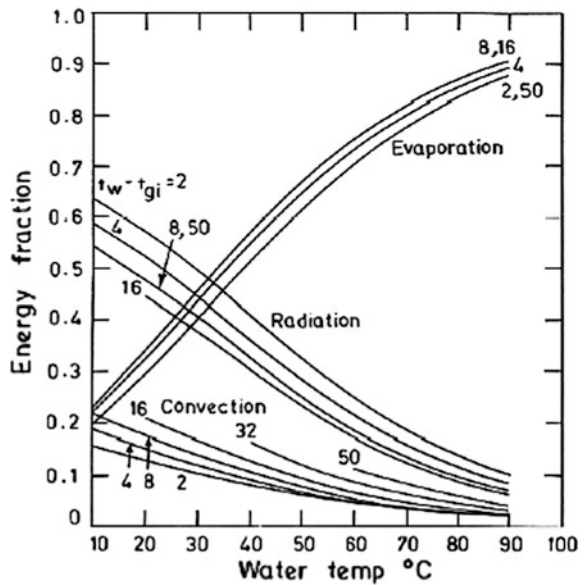
Total external heat transfer

(a) Top-loss coefficient

A fraction of the incident solar radiation is absorbed by the small thickness of the condensing cover of the solar-distillation system. Consequently, the heat transfer from the outer surface of the top condensing cover to the atmosphere takes place by way of convection and radiation. The total rate of external heat transfer from the top surface can be expressed as follows:

$$\dot{q}_g = \dot{q}_{rg} + \dot{q}_{cg} \quad (2.4.64)$$

Fig. 2.2 Variation of evaporative, convective and radiative energy fraction with respect to the water temperature as found by the Cooper (1973) (2.1/14/SDB)



The rate of radiative heat transfer from the condensing surface to the atmosphere is given as follows:

$$\dot{q}_{rg} = \sigma \epsilon_g \left[(T_g + 273)^4 - (T_{sky} + 273)^4 \right] \quad (2.4.65)$$

Or

$$\dot{q}_{rg} = h_{rg} (T_g - T_a) \quad (2.4.66)$$

where

$$h_{rg} = \frac{\sigma \epsilon_g \left[(T_g + 273)^4 - (T_{sky} + 273)^4 \right]}{(T_g - T_a)} \quad (2.4.67)$$

The rate of convective heat transfer from the condensing surface to the ambient air is expressed as:

$$\dot{q}_{cg} = h_{cg} (T_g - T_a) \quad (2.4.68)$$

On substituting $(\dot{q}_{rg})$ and $(\dot{q}_{cg})$ in Eq. (2.4.64), one can obtain the following:

$$\dot{q}_g = h_{lg} (T_g - T_a) \quad (2.4.69)$$

where

$$h_{lg} = h_{rg} + h_{cg} \quad (2.4.70)$$

The empirical relation for the top-loss coefficient (h_{lg}) is discussed later in the text. Several workers analyzed the heat transfer from a flat plate exposed to outside winds. The following equation for the convective heat-transfer coefficient was reported by McAdams [30]:

$$h_c = 5.7 + 3.8 V \quad \text{for } 0 \leq V \leq 5 \text{ m/s} \quad (2.4.71)$$

where V is the wind speed (m/s).

For zero wind speed, the above-mentioned Eq. 2.4.71 gives heat loss by natural convection. Here, the case is very complex because wind may not always flow parallel to the heating/cooling surface.

Watmuff et al. [31] modified Eq. 2.4.71 by including the effect of free convection and radiation and reported that this equation should be as follows:

$$h_c = 2.8 + 3V \quad \text{for } 0 \leq V \leq 7 \text{ m/s} \quad (2.4.72)$$

(b) Bottom- and side-loss coefficient

Heat loss from the basin water to the atmosphere also takes place through the insulating body of the distillation system such that it occurs by way of convection and radiation from the bottom and side surfaces of the system. The bottom-loss coefficient (U_b) can be expressed as follows:

$$U_b = \left[\frac{1}{h_w} + \frac{1}{h_b} \right]^{-1} = \left[\frac{1}{h_w} + \frac{L_i}{K_i} + \frac{1}{(h_{cb} + h_{rb})} \right]^{-1} \quad (2.4.73)$$

where K_i and L_i are the thermal conductivity and thickness of insulation respectively.

The side heat-loss coefficient (U_e) can be estimated as

$$U_e = U_b \left(\frac{A_{ss}}{A_s} \right) \quad (2.4.74)$$

where, A_s is the area of the basin of the solar-distillation system and A_{ss} is the side area in contact with water. In above equation, U_e can be neglected for small water depth ($A_{ss} \ll A_s$).

The rate of heat loss (per m^2) from the basin liner to the ambient air can be expressed as:

$$\dot{q}_b = h_b(T_b - T_a) \quad (2.4.75)$$

where

$$h_b = \left[\frac{L_i}{K_i} + \frac{1}{(h_{cb} + h_{rb})} \right]^{-1} \quad (2.4.76)$$

Example 2.9 Estimate the external radiative heat-transfer coefficient of a single-slope solar distiller unit for the condensing cover and the ambient temperature of 45 and 30 °C, respectively.

Solution

Here, $T_{sky} = T_a - 6 = 24$ °C

The radiative heat-transfer coefficient from the condensing cover to the ambient air is:

$$\begin{aligned} h_{rg} &= \frac{\sigma \epsilon_g \left[(T_g + 273)^4 - (T_{sky} + 273)^4 \right]}{(T_g - T_a)} \\ &= \frac{(5.64 \times 10^{-8}) \times 0.95 \times \left[(45 + 273)^4 - (24 + 273)^4 \right]}{15} = 27.43 \text{ W/m}^2 \text{ K} \end{aligned}$$

Example 2.10 Calculate the radiative heat-transfer coefficient from the condensing cover at 32 °C an ambient temperature at 20 °C as well s the convective heat-transfer coefficient when the wind is blowing at a velocity of 3 m/s. Compare the result with the combined radiative and convective heat-transfer coefficient.

Solution

Here, $T_{sky} = T_a - 6 = 24\text{ °C}$

The radiative heat-transfer coefficient from the condensing cover to the ambient air is:

$$h_{rg} = \frac{\sigma \epsilon_g \left[(T_g + 273)^4 - (T_{sky} + 273)^4 \right]}{(T_g - T_a)}$$

$$= \frac{(5.64 \times 10^{-8}) \times 0.95 \times \left[(32 + 273)^4 - (24 + 273)^4 \right]}{12} = 7.95 \text{ W/m}^2 \text{ K}$$

$$h_{cg} = 2.8 + 3 V = 11.8 \text{ W/m}^2 \text{ K}$$

$$h_{cg} = 2.8 + 3 V = 11.8 \text{ W/m}^2 \text{ K}$$

The total heat-transfer coefficient from the glass to the ambient air is $h_{lg} = 19.75 \text{ W/m}^2 \text{ K}$. The combined radiative and convective heat-transfer coefficient from Eq. (2.4.71) is

$$h_{cg} = 5.7 + 3.8 V = 17.1 \text{ W/m}^2 \text{ K}.$$

2.5 Overall Heat Transfer

The overall heat-transfer coefficient from different components of the solar still is given as follows.

(a) **Top-loss coefficient**

The top-loss coefficient (U_t) from the water surface to the ambient air (atmosphere) can be written as follows:

$$U_t = \left[\frac{1}{h_{lg}} + \frac{1}{h_{lw}} \right]^{-1} \quad (2.5.77)$$

Therefore, rate of heat loss in an upward direction of distillation system is as follows:

$$\dot{q}_t = U_t(T_w - T_a) \quad (2.5.78)$$

(b) Bottom-loss coefficient

The rate of heat loss from the water to the ambient air through the bottom of the insulation is as follows:

$$\dot{q}_b = U_b(T_w - T_a) \quad (2.5.79)$$

$$U_b = \left[\frac{L_i}{K_i} + \frac{1}{h_w} + \frac{1}{(h_{cb} + h_{rb})} \right]^{-1}$$

where U_b is the bottom heat-loss coefficient.

The rate of total heat loss per m^2 from the water surface to the ambient air through the bottom and the top of the system can be determined by adding Eqs. (2.5.78) and (2.5.79), and it can be expressed as follows:

$$\dot{q}_{\text{loss}} = U_L(T_w - T_a) \quad (2.5.80)$$

where $U_L = U_t + U_b$ is the overall heat transfer.

Example 2.11 Calculate the top-loss coefficient from a water surface at 20°C to the ambient air at 8.5°C . Given the temperature of glass, 12°C , $\epsilon_g = \epsilon_w = 0.9$.

Solution

Here, $\epsilon_{\text{eff}} = \left[\frac{1}{0.9} + \frac{1}{0.9} - 1 \right]^{-1} = 0.82$

The radiative, convective, and evaporative heat-transfer coefficients from the water to the glass are given as:

$$h_{rw} = 0.82 \times (5.67 \times 10^{-8}) \left[(20 + 273)^2 + (12 + 273)^2 \right] (20 + 12 + 546)$$

$$h_{rw} = 4.49 \text{ W/m}^2 \text{ }^\circ\text{C}$$

From Eq. (2.4.33),

$$P_w = \exp \left[25.317 - \left(\frac{5144}{273 + 12} \right) \right] = 2367.69 \text{ N/m}^2$$

$$P_g = \exp \left[25.317 - \left(\frac{5144}{273 + 12} \right) \right] = 1447.18 \text{ N/m}^2$$

$$h_{cw} = 0.844 \left[(8) + \frac{(2367.69 - 1447.18)(20 + 273)}{(2.689 \times 10^3 - 2367.69)} \right]^{\frac{1}{3}} = 1.84 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$h_{ew} = (0.016273 \times 1.84) \left(\frac{920.51}{8} \right) = 3.44 \text{ W/m}^2 \text{ }^\circ\text{C}$$

The total internal heat-transfer coefficient from the water surface to the internal surface of the condensing cover is as follows:

$$h_{1w} = 3.445 + 1.84 + 4.49 = 9.775 \text{ W/m}^2 \text{ }^\circ\text{C}$$

$$h_{cg} = 5.7 + 3.8V = 17.1 \text{ W/m}^2 \text{ }^\circ\text{C}$$

The top-loss coefficient from the water surface to the ambient air can be obtained as:

$$U_t = \left[\frac{1}{9.775} + \frac{1}{17.1} \right]^{-1} = 6.25 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Example 2.12 Calculate the bottom-loss coefficient from a solar still with 5 mm-thick insulation ($K = 0.04 \text{ W/m}^2 \text{ }^\circ\text{C}$) Given that $h_w = 100 \text{ W/m}^2 \text{ }^\circ\text{C}$.

Solution

Here, $h_{cb} + h_{rb} = 5.7 \text{ W/m}^2 \text{ }^\circ\text{C}$

The bottom-loss coefficient is given as follows:

$$U_b = \left[\frac{1}{100} + \frac{0.005}{0.04} + \frac{1}{5.7} \right]^{-1} = 3.23 \text{ W/m}^2 \text{ }^\circ\text{C}$$

2.6 Dunkle's Relation

The heat within the space between the water surface and the condensing cover is transported by of free convection across the bulk of humid air inside the solar-distillation system. During the mechanism of free convection, the buoyancy force arises due to the density variation in the space, which triggers the fluid motion. Furthermore, the density variation exists whenever there is a temperature gradient in the fluid. In contrast, the forced convection arises due to externally applied pressure gradient.

This humid air (conveyed the heat) release its enthalpy at the surface of glass cover, which is a comparatively at lower temperature. In general, the *Nusselt* number depends on the heat-transfer coefficients in the case of forced convection, whereas it is a function of the *Grashof* and *Prandtl* numbers in the case of natural convection,

$$Nu = f(GrPr) \quad (2.6.81)$$

By correlating the experimental data of Mull and Reiher for the flow of heat against the forces of gravity such that there is an upward flow of heat from the water surface, Jakob [14, 15] proposed the following relationship:

$$Nu = C(GrPr)^n \quad (2.6.82)$$

Using Eq. (2.4.19), Eq. 2.6.82 can be extended as given here:

$$Nu = \frac{h_{cw} \times d}{k} = C(GrPr)^n \quad (2.6.83)$$

where C and n are the constants. It becomes necessary to use a special *Grashof* number (Gr') for the case of convective heat transfer by humid air in the presence of the mass transfer of a fluid of lower molecular weight (i.e., water vapor). For non-isothermal evaporation, it has been shown by Sharpley and Boelter [16] as follows:

$$Gr' = \left(\frac{x_1^3 \rho_f^2 g}{\mu_f^2} \right) \left[\frac{M_\infty T'_o}{M_o T'_\infty} - 1 \right] \quad (2.6.84)$$

where the subscript o refers to the condition at the surface at which the evaporation originates, and ∞ refers to a point far away from this surface. The subscript f refers to air saturated with water vapor. For $M_o = M_\infty$, the term in brackets reduces to:

$$Gr' = \beta' \Delta T$$

$$\text{where } \beta' = \frac{1}{T'_\infty}$$

Let subscripts w and a refer to the diffusing (water vapor) and inert (air) gases, respectively. Assuming these to be ideal gases, which is a necessary condition for the modified Eq. (2.6.84), and remembering that:

$$P_{w\infty} + P_{a\infty} = P_{wo} + P_{ao} = P_T \text{ (Total gas pressure),}$$

the term in the square bracket in Eq. (2.6.84) can be expressed as follows:

$$\begin{aligned} \left[\frac{M_\infty T'_o}{M_o T'_\infty} - 1 \right] &= \left[\frac{M_\infty P_{w\infty} T'_o + M_a P_{a\infty} T'_o}{M_w P_{wo} T'_\infty + M_a P_{ao} T'_\infty} - 1 \right] \\ &= \frac{M_\infty (P_{w\infty} T'_o - P_{wo} T'_\infty) + M_a (P_{a\infty} T'_o - P_{ao} T'_\infty)}{T'_\infty (M_w P_{wo} + M_a P_{ao})} \\ &= \frac{[M_\infty P_{w\infty} + M_a (P_T - P_{wo})] (T'_o - T'_\infty) + (M_w - M_a) (P_{a\infty} - P_{wo}) T'_o}{T'_\infty [M_w P_{wo} + M_a (P_T - P_{wo})]} \end{aligned}$$

or

$$\left[\frac{M_\infty T'_o}{M_o T'_\infty} - 1 \right] = \frac{T'_o - T'_\infty}{T'_\infty} + \frac{(M_w - M_a) (P_{a\infty} - P_{wo}) T'_o}{T'_\infty [M_w P_{wo} + M_a (P_T - P_{wo})]} \quad (2.6.85)$$

For an air/water-vapor system at normal atmospheric pressure,

$$M_w = 18, M_w = 28.96, P_T = 98.07 \times 10^3 \text{ pa}$$

and with the above-mentioned substitution in Eq. (2.6.85) gives:

$$\begin{aligned} \left[\frac{M_\infty T'_o}{M_o T'_\infty} - 1 \right] &= \frac{T'_o - T'_\infty}{T'_\infty} + \frac{(P_{a\infty} - P_{wo})T'_o}{T'_\infty [268.91 \times 10^3 - P_{wo}]} \\ &= \beta' \left[\Delta T + \frac{(P_{a\infty} - P_{ao})T'_o}{[268.91 \times 10^3 - P_{wo}]} \right] \end{aligned}$$

or

$$\left[\frac{M_\infty T'_o}{M_o T'_\infty} - 1 \right] = \beta' \Delta T' \quad (2.6.86)$$

where $\Delta T'$ is the equivalent temperature difference. Therefore,

$$Gr' = \frac{x_1^3 \rho_f^2 g \beta' \Delta T'}{\mu_f^2} \quad (2.6.87)$$

The above-mentioned relationship is used by Dunkle [11]. For an equivalent temperature difference and a mean air temperature of 50 and 17 °C, respectively, assuming saturated air, the special *Grashof number* (Gr') in Eq. (2.6.87) can be expressed as $(2.81 \times 10^7)x_1^3$. The special *Grashof number* (Gr') may be seen to lie in the range for which $C = 0.075$ and $n = 1/3$ over the normal operating temperature range for values (not too small) of the mean water-to-cover spacing (x_1).

The length parameter conveniently cancels out for this value of the exponent. Consequently, the heat-transfer coefficient becomes substantially independent of the spacing (x_1). Dunkle [11] derived the following relationship by choosing the physical-parameter values occurring in the dimensionless variables that are relevant over the normal range of operation of the solar-distillation system,

$$\dot{q}_{cw} = 0.844 \left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})(T_w + 273)}{(2.69 \times 10^3 - P_w)} \right]^{\frac{1}{3}} (T_w - T_{gi}) \quad (2.6.88)$$

$$= h_{cw}(T_w - T_{gi}) \quad (2.6.89)$$

where,

$$h_{cw} = 0.844 \left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})(T_w + 273)}{(2.69 \times 10^3 - P_w)} \right]^{\frac{1}{3}} \quad (2.6.90)$$

2.7 New Model

The internal convective and evaporative heat transfers occur simultaneously in a solar-distillation system. The expressions derived for the convective heat-transfer coefficient (h_{cw}) (Eq. 2.6.90) and the evaporative heat-transfer coefficient (h_{ew}) (Eq. 2.4.56) have many limitations, and this model with limitations is known as the “*Dunkle* model [11] with constants” as $C = 0.075$ and $n = 1/3$. Most of the researchers in this field generally use these relationships, even in non-suitable conditions under the model limitations. Therefore, it is believed essential to inspect the validity of the *Dunkle* model at least for those conditions not falling within its limitations.

In this aspect, *Clark* [17], amongst others, made attempts by conducting experiments (steady-state indoor) on the basin-type solar-distillation system using a solar simulator. He pointed out that the *Dunkle* model of heat transfer for such a solar distiller is effective. However, an additional factor of “1/2” (to account for saturation) must be introduced in the expression of the evaporative heat-transfer coefficient (h_{ew}). The purpose for introducing this factor is because the rates of evaporation and condensation are equal under an ideal condition. This state is attained by cooling the condensing cover using a fan. It is impracticable for solar-distillation systems operating in actual field conditions. The following values of C and n were proposed for different *Grashof number* ranges on the basis of steady-state experimental results:

$$(i) \quad C = 0.21, n = 1/4 \text{ for } 10^4 < Gr < 10^5$$

$$(ii) \quad C = 0.1255, n = 1/3 \text{ for } 2.51 \times 10^5 < Gr < 10^7$$

To develop an empirical relation, *Shawaqfeh and Farid* [18] performed simulation studies based on the best fit. The obtained correlations delivered expressions for the convective heat-transfer coefficients, which are independent of the solar-distiller geometry. *Dunkle* suggested a value of $n = 1/3$ and a reduced value of $C = 0.067$ to account for the turbulent flow inside a solar-distillation system. All of these correlations are developed for indoor simulations and steady-state conditions.

Kumar and Tiwari [19, 20] suggested the values of $C = 0.0322$, $n = 0.4144$ for $1.794 \times 10^6 < Gr < 5.724 \times 10^6$ using regression analysis by performing experiments on a single-slope solar-distillation system under actual field conditions.

In the literature, it is reported that the same values of C and n are used for the analysis of a double-slope solar-distillation system as well. However, the suggested values of C and n for a single-slope solar-distillation system are not valid for a double-slope solar still due to the following reasons:

- (i) There are two condensing surfaces for one evaporating surface in double-slope solar still.

- (ii) The temperatures of both of the condensing surfaces are different at any given time interval.
- (iii) The solar intensity falling on both condensing surfaces is also different at any given time interval.

Taking these facts into account, Agrawal [21] developed a thermal model and experimentally validated it for evaluating the values of C and n with the help of regression analysis for the following:

- (a) A conventional single-slope solar-distillation system,
- (b) A conventional double-slope solar-distillation system,
- (c) A double condensing-chamber solar-distillation system, and
- (d) An active single-slope solar-distillation system.

Agrawal and Tiwari [22] and Kumar and Tiwari [19, 20] used the following methodology for evaluating C and n :

On substituting h_{cw} from Eq. (2.6.83) into Eq. (2.4.56), one can obtain the following:

$$h_{cw} = (16.273 \times 10^{-3}) \left(\frac{P_w - P_{gi}}{T_w - T_{gi}} \right) \left(\frac{k}{d} \right) [C(GrPr)^n] \quad (2.7.91)$$

Substitute the above Eq. in (2.4.55), one can obtain:

$$\dot{q}_{ew} = (16.273 \times 10^{-3}) (P_w - P_{gi}) \left(\frac{k}{d} \right) [C(GrPr)^n]$$

Finally, Eq. (2.4.59) can be expressed as follows:

$$\dot{m}_{ew} = (16.273 \times 10^{-3}) (P_w - P_{gi}) \left(\frac{k}{d} \right) \left(\frac{3600}{L} \right) [C(Ra)^n] \quad (2.7.92)$$

where

$$Ra = GrPr. \quad (2.7.93)$$

The above-mentioned equation can be rewritten as follows:

$$\dot{m}_{ew} = RC(Ra)^n \quad \text{or} \quad \frac{\dot{m}_{ew}}{R} = C(Ra)^n \quad (2.7.94)$$

where

$$R = (16.273 \times 10^{-3}) (P_w - P_{gi}) \left(\frac{k}{d} \right) \left(\frac{3600}{L} \right) \quad (2.7.95)$$

Equation (2.7.94) can be expressed in the following form:

$$y = ax^b \quad (2.7.96)$$

where $y = \frac{\dot{m}_{ew}}{R}$; $x = Ra$; $a = C$, and $b = n$

Equation (2.7.96) can be reduced into a straight-line equation by taking log on both sides:

$$\ln(y) = \ln(a) + b \ln(x) \quad (2.7.97)$$

or

$$Y = A + BX \quad (2.7.98)$$

where

$$Y = \ln(y); A = \ln(a); B = b, \text{ and } X = \ln(x) \quad (2.7.99)$$

From Eq. (2.7.99), the values of coefficients A and B are computed using linear-regression analysis. The expression for A and B are given by:

$$B = \frac{N(\sum XY) - (\sum X)(\sum Y)}{N(\sum X^2) - (\sum X)^2} \quad (2.7.100)$$

$$A = \frac{\sum Y}{N} - B \frac{\sum X}{N} \quad (2.7.101)$$

where N is the number of experimental observations. After calculating the values of coefficients A and B from Eqs. (2.7.100) and (2.7.101), respectively, one can obtain C and n by the following expressions:

$$C = \exp(A) \text{ and } n = B \quad (2.7.102)$$

They considered the following facts for the proposed and tested the values of C and n , which have not been considered explicitly in previous models:

- (i) the effect of the solar-still cavity,
- (ii) the operating temperature range, and
- (iii) the orientations of the condensing covers.

By using new values of C and n within an average accuracy of 19% (except for some extreme cases), a reasonable agreement is observed between the experimental and theoretical values.

They performed an extensive year-round experiment for a year under actual field conditions for all four above-mentioned solar-distillation systems. To evaluate

C and n , the average values of temperatures and the hourly distillate output were used. During experimentation, the hourly observations of distillate outputs and various temperatures were obtained and classified in the following three operating temperature ranges:

Case I	24–55 °C	(Dunkle's operating temperature range)
Case II	24–42 °C	(Lower operating temperature range)
Case III	55–75 °C	(Greater operating temperature range)

The temperature ranges of cases I and II (for a conventional solar still) and case I (for a double condensing–chamber solar-distillation system) are close to the winter conditions for New Delhi. The values of C and n are significantly different for case III because both the stills belong to monthly summer conditions ($C = 0.1265$ and $n = 0.284$ for the months of August and September) than Dunkle's ($C = 0.075$ and $n = 0.333$) cases. Hence, this verifies that without confirming the validity of the values of C and n for different designs of solar-distillation systems under different operating temperature ranges, the values proposed by *Dunkle* cannot be used. The investigators observed that under similar climatic conditions:

- $C = 0.8100$ and $n = 0.3572$ for a double-slope solar-distillation system (east side).
- $C = 0.0845$ and $n = 0.3432$ for a double-slope solar-distillation system (west side).
- $C = 0.0278$ and $n = 0.3513$ for an active single-slope solar-distillation system.

These are different from the values for a conventional single-slope solar-distillation system. They studied all of the three cases of temperature ranges regarding the double-condensing solar-distillation system. They perceived that their suggested thermal model to evaluate C and n is in close agreement with experimental results within an accuracy of 20%. However, the Dunkle's model has more deviation— $\leq 48\%$ —as shown in Figs. 2.3 and 2.4, respectively, for the east and west condensing surfaces of the system. However, the deviation from Dunkle's model goes up to 68% in case of an active single-slope solar-distillation system.

Now, from the above-mentioned thermal modeling, experimental results, and analysis, one can conclude that it is essential to evaluate C and n values in order to precisely predict the performance of solar stills. Under simulated conditions, the calculated values of C and n are no longer valid for stills operating under actual field conditions. This is due to the fact that the variations of climatic parameters are under human control in the laboratory conditions, whereas the same is not true for actual operation condition of the solar-distillation system at the user's end. One can conclude that Dunkle's C and n values can be used only for an operating temperature range of 50 (or 55 °C at the maximum) for a conventional single-slope, double-condensing chamber and an active single-slope solar-distillation system.

These values of Dunkle for other types of solar-distillation systems and temperature ranges cannot be used.

The analysis of Agrawal [22] strongly supports that it is essential for the estimation of convective mass transfer to predict the performances of each type of solar-distillation system under actual field conditions. Different values of operating temperature range and shape of the condensing cover gives different values of C and n . Therefore, incorrect results will be obtained on using the values of C and n estimated under simulation conditions. Hence, it is recommended that experiments be performed on a specific model of solar-distillation system for given climatic conditions to estimate the values of C and n from the thermal model before predicting the performance theoretically. Thus, the obtained values of C and n will have no limitations. Consequently, the convective heat-transfer (h_{cw}) and radiative

Fig. 2.3 Comparison of experimental outputs with theoretical outputs of other models for east condensing surface

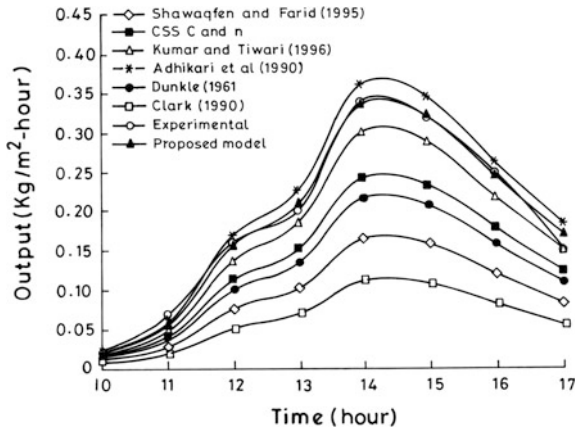


Fig. 2.4 Comparison of experimental outputs with theoretical outputs of other models for west condensing surface

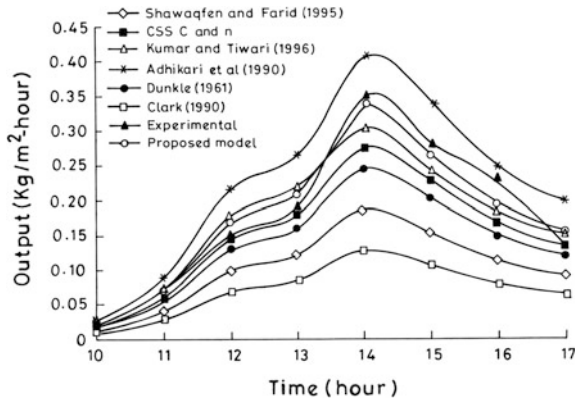


Table 2.11 Values of C , n and heat transfer coefficients (h_{cw} and h_{ew}) for different inclinations of the condensing cover

Values obtained	15°	30°	35°
Value of C	1.418	2.536	0.968
Value of n	0.148	0.158	0.209
Average, h_{cw} (W/m ² °C)	1.67	2.44	2.01
Average, h_{ew} (W/m ² °C)	13.36	16.93	12.84

heat-transfer coefficients (h_{ew}) can be obtained by evaluating C and n experimentally from Eq. (2.7.102) without any limitations by using the following expressions:

$$h_{cw} = \left(\frac{k}{d}\right)[C(GrPr)^n]. \quad (2.7.103)$$

$$h_{ew} = \frac{\dot{q}_{ew}}{3600 \times (T_w - T_{gi})} \quad (2.7.104)$$

The values of C and n for a single-slope solar-distillation system for different inclinations of condensing cover for New Delhi summer climatic conditions are listed in Table 2.11. This table clearly indicates the substantial change in the values of C and n for different inclinations of the condensing cover.

Evaporative heat-transfer (h_{ew}) and convective heat-transfer coefficients (h_{cw}) have been evaluated from Eqs. (2.7.104) and (2.7.103), respectively. These coefficients are evaluated for the values of C and n for a 15 °C inclination of condensing cover as well as for positive values of temperature difference between the water surface and the inner surface of the condensing cover. The results are shown in Fig. 2.5a, b. The values of convective and evaporative heat-transfer coefficients obtained by Dunkle's model are also shown. Significant difference in the results has been perceived from the present model as well as Dunkle's model.

Example 2.13 Evaluate the evaporative heat-transfer coefficient using the new model for a single-slope solar-distillation system having heat flow in an upward direction for example 2.3.

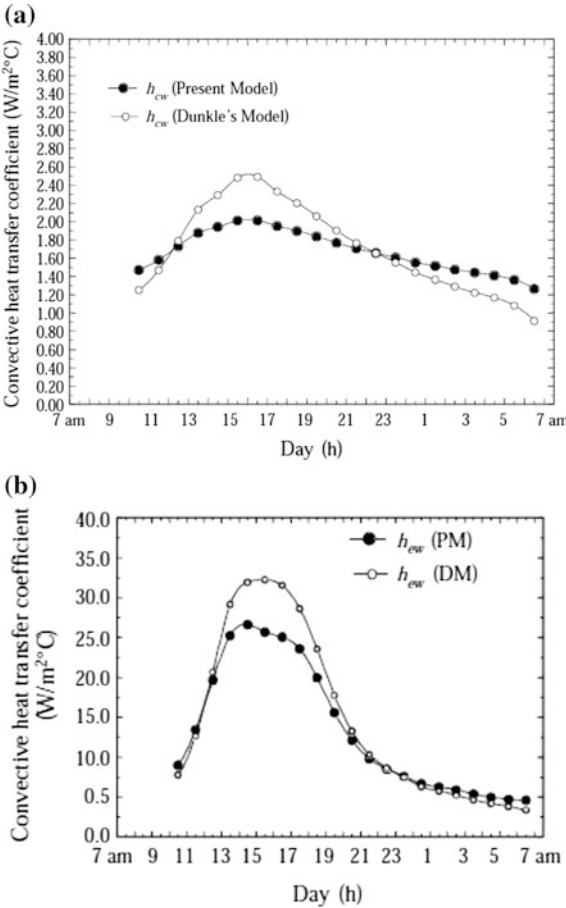
Solution

From Example 2.3; $Gr = 0.29 \times 10^7 \cong 3 \times 10^6$ and $Pr = 0.695$

Equation (2.7.91) gives:

$$\begin{aligned} h_{ew} &= (16.273 \times 10^{-3}) \left(\frac{7795.21}{20}\right) \left(\frac{0.0275}{0.30}\right) [0.54(2.085 \times 10^6)^{0.25}] \\ &= 11.92 \text{ W/m}^2 \text{ K} \end{aligned}$$

Fig. 2.5 a Variation of convective heat transfer coefficient (h_{cw}) evaluated by the present and Dunkle's models for positive values of ΔT and 15° cover inclination. **b** Variation of evaporative heat transfer coefficient (h_{ew}) evaluated by present and Dunkle's models for positive values of ΔT and 15° cover inclination



2.8 Thermal Efficiency

The thermal efficiency of a solar-distillation system can be defined as the ratio of the amount of thermal energy used to obtain a certain amount of distilled water to the incident solar energy within a given time span.

2.8.1 Instantaneous Efficiency

All of the absorbed solar radiation inside a solar distiller is consumed for the evaporation of water and thermal losses (top, bottom, and side) when considering the evaporation process to be an isobaric (at atmospheric pressure) process at thermal equilibrium.

The energy balance around the water basin for steady-state conditions can be expressed as [23]:

$$[\alpha'_w + \alpha'_b]I(t)A_s = \dot{Q}_{ew} + \dot{Q}_{loss} \quad (2.8.105)$$

Rate of energy in = Rate of energy out

where $\dot{Q}_{ew} = \dot{m}_w L$ and $\dot{Q}_{loss} = U'_L(T_w - T_a)A_s$

U'_L is the overall heat-transfer coefficient from the water surface to the ambient air through the top, bottom, and sides of the solar-distiller unit. It is assumed that:

$$\alpha'_w + \alpha'_b = (\alpha\tau)_w$$

where $\dot{Q}_{loss}$, i.e., the losses in the *Tamini* model, does not consider the evaporative heat loss. On comparing the analysis with that of a flat-plate collector, it has been observed that the upward losses should be minimum in case of a flat-plate collector, whereas the upward losses should be maximum in a solar-distiller unit in order to obtain a greater yield. As discussed previously, in the conventional solar still, radiative, convective, and evaporative losses are grouped together and considered as the total internal heat-transfer coefficient from the water surface to the inner surface of the condensing cover [2, 24].

Equation (2.8.105) can be expressed as follows:

$$\dot{Q}_{ew} = \dot{m}_w L = (\alpha\tau)_w I(t)A_s - U'_L(T_w - T_a)A_s \quad (2.8.106)$$

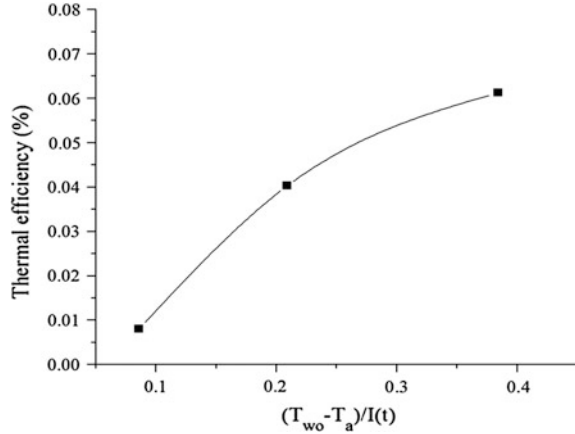
The expression for instantaneous efficiency (η_i) can be expressed as shown:

$$\eta_i = \frac{\dot{m}_w L}{I(t)A_s} = (\alpha\tau)_w - \frac{U'_L(T_w - T_a)}{I(t)} \quad (2.8.107)$$

The plot of η_i versus $\frac{(T_w - T_a)}{I(t)}$ represents a straight line with $(\alpha\tau)_w$ and $-U'_L$ as the intercept and the slope, respectively.

where U'_L can be considered as a constant [25]. The expression of instantaneous efficiency (η_i) is exactly similar to that of a conventional flat-plate collector excluding the heat-removal factor. An actual variation of η_i versus $\frac{(T_w - T_a)}{I(t)}$ (known as the “characteristic curve”) is shown in Fig. 2.6. According to Tamini [23], the solar-distillation system or distiller unit can be deliberated as a special type of flat-plate collector that produces distilled water on trapping and using (harvesting) the incident solar energy.

Fig. 2.6 Variation of instantaneous efficiency of solar distillation system



Example 2.14 Calculate (a) the rate of evaporative heat loss for example 2.8, (b) the hourly output (take $L = 2390 \times 10^3 \text{ J/kg}$), and (c) the instantaneous efficiency of a distillation unit for a solar intensity of 900 W/m^2 .

Solution

$$(a) \quad \dot{q}_{ew} = h_{ew}(T_w - T_g) = 3.445 \times (20 - 12) = 27.56 \text{ W/m}^2$$

$$(b) \quad \dot{m}_{ew} = \left[\frac{h_{ew}(T_w - T_g)}{L} \right] \times 3600 = 0.0415 \text{ kg/m}^2 \text{ h}$$

$$(c) \quad \eta_i = \frac{\dot{q}_{ew}}{I(t)} = \frac{27.56}{900} = 0.0306 = 3.06\%$$

2.8.2 Overall Thermal Efficiency

The overall thermal efficiency of the solar-distillation system in passive and active modes of operation can be mathematically written as follows:

$$\eta_{\text{passive}} = \left[\frac{\sum \dot{m}_w L}{A_s \int I(t) dt} \right] \times 100 \quad (2.8.108)$$

$$\eta_{\text{active}} = \left[\frac{\sum \dot{m}_w L}{A_s \int I(t) dt + A_s \int I'(t) dt} \right] \times 100 \quad (2.8.109)$$

where N is the number of collectors connected either in series or in parallel.

The latent heat of vaporization L (J/kg) is a function of temperature and can be expressed as [26, 27]

$$L = 3.1615 \times 10^6 [1 - (7.616 \times 10^{-4})T] \quad \text{for } T > 70^\circ\text{C}$$

and

$$L = 2.4935 \times 10^6 [1 - (9.477 \times 10^{-4})T + (1.313 \times 10^{-7})T^2 - (4.497 \times 10^{-9})T^3]$$

for $T < 70^\circ\text{C}$.

Problems and descriptive questions

- 2.1 Calculate the rate of evaporation for an exposed wetted surface having a temperature of 35°C and a relative humidity of 50% when the ambient air temperature is 15°C . In addition, calculate the evaporative heat-transfer coefficient.
- 2.2 Calculate the convective heat-transfer coefficient for an insulated hot plate at 60°C facing upward with a water column at 40°C . The dimension of the hot plate is $1\text{ m} \times 1\text{ m}$.
- 2.3 Calculate the convective heat-transfer coefficient from a blackened surface to (a) the water (basefluid) and (b) the nanofluid (TiO_2 nanoparticles) of a passive double-slope solar still for the parameters given in example 2.2. The properties of the TiO_2 nanoparticle are given below;
 $C_{pp} = 697\text{ (J/kg K)}$, $\beta_p = 8.1 \times 10^{-6}\text{ (K}^{-1}\text{)}$, $\phi_p = 0.004\%$, $\rho_p = 4.230 \times 10^3\text{ (kg/m}^3\text{)}$, thermal conductivity of particle $k_p = 17.5\text{ (W/m}^\circ\text{C)}$, diameter of nanoparticle, $(d_p) = 15\text{ nm}$.
 Take the temperature of the water as $(T_w) = 60.25^\circ\text{C}$, The temperature of the nanofluid $(T_{nf}) = 61.65^\circ\text{C}$.
- 2.4 For the parameters given in problem 2.3, evaluate the convective heat-transfer coefficient of a passive double-slope solar still from the blackened surface to (a) the water (basefluid) and (b) the nanofluid (TiO_2 nanoparticles) for 0.008 and 0.015% volumetric concentration of nanoparticles.
- 2.5 Calculate the total solar radiation from the first method for an inclined surface having an inclination of 30° facing south at 9 am for New Delhi on 23 September 2015 ($T_R = 4.75$ and $\rho = 0.2$).
- 2.6 Calculate (a) the *Grashof* number (Gr), the *Prandtl* number (Pr), the *Reynolds* number (Re), and the *Rayleigh* number (Ra) for a temperature difference of 10°C and a fluid layer thickness of 0.20 m as well as (b) the *Nusselt* number for free and forced convection for a hot surface facing upward ($C = 0.54$, $n = 0.25$). Use $v_0 = 0.01\text{ m/s}$ and $X_0 = 1$.
- 2.7 Evaluate and compare all of the thermophysical properties of vapor listed in Tables 2.5 [2] and 2.6 [28].

- 2.8 Calculate (a) the convective heat-transfer coefficient from Dunkle's model and (b) the radiative heat-transfer coefficient for a passive single-slope solar-distillation system having a temperature of water surface and an inner surface of the condensing cover at 45 and 35 °C., respectively. Use $\varepsilon_w = \varepsilon_g = 0.9$ and $F_{12} = 1$.
- 2.9 Calculate the radiative and convective heat-transfer coefficients from the condensing cover at 30 °C. the ambient air at 15 °C when the wind is blowing at a velocity of 2 m/s. Compare the result with the combined radiative and convective heat-transfer coefficients.
- 2.10 Evaluate (a) the top-loss coefficient from a water-surface at temperature 30 °C to the ambient air at 15 °C. Given the temperature of glass, 20 °C, $\varepsilon_g = \varepsilon_w = 0.9$ and (b) the bottom-loss coefficient from a solar still with an insulation of (i) 2 mm and (ii) 4 mm thickness ($K = 0.05 \text{ W/m}^2 \text{ °C}$). Given, $h_w = 80 \text{ W/m}^2 \text{ °C}$.
- 2.11 Evaluate the evaporative heat-transfer coefficient using the new model for (a) free convection and (b) forced convection of a passive single-slope solar distiller unit for a hot surface facing upward ($C = 0.54, n = 0.25$) for the following parameters: $\Delta T = 10 \text{ °C}$, $d = 0.10 \text{ m}$, $v_0 = 0.01 \text{ m/s}$ and $X_0 = 1$.
- 2.12 Estimate (a) the convective and evaporative heat-transfer coefficients for a passive single-slope solar-distillation system having a temperature of water surface and inner surface of the condensing cover at 20 and 15 °C, respectively, and (b) the hourly output (take $L = 2250 \times 10^3 \text{ J/kg}$) and (c) instantaneous efficiency of a distillation unit for a solar intensity of 850 W/m^2 .
- 2.13 Discuss the first and second method to calculate the total solar radiation incident on an inclined surface.
- 2.14 Explain briefly the heat transfer of (a) convection, (b) conduction, and (c) radiation.
- 2.15 Derive an expression for Dunkle's relation of convective heat transfer.
- 2.16 Explain all internal and external heat-transfer coefficients of a passive solar-distillation system.
- 2.17 Discuss the new model and explain the regression method to obtain the values of C and n .

Objective questions

- 2.1 The solar constant is measured near:
- (a) the Sun
 - (b) the Earth
 - (c) the extra-terrestrial region
 - (d) the terrestrial region.

- 2.2 The short-wavelength radiation reaching the Earth measures:
- (a) $30\ \mu\text{m}$
 - (b) $3\text{--}30\ \mu\text{m}$
 - (c) $0.3\text{--}3\ \mu\text{m}$
 - (d) None of these
- 2.3 The value of solar radiation in summer is maximum on the surface having An inclination equal to:
- (a) Latitude
 - (b) Zero
 - (c) 45°
 - (d) 90°
- 2.4 The value of the solar constant is:
- (a) $1000\ \text{W/m}^2$
 - (b) Zero
 - (c) $1367\ \text{W/m}^2$
 - (d) $500\ \text{W/m}^2$.
- 2.5 The relation between the zenith (θ_z) and the solar-altitude (α) angles is:
- (a) $\theta_z + \alpha = 60^\circ$
 - (b) $\theta_z + \alpha = 90^\circ$
 - (c) $\theta_z + \alpha = -90^\circ$
 - (d) $\theta_z + \alpha = 0^\circ$
- 2.6 The surface-azimuth angle (γ) for a surface sloped toward the south is:
- (a) 90°
 - (b) 180°
 - (c) 0°
 - (d) -90°
- 2.7 The radiation from the Sun is governed by:
- (a) Stefan–Boltzmann law
 - (b) Fourier’s law of conduction
 - (c) Faraday’s law
 - (d) Wein’s displacement law.
- 2.8 The radiation from the Earth is governed by:
- (a) Fourier’s law of conduction
 - (b) Stefan–Boltzmann law
 - (c) Wein’s displacement law
 - (d) None of these.

2.9 Thermal-expansion coefficients depend on:

- (a) Temperature
- (b) Thermal air conductance
- (c) Thermal conductivity
- (d) None of these

2.10 Which of the following represents the correct form of Fourier's law of heat conduction?

- (a) $\dot{Q} = -KA \frac{dT}{dx}$
- (b) $\dot{Q} = -\left(\frac{K}{A}\right) \frac{dT}{dx}$
- (c) $\dot{Q} = KA \frac{dT}{dx}$
- (d) $\dot{Q} = \left(\frac{K}{A}\right) \frac{dT}{dx}$

2.11 Convective heat transfer depends on:

- (a) Physical properties of fluid
- (b) Physical properties of solid
- (c) Characteristics dimension
- (d) All of these.

2.12 The convective heat-transfer coefficient from Dunkle's relation is:

- (a) $h_{cw} = 0.844 \left[(T_w - T_{gi}) - \frac{(P_w - P_{gi})(T_w + 273)}{(2.69 \times 10^3 - P_w)} \right]^{\frac{1}{3}}$
- (b) $h_{cw} = 0.844 \left[\frac{(P_w - P_{gi})(T_w + 273)}{(2.69 \times 10^3 - P_w)} \right]^{\frac{1}{3}}$
- (c) $h_{cw} = 0.844 \left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})(T_w + 273)}{(2.69 \times 10^3 - P_w)} \right]^{\frac{1}{3}}$
- (d) $h_{cw} = 0.844 \left[(T_w - T_{gi}) + \frac{(P_w + P_{gi})(T_w + 273)}{(2.69 \times 10^3 + P_w)} \right]^{\frac{1}{3}}$

2.13 The radiation heat transfer between two surfaces is mainly due to:

- (a) Short wavelength
- (b) Infra-red
- (c) UV
- (d) Long-wavelength radiation

2.14 An expression for a wind-dependent convective heat-transfer coefficient is

- (a) $h_c = 3 + 2.8 V$
- (b) $h_c = 2.8 + 3 V$
- (c) $h_c = 3 + 3 V$
- (d) None of these

- 2.15 The evaporative heat-transfer coefficient (h_{ew}) is:
- Proportional to h_{cw} (convective heat-transfer coefficient)
 - Inversely proportional to h_{cw}
 - Independent of convective heat-transfer coefficient
 - None of these
- 2.16 The evaporative heat-transfer coefficient (h_{ew}) depends on the convective heat-transfer coefficient due to:
- Lewis relation
 - Newton's law
 - Fourier's law
 - None of these
- 2.17 Which of the following form represents an expression for instantaneous efficiency (η_i) ?
- $\eta_i = (\alpha\tau)_w + \frac{U'_L(T_w - T_a)}{I(t)}$
 - $\eta_i = (\alpha\tau)_w - \frac{U'_L(T_w - T_a)}{I(t)}$
 - $\eta_i = (\alpha\tau)_w - \frac{U'_L}{(T_w - T_a)I(t)}$
 - $\eta_i = (\alpha\tau)_w - \frac{(T_w - T_a)}{U'_L I(t)}$

Answers

2.1 (c) 2.2 (c) 2.3 (b) 2.4 (c) 2.5 (b) 2.6 (c) 2.7 (a) 2.8 (b) 2.9 (a) 2.10 (a) 2.11(a) & (c) 2.12 (c) 2.13(d) 2.1 4(c) 2.15 (a) 2.16(a) 2.17 (b)

References

- G.N. Tiwari, R.K. Mishra, *Advanced Renewable Energy Sources* (RSC Publishing Cambridge, UK, 2012)
- G.N. Tiwari, *Solar Energy: Fundamentals, Designs* (Narosa Publishing House New Delhi, Modeling and Applications, 2002)
- B.Y.H. Liu, R.C. Jordan. The interrelationship and characteristics distribution of direct, diffuse and total solar radiation. *Solar Energy* **4** (1960)
- H.N. Singh, G.N. Tiwari, Monthly performance of passive and active solar stills for different Indian climatic conditions. *Desalination* **168**, 145 (2004)
- F. Kasten, A new table and approximate formula for relative optical air mass. *Arch. Meteorol. Geophys. Bioklimatol Ser. B.* **14**, 206–223 (1965)
- F. Kasten, A.T. Young, Revised optical air mass tables and approximation formula. *Appl. Opt.* **28**, 4735–4738 (1989)
- G.N. Tiwari, A.K. Tiwari, *Solar Distillation Practice for Water Desalination Systems* (Anamaya Publishers, New Delhi, 2008)
- A.F. Whillier, Solar radiographs. *Sol. Energy* **9**, 164 (1967)
- V.A. Baum, R. Bairamov, Heat and mass transfer process in solar stills of hot box type. *Sol. Energy* **8**, 78 (1964)

10. I.S. Bowen, in *The Ratio of Heat Loss by Conduction and Evaporation for Any Water Surface. The Physical Review*, vol. 27, 2nd Series, p. 779 (1926)
11. R.V. Dunkle, *Solar Water Distillation: The Roof Type Still and a Multiple Effect Diffusion Still*, International Developments in Heat Transfer, A.S.M.E., In Proceedings of International Heat Transfer, University of Colorado, Part V, p. 895 (1961)
12. P.I. Cooper, Digital simulation of experimental solar still data. *Sol. Energy* **14**, 451 (1973)
13. P.I. Cooper, Maximum efficiency of single effect solar still data. *Sol. Energy* **15**, 205 (1973)
14. M. Jacob, *Heat Transfer*, vol. I (Wiley & Sons, New York, 1949)
15. M. Jacob, *Heat Transfer*, vol. II (Wiley & Sons, New York, 1957)
16. B.F. Sharpley, L.M.K. Boelter, Evaporation of water into quit air. *Indus. Eng. Chem.* **30**, 1125 (1938)
17. J.A. Clark, The steady-state performance of a solar still. *J. Solar Energy* **44**, 43 (1990)
18. A.T. Shawaqfeh, M.M. Farid, New development in the theory of heat and mass transfer in solar stills. *Sol. Energy* **55**, 527 (1995)
19. S. Kumar, G.N. Tiwari, Performance evaluation of an active solar distillation system. *Energy* **21**, 805 (1996)
20. S. Kumar, G.N. Tiwari, Estimation of convective mass transfer in solar distillation systems. *J. Solar Energy* **57**, 459 (1996)
21. S. Agrawal, *Computer based thermal modeling of advanced solar distillation system. Ph.D thesis*. Submitted to I.I.T. Delhi (1999)
22. S. Agrawal, G.N. Tiwari, Convective mass transfer in a double-condensing chamber and a conventional solar still. *Desalination* **115**, 181–188 (1998)
23. A. Tamini, Performance of a solar still with reflectors and black dye. *Int. J. Solar Wind Tech.* **4**, 443 (1987)
24. R. Dev, G.N. Tiwari, Characteristic equation of a passive solar still. *Desalination* **245**, 265 (2009)
25. J.K. Nayak, G.N. Tiwari, M.S. Sodha, Periodic theory of solar still. *Int. J. Energy Res.* **4**, 41 (1980)
26. J. Fernandez, N. Chargoy, Multistage, Indirectly heated solar still. *J. Solar Energy* **44**, 215 (1990)
27. S. Toyama, *Kagaku Kikai Gijutsu*. Maruzen, Tokyo **24**, 159 (1972)
28. P.T. Tsilingiris, The influence of binary mixture thermo physical properties in the analysis of heat and mass transfer processes in solar distillation system. *Sol. Energy* **81**, 1482–1491 (2008)
29. C. Popiel, J. Wojtkowiak, Simple formulas for thermo-physical properties of liquid water for heat transfer calculations (from 0 °C to 150 °C). *Heat Transf. Eng.* **19**, 87–101 (1998)
30. W.H. McAdams, *Heat transmission*, 3rd edn. (McGraw-Hill, New York, 1954)
31. J.H. Watmuff, W.W.S. Charters, D. Proctor, Solar and wind induced external coefficients solar collectors 2nd quarter. *Revue International d'Helio- technique*, 56 (1977)

Chapter 3

History of Passive Solar-Distillation Systems

3.1 Introduction

Solar distillation is a simple and environmentally friendly technology. The first known use of solar stills dates back to 1551 when it was used by Arab alchemists. Other scientists and naturalists—including Della Porta (1589), Lavoisier (1862), and Mauchot (1869)—used solar stills over the coming centuries. The first conventional solar-still plant in the mining community of Las Salinas was built by the Swedish engineer Charles in 1872. It was a huge basin-type still used to produce fresh water from brackish water for the nitrate-mining community. Around the world, hundreds of solar-still plants and thousands of individual stills have been built over the past century (Tables 1.6 and 1.7 in Chap. 1).

The temperature difference among the water surface and the inner surface of the condensing cover acts as a driving force for the distillate output of the solar still as discussed in detail in Chap. 1. This temperature difference in the cavity of the solar still can be enhanced by properly using a non-conventional source of energy or renewable energy. Worldwide, researchers have proposed and studied various designs of the passive solar still to improve its performance or productivity (yield). In recent times, phase-change materials (PCM) and nanofluids (NFs) have been cultivated experimentally and theoretically, and they found to be proficient techniques for harvesting solar thermal energy.

3.2 Conventional Solar Still

Conventional solar stills are categorized into two types: single-slope solar still and double-slope solar still. Illustrative views of both types of still are shown in Fig. 3.1a, b, respectively. The basic principle of a conventional solar still is

3.3 Asymmetric Solar Still with Double Effect

Illustrative view of asymmetric solar still with double effect is shown in Fig. 3.2. The still is fabricated with aluminum due to its low cost, easy formation, medium temperature, and good resistance to corrosion. The sides and basins of the still are insulated with polystyrene and covered with a wooden box to reduce the heat losses. The basin of the still (first effect) is painted dark black to enhance absorptivity. The still consists of a double-story basin with a transparent glass cover for each basin. The glass cover of the first basin (first effect) is used as a base for the second basin (second effect). The temperature of the glass cover decreases by continuously flowing water (film cooling) over the outer surface of the glass cover, which enhances the temperature difference between the water surface and the inner surface of the glass cover in the first effect. The evaporated water vapours condense on the inner surface of the cover and release latent heat, which raises the temperature of the glass cover in the first effect. Therefore, more fresh water is produced in the second effect using the latent heat produced in the first effect [2].

An asymmetric solar still with double effect gives higher productivity (yield) than the conventional symmetric double-slope solar still under the same climatic conditions and parameters (basin area, glass-cover inclination, basin-water depth, etc.) of the solar still. Orientation is one of the main parameters, among other optimized others, that enhances the performance of an asymmetric solar still with double effect. Among other types of solar still, the asymmetric solar still with double effect is the most simple and least expensive to manufacture with local materials; therefore, this subject merits further exploration.

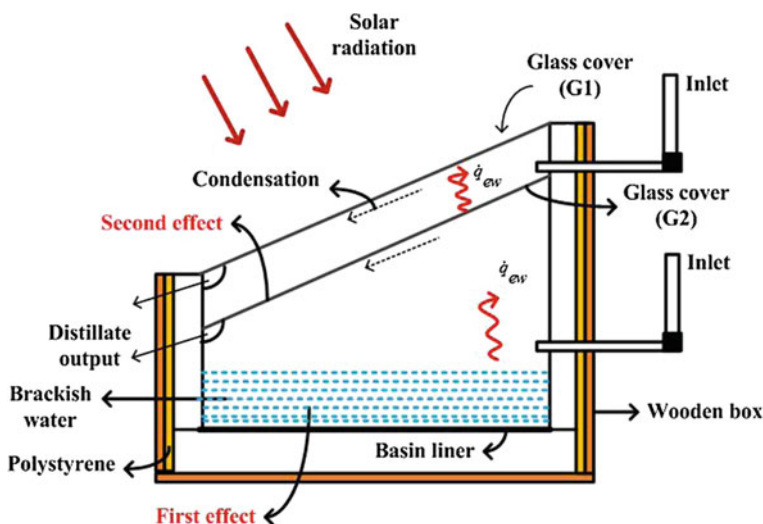


Fig. 3.2 Systematic diagram of asymmetric solar still with double effect

3.4 Hemispherical Solar Still

A systematic diagram of a hemispherical solar still is shown in Fig. 3.3. The basin of the solar still is constructed using mild steel with a diameter of 0.95 m and a height of 0.10 m. The basin surface is painted black to enhance absorptivity of the surface [3]. The water-drainage section is fixed at the inner perimeter of the basin at a height of 0.02 m. The top cover of the still consists of a transparent acrylic sheet (88% transmittance) of hemispherical shape with a diameter of 0.95 m, height of 0.20 m, and a thickness of 3 mm. The saline water is filled in the solar still up to a depth of 0.05 m. The outer box of the still is constructed with wood (insulation) with a thickness of 4 mm and dimensions of 1.10 m $\times$ 1.10 m $\times$ 0.25 m. The sides of the still are insulated with glass wool, and sawdust is filled in the basin up to a height of 0.15 m to reduce heat losses. Sawdust is used underneath the basin because it has to support the weight of the solar still.

Sawdust is less expensive in comparison with glass wool, but it may have problems of durability if it gets wet. Variation of insulation can have a 10% effect on the overall productivity (yield) of the solar still. The temperature difference between the evaporative and the top-glass surfaces is the main driving force in the solar-distillation technique. Moreover, the productivity (yield) rate depends on the water depth in the basin, top-cover inclination, and climatic conditions. The efficiency of the system for climatic conditions of Coimbatore, India (11° North latitude), has been improved from 34 to 42% for a fixed flow rate of

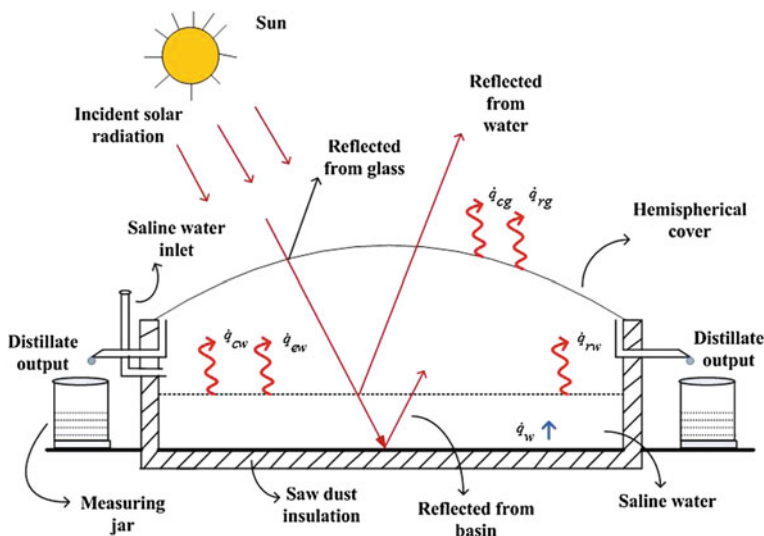


Fig. 3.3 Schematic view of hemispherical solar still

0.000161/s over the top cover. The performance of the hemispherical solar still is enhanced by a factor of 1.25 due to the cooling effect of the top cover for the same amount of incident solar radiations.

3.5 Spherical Solar Still

A schematic view of a spherical solar still is shown in Fig. 3.4. It consists of a circular basin, which is made of aluminum, and an absorber plate, which is coated with black paint to absorb the maximum solar radiation. The absorber plate with an area of 0.4 m^2 and a diameter of 0.61 m is used to store saline water in the basin. The circular basin is placed at middle of the spherical rings with a height of 0.28 m with respect to the total height of the still (0.68 m).

A low-density polythene (LDPE) sheet is used to fit the basin of the spherical solar still without any physical contact. In addition, it is spread over the spherical-shaped aluminum ring. A spherical solar still gives higher productivity (yield) using a lower thickness of the top LDPE in comparison with the still with a higher thickness of the top LDPE cover. This is due to the higher internal and lower external heat-transfer coefficients obtained using a lower thickness of LDPE cover in the system. A maximum efficiency of the system, 22%, has been observed under the climatic conditions of Coimbatore, India (11° North latitude) [4].

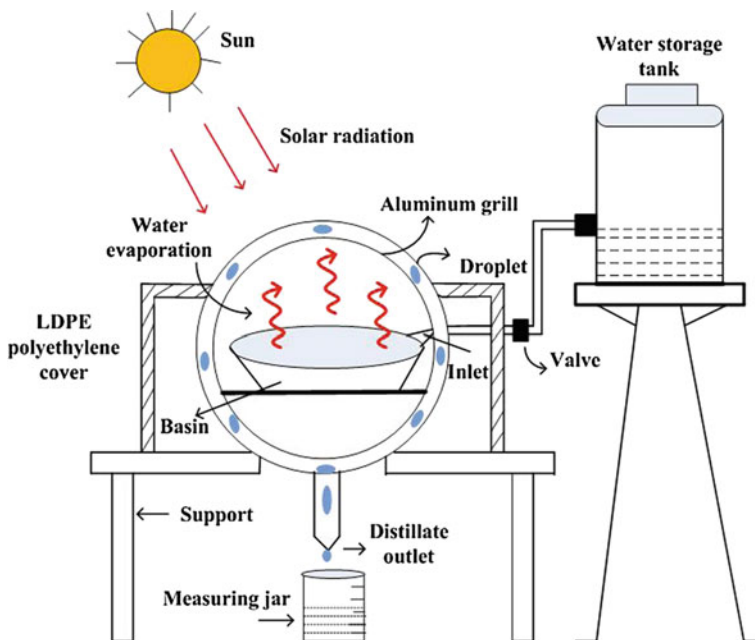
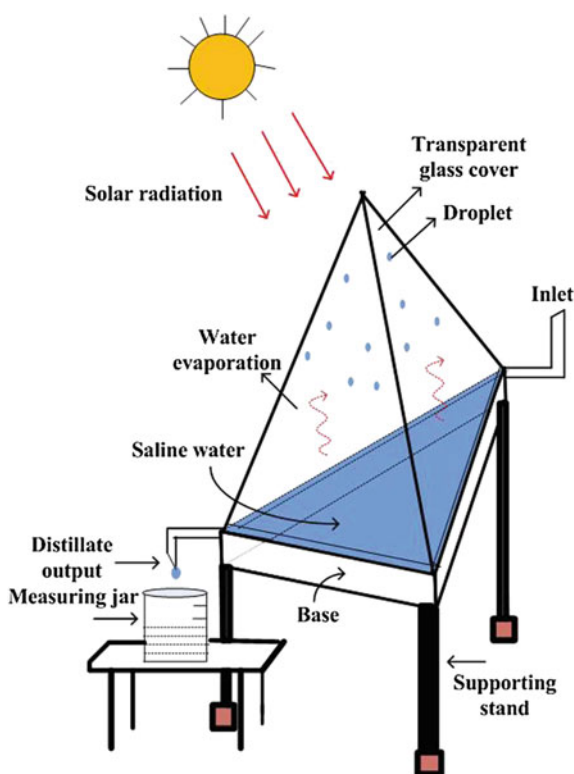


Fig. 3.4 Systematic view of spherical solar still

3.6 Triangular Pyramid Solar Still

Figure 3.5 shows an illustrative view of a triangular pyramid solar still. It consists of a black-painted basin, which is kept inside a wooden box at a pre-determined height. Sawdust is used as insulation underneath the basin to reduce losses. A small piece of glass is fixed on the inner surface of the glass cover. It is fixed to assist the return of condensate into the collection channel, which in turn is joined with the still. A plastic tank for water storage is used to avoid corrosion, and it is connected to the still by way of flexible hoses (polyvinyl chloride). The mass flow rate-controllable valve maintains a constant water level in the still. The flowing water is transferred through the flexible pipes into the measuring jar. The productivity (yield) increases with increasing wind speed. An enhancement of 8 and 15.5% in productivity has been seen with increasing wind speed from 1.5 to 3 m/s and from 3 to 4.5 m/s, respectively, under the climatic conditions of Chennai, India (13° North latitude) [5]. It has been observed that evaporative and convective heat-transfer coefficients are important in designing the solar still; in addition, the temperature difference between the evaporative surface and the inner surface of the top glass cover is also a vital factor for the optimization of operating temperature range.

Fig. 3.5 Diagrammatic view of triangular pyramid solar still



3.7 Double-Basin Double-Slope Solar Still

A double-basin double-slope solar still is fabricated with mild steel plate with a thickness of 1.4 mm and a transparent glass cover with a thickness of 4 mm. The inclination of the glass cover is fixed at 30° . The dimensions of the basin of the still are $0.9 \text{ m} \times 0.7 \text{ m} \times 0.008 \text{ m}$. A schematic view of the still is shown in Fig. 3.6.

The lower basin is coated with black paint to absorb the maximum solar radiation. The height of the lower cover above the basin surface is 8 cm, and the gap between both covers is fixed at 10 cm. Thermocol has been used as insulation to minimize the heat losses. Channels and collection troughs are provided at the lower end of the glass covers to collect the distillate output. Separate sections are provided for basin-water drainage, for water supply, and for insertion of thermocouples, etc. The performance of a double-basin double-slope solar still has been analyzed for the climatic conditions of Tamil Nadu, India [6]. It has been observed that the productivity (yield) of the still increases with increase in water mass in both the lower and upper basins. The lower basin also has higher production with lower water mass in the lower basin. A maximum productivity, 2.991/day, from the double-basin double-slope solar still been determined. Moreover, it is concluded that only pure transparent raw water can be used in the upper basin; however, this system is appropriate for testing impure sewage water in the lower basin while simultaneously testing pure brackish water in the upper basin. However, it is difficult as well as expensive to maintain the lower basin.

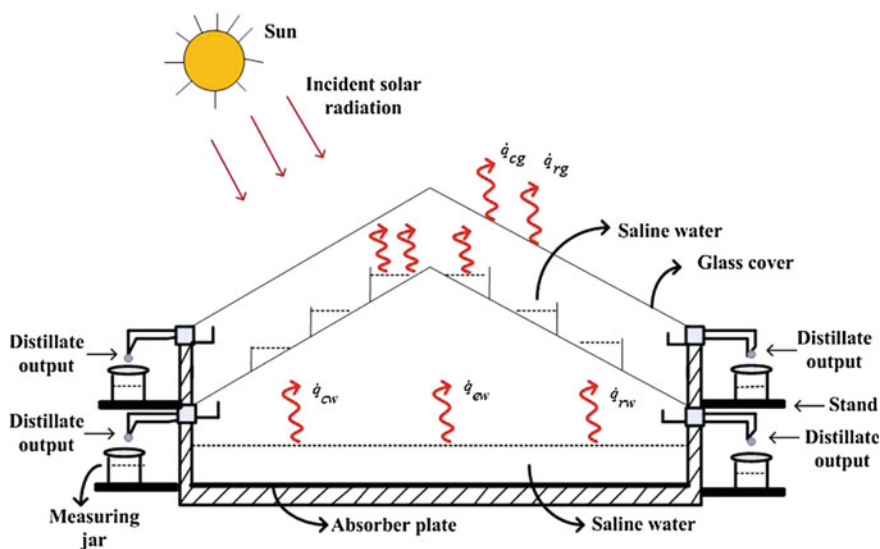


Fig. 3.6 Schematic view of double basin double slope solar still

3.8 V-Shape Solar Still

The design of a V-shaped solar still is shown in Fig. 3.7. The thickness of the transparent top glass cover is 4 mm. A rectangular basin of the still, with dimensions of $2\text{ m} \times 0.75\text{ m} \times 0.005\text{ m}$, is painted black to improve its absorptivity. The basin of the solar still is kept in a woolen case, and the inner space between the wooden case and the basin is filled with sawdust to minimize heat losses at low cost. The diameter of the inlet pipe used for carrying contaminated water is 13 mm. An external water tank is connected to the inlet of the still and the distribution hoses over the transparent glass cover by a valve.

Other specifications and operational parameters are listed in Table 3.1. The transparent top cover is cemented with chemical adhesive to minimize leakage, and the inward slope of the glass cover is maintained toward the center of the still. An outlet is also provided at the lower segment of the glass covers (i.e., the center of the still) as shown in Fig. 3.7a. A slope of 2° is maintained for the outward water-collection channel for outward flow of the distillate water.

The productivity (yield) of the V-shape solar still has been analyzed for evenly distributed water flowing over the glass cover using cotton-gauze top-cover cooling (CGTCC) for the climatic conditions of Coimbatore, India. A cross-sectional view of cotton gauze is shown in Fig. 3.7b. The productivity is enhanced through the effect of cooling air and water flowing over the condensation surface by way of the cotton gauze. A yield of $3300\text{ (ml/m}^2\text{ day)}$ without CGTCC, $4300\text{ (ml/m}^2\text{ day)}$ with CGTCC, and $4600\text{ (ml/m}^2\text{ day)}$ with CGTCC and air flow has been observed [7].

The increase in cost is lower than the increase in productivity with CGTCC and no fans are required, thus providing lower-cost water. However, the increase in cost is greater than the increase in productivity for CGTCC and fans, which implies that it is cost-ineffective. Consequently, in windy areas, the use of CGTCC without a fan would be more effective. The cost-effective simple CGTCC without air-flow design is expected to be a proficient way to convert brackish water into potable water for rural arid regions.

3.9 Conical Solar Still

A systematic diagram of the conical solar still is shown in Fig. 3.8. The conical solar still consists of a galvanized iron circular base of basin with an area of $0.8\text{ m} \times 0.8\text{ m}$ and a cone height of 33 cm. The sides and basin are sheltered with 0.7 mm-thick galvanized iron and painted black to enhance solar absorptivity. Foam with a thickness of 5 cm is used to insulate the sides and base of the still. The transparent top-condensing acrylic cover, with a thickness of 5 cm, is fixed on the edge of circular side of the still at an angle of 31° (latitude of Sheben El Kom city, Egypt) to retrieve maximize solar radiation [8]. The still is mounted on a woody

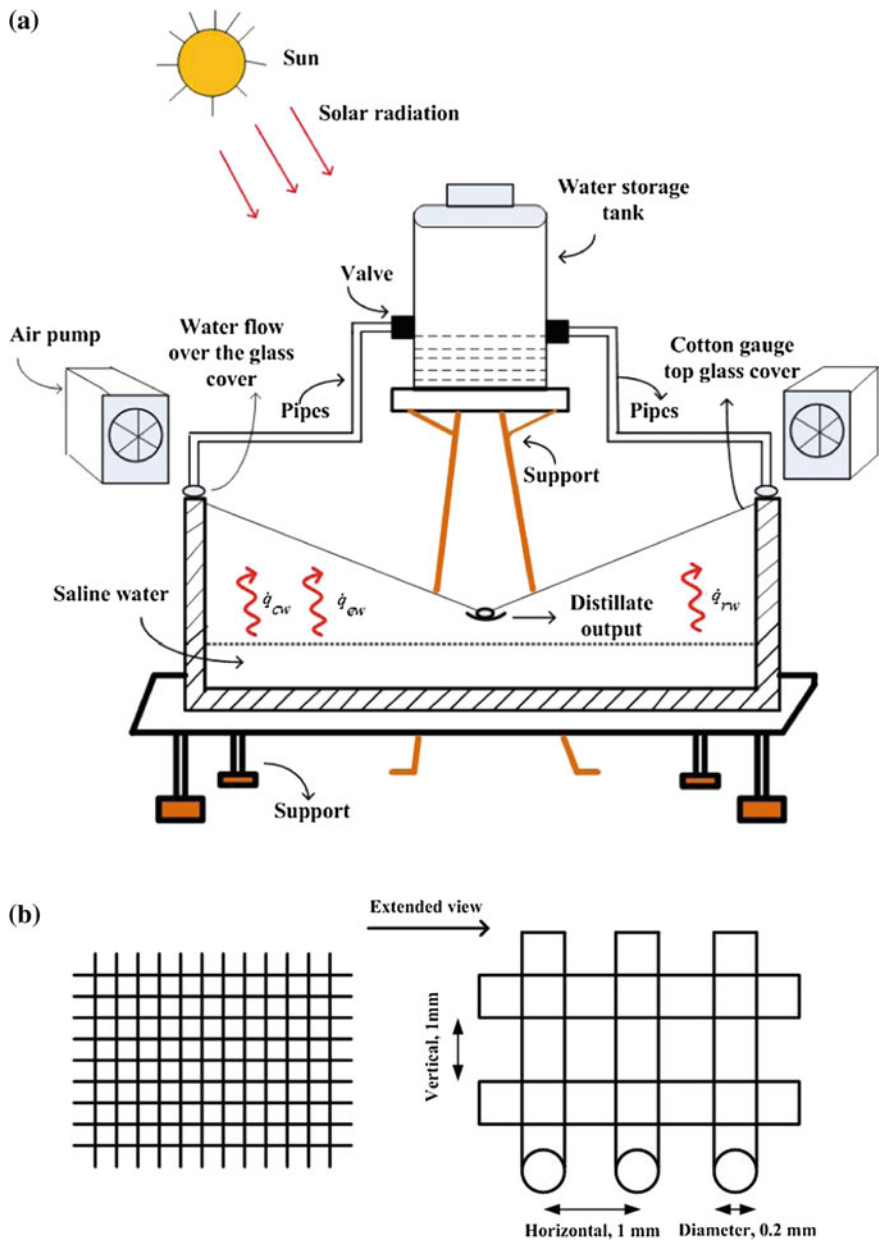


Fig. 3.7 **a** Schematic view of V-shape solar still and **b** cross-section view of cotton gauze

frame. The black galvanized-iron tank of water is connected to the still with polyvinyl chloride (PVC) hoses by way of ball valves. A water-level indicator is used to adjust the water depth in the still, and temperature sensors are connected

Table 3.1 Design and operational parameters

Climatic conditions	Parameter	Numerical value
Clear sky	Ambient temperature (°C)	24–35
	Average wind velocity (m/s)	1
	Relative humidity (%)	22–55
	Solar radiation (W/m ²)	0–1110
Design	Basin absorptivity	0.90
	Basin emissivity	0.90
	Breadth (m)	0.75
	Cover absorptivity	0.05
	Length (m)	2
	Reflectance of cover	0.05
	Specific heat of water (J/kg K)	4190
	Thickness of cotton gauze (m)	2×10^{-4}
	Thickness of glass cover (mm)	4
	Transmittance of glass	0.90

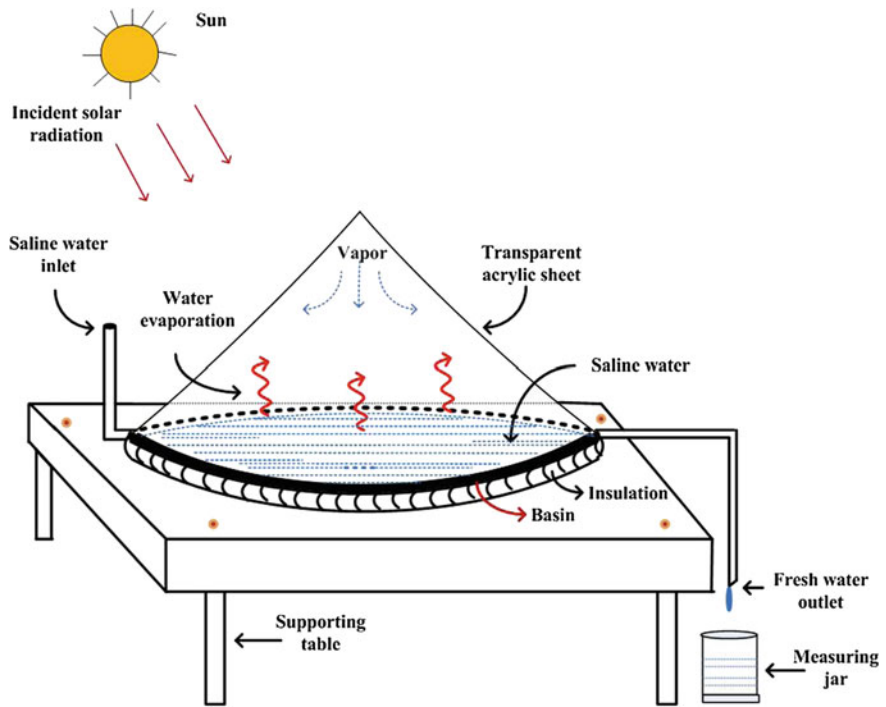


Fig. 3.8 Diagrammatic view of conical solar still

with data acquisition, which measures the basin, water, space, and acrylic temperatures. The performance of the system has been analyzed for the climatic conditions of Sheben El Kom city, Egypt. The basin water in the solar still absorbs the solar energy, and evaporation process takes place; the water vapour is freely transmitted to the inner surface of the glass cover in the solar still cavity due to the buoyancy force caused by density variation. The temperature difference between the evaporative surface (basin water) and the inner surface of the glass cover drives the circulation of humid air, which causes the heat and mass transfer by natural-convection mode. The water vapour releases its latent heat at the inner surface of the glass cover and is condensed there as explained previously. The distilled water is collected through an inclined circular-collection channel fixed at one side.

It has been noted that the productivity (yield) of the conical solar still is higher in comparison with that of the conventional single-basin solar still (dimensions: area of the basin = 0.8 m × 0.8 m and depth ratio of the higher and lower walls = 70 cm: 10 cm) fabricated with the same material used for the conical solar still.

3.10 Wick-Type Solar Still

The basic concept of using a porous multi-wick or jute cloth (acts as a capillary) in a solar still is to attain a water film on the absorber for faster heating and evaporation processes. Four different configurations of wick-type solar stills are discussed.

3.10.1 *Multi-wick Solar Still (Conventional)*

A cross-sectional view of a conventional multi-wick solar still is shown in Fig. 3.9. The body of solar still is made up of fibre-reinforced plastic (FRP) material. In this design, the maximum temperature difference (between the water surface and the inner surface of the glass cover) inside the cavity can be attained by minimizing the heat capacity of the water mass in the still. A water film is sustained on the absorber for quick evaporation and fast heating. The porous multi-wick (jute cloth) is used to attain the water film as shown in Fig. 3.9. A black polythene sheet is placed between the layers of jute cloth so that each layer of the jute cloth can perform independently. Figure 3.9 clearly shows an arrangement of jute cloth in the still. One end of the jute cloth sheets is immersed in the water reservoir and other ends are spread over the base of solar still. For better capillary action, the jute cloth should be wetted properly before spreading it over the base of the solar still. To retrieve the maximum solar radiation, the surface is tilted to the finest angle so that the jute cloth sucks the water from reservoir (with capillary action) up to the upper end of inclined surface. The glass cover is placed over the unit for the condensation of the vapour on its inner surface.

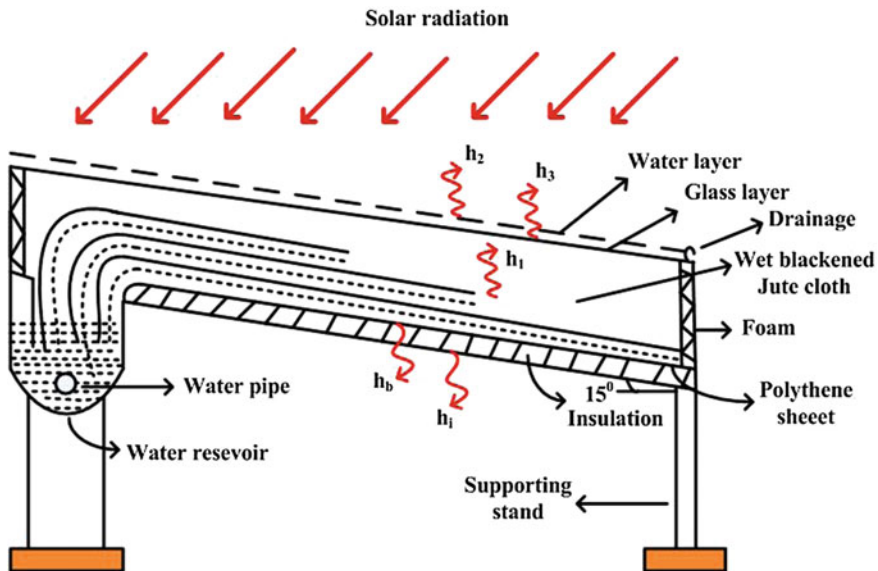


Fig. 3.9 Cross-section view of multi-wick solar still

The penetrated solar radiation is absorbed by the blackened jute cloth; consequently, the water in the jute cloth becomes heated, and the process of evaporation takes place. The heated water condenses at the inner surface of the glass cover after releasing its latent heat there, which is lost to the atmosphere by convection and radiation. The condensed water is collected through the channels provided at lower end of the solar still [9]. This solar still even works under cloudy conditions due to its lowest heat capacity of water flow.

3.10.2 Concave-Wick Solar Still

A schematic view of the concave-wick solar still is shown in Fig. 3.10. A concave basin of the still with a square aperture area of $1.2 \text{ m} \times 1.2 \text{ m}$ is made of a galvanized sheet. The frame of the still is constructed of steel with a thickness of 0.2 cm, and the bottom as well as sides of the basin are insulated by a 5 cm-thick glass wool layer to minimize heat losses. The thickness of the wick surface is 5 cm and covers the basin area, and it is coated black to absorb the maximum solar radiation as explained previously. The basin depth and the saline-water depth in the still at the center is 30 and 10 cm, respectively. A transparent glass cover at an inclination angle of 45° (to the horizontal surface) and a thickness 0.3 cm is used at all the four sides of the still. One of the four glass covers faces south (depends on hemisphere). Galvanized-iron channels are provided at the lower section of the

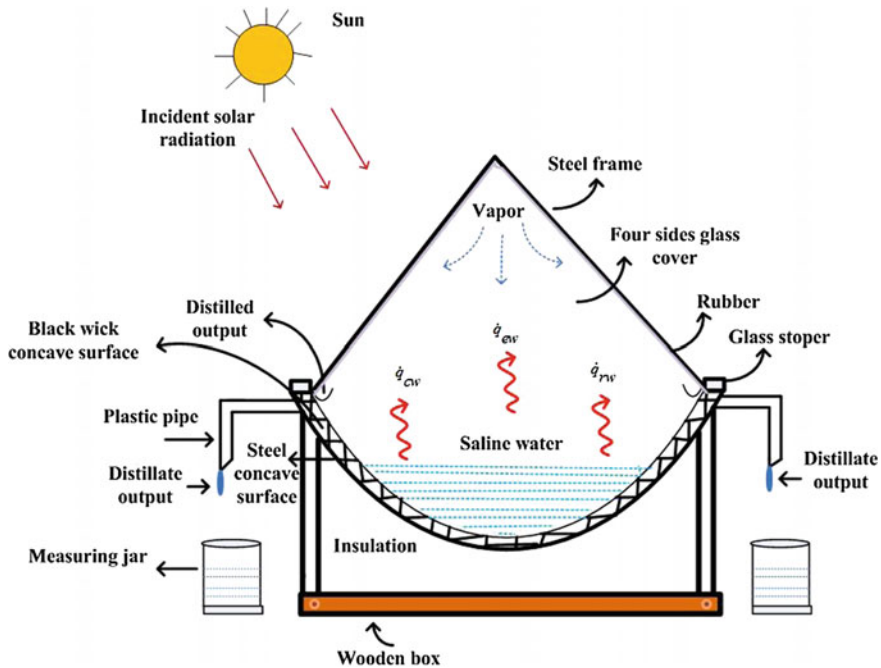


Fig. 3.10 Concave wick type solar still

glass cover to save the distillate output and collected into the measuring jars by way of polyvinyl chloride (PVC) pipes as shown in Fig. 3.10 [10].

The channels are inclined to avoid the accumulation of water. Silicon rubber as a sealant is used to prevent any vapour leakage in the entire system. The jute cloth enhances the extent of the absorbed solar radiation due to capillary action, which consequently raises the evaporation- surface area of the concave-shaped wick surface. The productivity (yield) of the concave-wick solar still is 4.11/day. Maximum instantaneous system efficiency and daily efficiency of 45 and 30%, respectively, have been observed.

3.10.3 Inclined Wick-Type Solar Water-Distillation System

The inclined solar water-distillation system comprises mainly a transparent glass cover and an absorber plate made of a galvanized sheet, which creates a cavity as shown in Fig. 3.11. The cavity dimensions are $1\text{ m} \times 1\text{ m} \times 0.2\text{ m}$ (length $\times$ width $\times$ height). The absorber plate is painted to form a matte black surface (absorptivity 0.96 and emissivity 0.08) to increase its absorptivity [11].

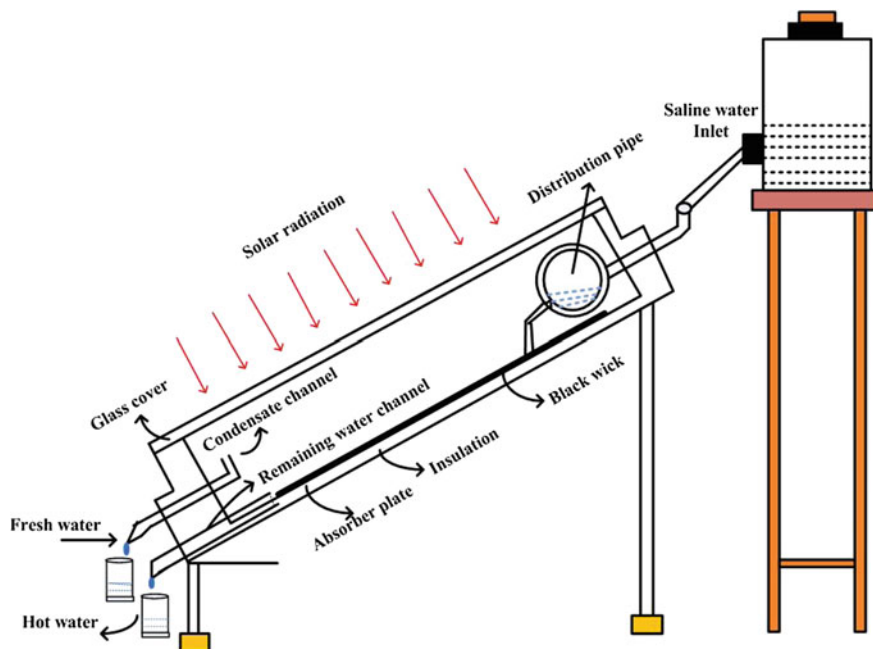


Fig. 3.11 Schematic view of inclined wick type solar distillation system

All of the metallic components of the system that come in contact with the water are preferably made of stainless steel, brass, or copper to avoid corrosion. A black wick is placed over the absorber plate to increase the thickness of the water film and for even distribution of water on the plate. The bottom of the absorber plate is insulated to reduce losses. The thickness of the transparent top glass cover is 3 mm (transmissivity 0.8), and the system is inclined at an angle of 30° . Proper inclination of the system is essential in order to make the dripping water run down onto the absorber plate. In addition, it increases the amount and frequency of solar radiation reaching the surface aperture during the day. A water-storage tank with a longitudinal slot of 2 mm is connected to the distribution pipe (diameter 11 mm). The water spreads through this slot onto the black wick or black absorber plate, thus creating a water film all over the absorber plate. The penetrated solar energy in the cavity warms the absorber plate; consequently, the process of evaporation of water takes place and condenses as it touches the cooler inner glass surface. The condensate water trickles down under the force of gravity and is collected into the channel furnished at lower section of the cavity as shown in Fig. 3.11. The rest of the contaminated feed or hot water flows into another channel at the same lower end and is collected in a separate measuring jar. The effects of different wicks—such as bare plate, black-cloth wick, and black-fleece wick—have been analyzed under the

climatic conditions of northern Cyprus. Eventually, it was concluded that the productivity (yield) of pure water is enhanced significantly when including wicks in comparison with a bare surface.

3.10.4 Tilted-Wick Solar Still with Flat-Plate Bottom Reflector

The tilted-wick solar still with flat-plate bottom reflector facing due south is depicted in Fig. 3.12. The still comprises a transparent glass cover, bottom insulation, a flat-plate bottom reflector, and an evaporative wick. The flat-plate bottom (mirror-finished metal plate) reflector is made of highly reflective materials and extends from the lower edge of the still. The bottom reflector is inclined at angle of θ_m from the horizontal, and the solar still is assumed to be fixed at $\theta_s = 30^\circ$ in this circulation.

The contaminated water-storage tank is connected to the distributing pipes, and water spreads constantly all over the wick. All of the solar radiations (direct, diffused, and reflected) penetrate through the transparent glass cover and are absorbed onto the wick. The mechanism of evaporative heat transfer and condensation takes place between the wick surface and the inner surface of the glass cover. The distilled water is collected through a channel placed at the lower end of the glass cover, and the remaining concentrated saline water (hot water) flows out from the still and is collected through a separate channel. The performance of the system for the fixed inclination $\theta_s = 30^\circ$ of the still and the reflector's length (same as the still's length) was analyzed for 4 days (spring and autumn equinox, summer and winter solstices) [12].

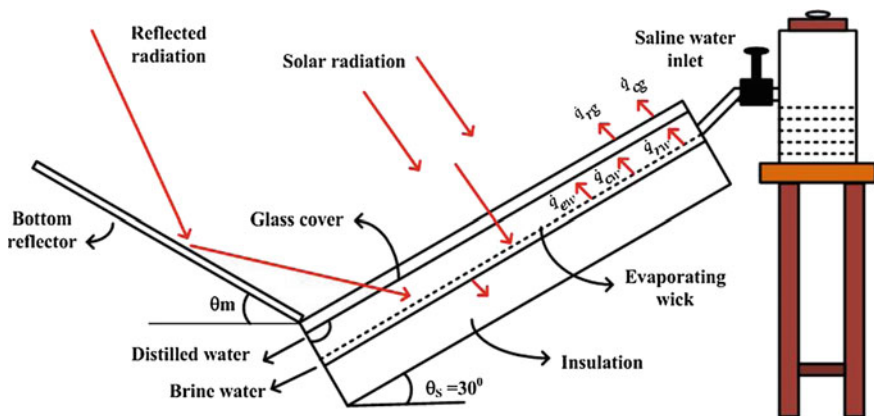


Fig. 3.12 Systematic diagram of tilted wick solar still with flat plate bottom reflector

The productivity of the system is enhanced on integrating a flat-plate bottom reflector, and this critically depends on the inclination of the reflector (θ_m). The enhancement is greater for an inclination θ_m greater than approximately 25° on the summer solstice and approximately 15° on the spring and autumn equinox as well as the winter solstice. The daily yield is maximum in the case of a reflector inclination θ_m at 50° on the summer solstice, 30° on the spring and autumn equinoxes, and 20° on the winter solstice, respectively. Enhancement in daily yield is lowest on the winter solstice (10%) and highest on the summer solstice (25%) on including a bottom reflector. For the reflector inclination at $\theta_m = 35^\circ$, the average value of daily yield for the 4 days was found to be greater at approximately 13% in comparison with the conventional tilted-wick solar still.

3.11 Stepped Solar Still

The rate of heat transfer between the evaporative and condensing surface of the still can be improved by changing the shape of the conventional basin to the stepped tray-type basin. Different configurations of stepped solar stills are discussed herein.

3.11.1 *Stepped-Type Basin Solar Still*

A view of the stepped-type basin solar still is shown in Fig. 3.13. The system of a stepped-type basin solar still comprises a wooden box with an area of $1.1 \text{ m} \times 1.1 \text{ m}$, a greater height of 0.61 m, and a lower height of 0.4 m. The vacant space of 0.2 m between the wooden box and the sides of the tray is filled with sawdust to reduce heat losses. The area of the basin is $1 \text{ m} \times 1 \text{ m}$, and stepped-type absorber plate is fixed over the conventional basin. The stepped solar still has subsequent trays, which consists of four compartments with a total area of 240 cm^2 and inclined flat-plate collectors. Due to low cost and easy fabrication, the trays are made of iron sheet with a thickness of 2 mm. Three inclined flat-plate collectors, each with a size of $60 \times 70 \text{ cm}^2$, are sandwiched between the three trays, and wicks are placed over the inclined flat-plate collectors to enhance the rate of evaporation by capillary action. The transparent glass cover, with a thickness of 3 mm and an area of $1.1 \text{ m} \times 1.1 \text{ m}$, is fixed on the top of the still to receive the solar radiation. The south-facing glass cover is inclined at an angle of 11° . The condensed (potable) water on the inner surface of the glass trickles down under the force of gravity and is collected in the collection trough by a piece of glass gutter attached to the lower end of the glass cover. The water-storage tank connected to the system supplies feed water through a pipe. A plastic tank is used to collect the contaminated water from the basin. The saline water from the storage tank enters the first tray of the stepped-type basin, and the excess water is overflowed to the subsequent trays

through the inclined flat-plate collector that connects the other trays. Because the flat-plate collector is covered with wicks, the saline water wets the wick. Finally, the excess water is collected in the conventional basin at the bottom.

The stepped-type tray basin, along with the flat-plate collector, enhances the evaporative heat-transfer rate. The connected stepped trays improve the water-collection area. A productivity (yield) of 1468 and 1150 kg/cm² has been obtained for a water depth of 2 and 4 cm, respectively, for the climatic conditions of Madurai, India [13]. Such a system gives enhanced productivity with the combination of sponge and wick such that a productivity of 1305 kg/cm² has been obtained for a water depth of 2 cm. In contrast, the lowest productivity obtained with the sponge combination is 1205 kg/cm².

Different packing materials—such as wooden chips, coconut coir, sand, and coal—are added to the inclined flat-plate collector to enhance the area of exposure. The combination of rock, sponge, and wick produces a maximum productivity of 1745 kg/cm², and a minimum productivity was obtained for the sand-and-wick combination (1200 kg/cm²). The daily efficiency of various combinations of different materials was estimated, and among all combinations, the combination of coconut coir and wick produced 16.36%, a nearly 3% increase in efficiency compared with the conventional still.

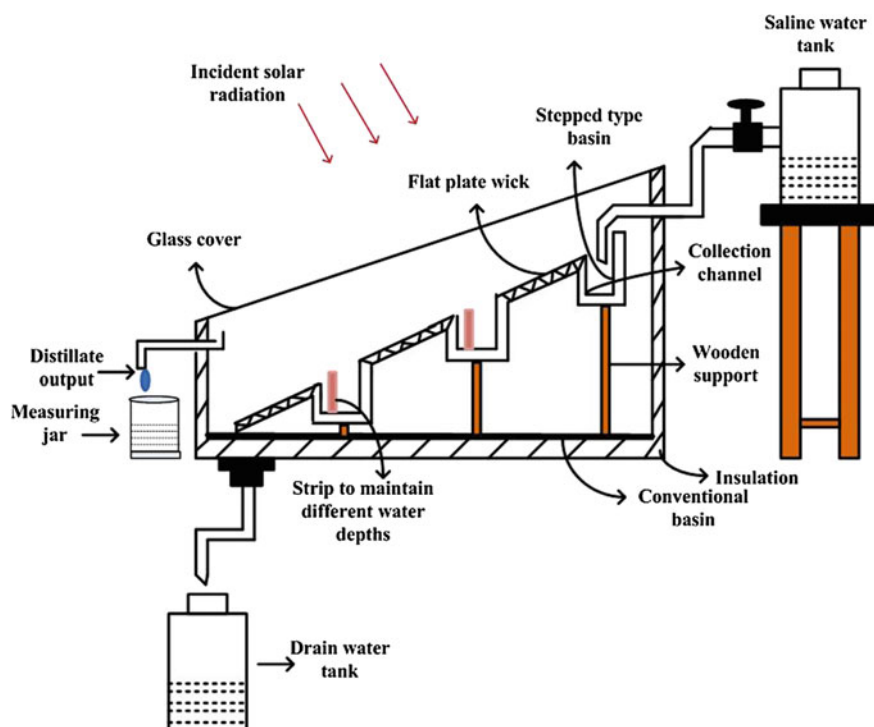


Fig. 3.13 Schematic diagram of stepped type basin solar still

3.11.2 Modified Stepped Solar Still

A schematic diagram of a modified stepped solar still is shown in Fig. 3.14a. It comprises a saline-water or contaminated water-supply tank, a vacuum tubular solar collector, a conventional (single slope), and stepped solar still. A vacuum tubular solar collector has been incorporated in order to preheat the saline water. The solar still is constructed with galvanized steel sheets. The basin area of the conventional solar still is $1\text{ m} \times 1\text{ m}$; the height of the higher side wall is 45 cm, and the height of the lower side wall is 16 cm. The basin of the still is painted black to increase the absorptivity of the surface. The sides and bottom of the still are insulated (supported by a wooden frame) with sawdust with a thickness of 4 cm to minimize heat losses

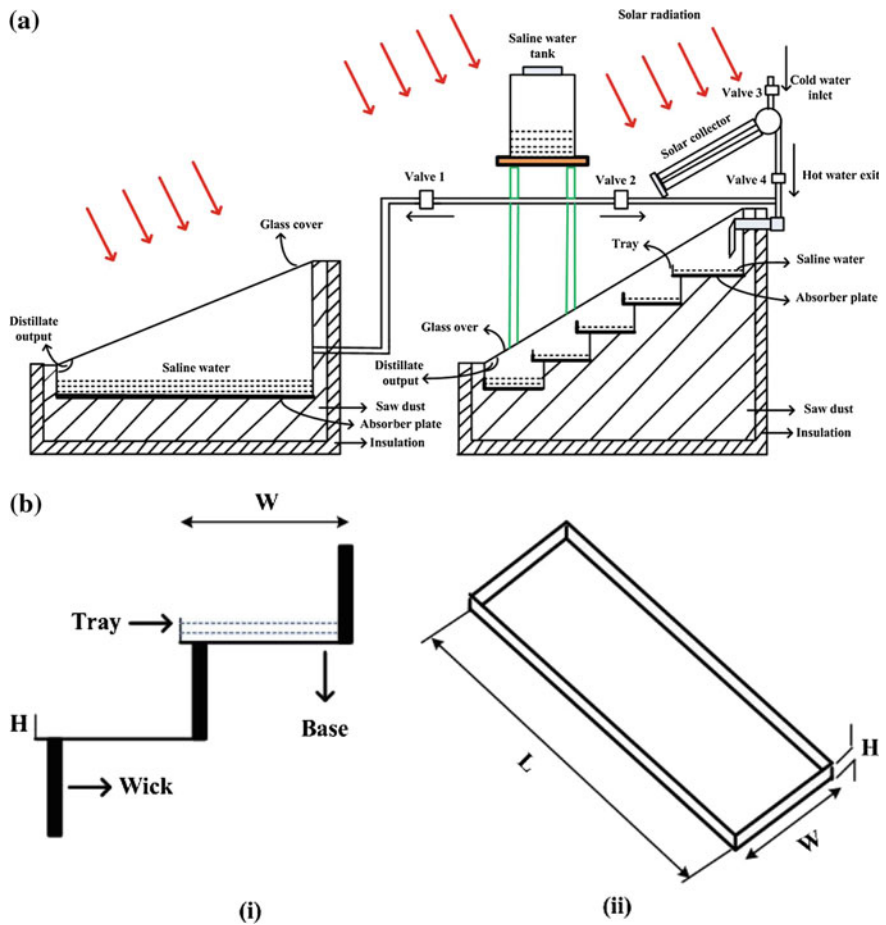


Fig. 3.14 a Schematic view of modified stepped solar still and b View of wick and tray on the steps of stepped solar still

from the still to ambient. The still is covered with a 3 mm-thick transparent glass cover at 30° inclination angle with horizontal. The system is kept in the southern direction to receive the maximum solar radiation. In a stepped still, the absorber plate consists of five steps (each of size $0.1 \text{ m} \times 2 \text{ m}$); however, the other dimensions are similar to those of a conventional still.

Figure 3.14b shows a (i) view of a wick on the vertical side and trays on horizontal side of the stepped solar still and (ii) a cross-sectional view of the tray. The performance of the system has been analyzed for the climatic conditions of Kafrelsheikh University, Egypt [14]. The high performance of the stepped solar still is achieved for the water depth and tray width of 0.5 and 12 cm, respectively. The productivity (yield) was found to be 57.3% greater in comparison with that obtained from the conventional solar still. Pre-heating of the saline through a vacuum tube solar collector marginally improves the productivity of the system, but the system efficiency decreases to approximately one half.

3.11.3 Stepped Solar Still with Internal and External Reflectors

A systematic view of the stepped solar still with internal and external reflectors is shown in Fig. 3.15. The description of the system is same as described previously in Sect. 3.11.2 for the modified solar still excluding additional reflectors only.

Mirrors as internal reflectors are coupled on the vertical sides of the steps, and the top external reflector is inclined backward as illustrated in Fig. 3.15. The length and width of the external (top and bottom) reflector are 2 and 0.6 m, respectively, which is nearly the same area of the transparent top glass cover of the still. Forward and backward movement of the inclined top reflector depends on the seasons. Table 3.2 lists the optimized inclination of both external reflectors (top and bottom). The altitude angle of the Sun declines during the winter season; consequently, a significant amount of the reflected radiation from the vertical reflectors of the steps do not hit the still such but escape to the ground directly. Therefore, the top reflector should be inclined slightly forward to trap the maximum solar radiation. During summer, the altitude angle of the Sun upturns so that the vertical reflector cannot effectively reflect sunrays to the still. Thus, the inclination angle of the reflector throughout the year would be $<25^\circ$, and the top reflector would be slightly inclined toward the back [15].

Absorption of solar radiation or productivity (yield) of the still can be enhanced by regulating the inclination of the flat-plate bottom reflector and extending it from the lower corner of the still [16]. The distillation system, coupled with the internal and external (top and bottom) reflectors, gives better productivity (125%) in comparison with the conventional solar still.

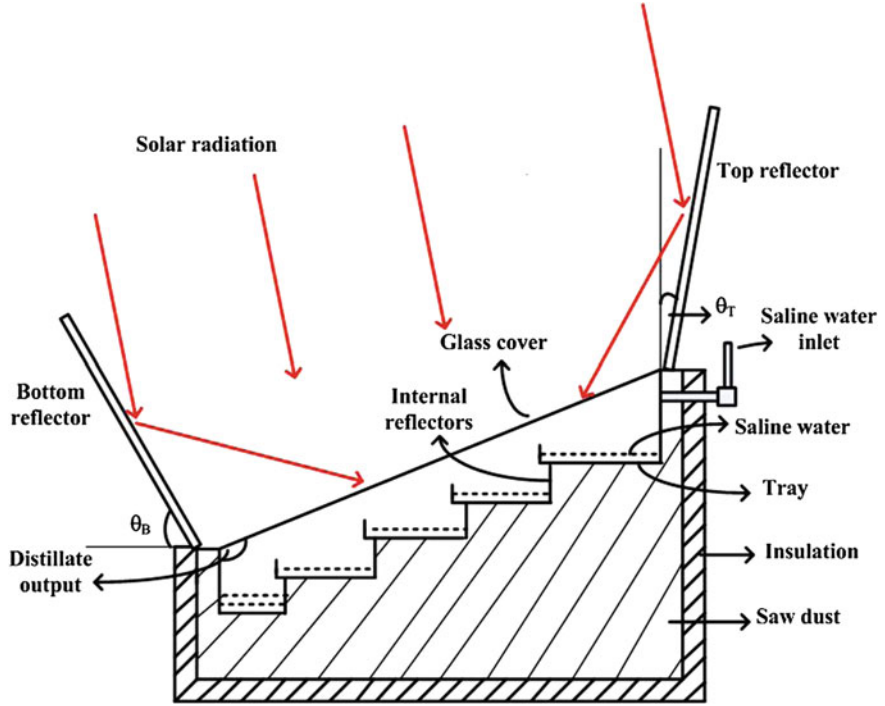


Fig. 3.15 Systematic view of stepped solar still with internal and external reflectors

Table 3.2 The optimum reflector inclination for different seasons

Reflector angle	Autumn	Spring	Summer	Winter
Bottom, (θ_B)	8°	7°	15°	15°
Top, (θ_T)	30°	30°	50°	20°

3.12 Solar Still Using Phase-Change Material (PCM)

The main advantages of the latent-heat thermal-energy storage (LHTESS) system compared with sensible-heat storage systems are their higher energy storage capacity per unit volume and their almost constant temperature for charging and discharging. Basically, a PCM is a substance with a high heat of fusion that is capable of storing and releasing large amounts of energy on melting and solidifying at a certain temperature. In general, heat is absorbed or released when the material changes from liquid to solid and vice versa.

The PCM stores the excess energy produced during sunshine hours inside the solar still and uses it later during the night, which in turn improves the productivity of the still. During sunshine hours, the absorber temperature is greater than that the PCM such that the heat is transferred to the PCM. This triggers the charging process

to store solar energy as sensible heat until the PCM reaches its melting temperature. Therefore, during the melting process, an excessive charging of heat is stored in the form of latent heat, and additional heat will be stored as liquid-wax sensible heat. The reverse process takes place (discharging process) until the phase-change material layer is fully solidified during off-sunshine hours (i.e., the absorber temperature is lower than that of the PCM).

Moreover, use of aspecific PCM depends closely on the maximum temperature of the brackish water (salinity) in the basin. Therefore, it is essential that the temperature of brackish water is close to the melting temperature of the PCM.

3.12.1 Conventional Single-Slope Solar Still with PCM

A systematic diagram of a conventional single-slope solar still with in-built phase-change material (PCM) is shown in Fig. 3.16. Physical properties of some common PCMs are listed in Table 3.3. The basin area (1 m × 1 m) of the still is painted black to absorb the maximum solar radiation. The PCM is placed underneath the basin liner, and the sides and bottom of the still are insulated to minimize heat losses. The basin of the still is fed by a brackish-water reservoir through a non-returning valve.

The solar radiation penetrating through the transparent glass cover is first absorbed by the brackish water, the basin liner, and then the PCM. The PCM stores the thermal energy during the sunshine hours and releases it later during the off-sunshine hours as well as delivers energy on cloudy days (Sect. 3.12). Consequently, a higher temperature difference inside the solar-still cavity (between the evaporative surface and the inner surface of glass the cover) improves the evaporative heat-transfer mechanism. The water vapours condenses at the inner surface of the glass cover after releasing its latent heat there as explained previously in Sect. 3.2. The distilled output is collected through a channel at the lower end of the glass cover of the still as shown in Fig. 3.16. It has been concluded that the productivity (yield) and the efficiency of the system can be improved significantly by incorporating the heat energy-storage material (PCM).

3.12.2 Weir-Type Cascade Solar Still with Built-in Latent-Heat Thermal Energy-Storage System (LHTESS)

An illustrative diagram of the weir-type cascade solar still incorporating phase-change material is presented in Fig. 3.17a. The system is fabricated with aluminium sheet due to its low weight, easy formation, and ability to avoid the corrosion at low and medium temperatures. The absorber plate consists of 15 steps

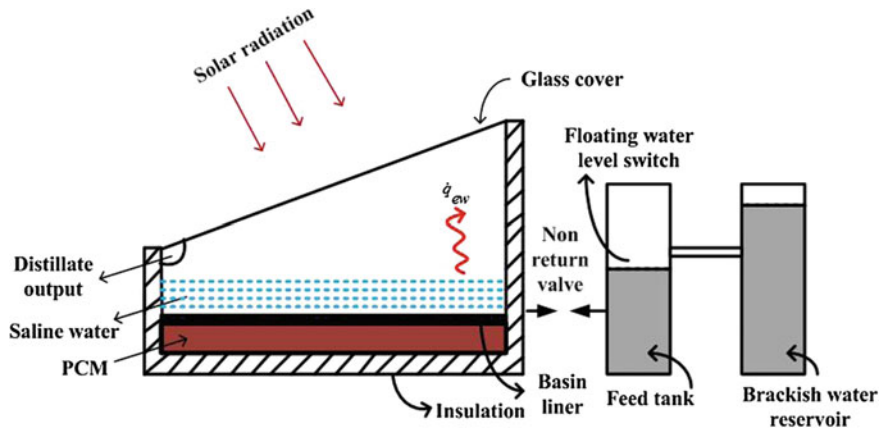


Fig. 3.16 Schematic view of conventional single slope solar still with in-built phase change material

Table 3.3 Physical properties of phase changing materials [17]

	Specific heat (solid/liquid) (J/kg K)	Thermal conductivity (solid/liquid) (W/m K)	Density (solid/liquid) (kg/m ³)	Melting temp. (°C)	Latent heat (kJ/kg)
Paraffine-C18	1900/2240	0.376/0.148	814/774	42	242
Paraffin 52– 54	2195/2950	0.232/0.150	900/814	52	188
Paraffin wax	2950/2510	0.24/0.24	818/760	56	226

(width of 60 cm each) with horizontal (length of 5 cm and vertical (length of 3 cm surfaces, respectively. The whole absorber plate is coated with matte black paint to increase its absorptivity; and the still is covered with a top transparent-glass cover to allow the incident solar radiation. The ratio of height (3 cm) to length (5 cm) is considered on the basis of optimum inclination through the year. Therefore, the total surface area of evaporation is approximately 0.45 m². It has been shown that the optimum inclination is nearly equal to the location latitude throughout the year. The optimum angle of inclination is 30° (Zahedan city, Iran). A weir with 59 cm length and 0.5 cm height is located in each step for the purpose of ensuring proper water flow through the stepped absorber plate. Furthermore, it raises the residence time of water flow and reduces the problem of channelization in the inclined still due to even distribution of water on the absorber plate. The sides and bottom of the still are well insulated to reduce heat loss as explained previously. The top view of the path followed by the water flow on the absorber plate is shown in Fig. 3.17b.

A phase-change material (PCM) is filled in a heat reservoir with a thickness of 3 cm, which is integrated with the still. In the present system, paraffin wax—which is chemically inert and stable below 500 °C with a melting point of 57 °C—has

thermal conductivity, incompatibility with the plastic container, and issues of expansion. The behaviour of PCM was explained previously in Sect. 3.12.

The solar radiation penetrating through the transparent glass cover heats up the feed water (i.e., passes through the steps). The evaporated water releases latent heat to the inner surface of the glass cover and condenses there. In the same manner as explained previously, the distilled water is collected at the lower end of the steps through the collection channel.

The system has been analyzed for the climatic conditions of Zahedan city, Iran. It has been observed that total productivity (yield) of the still with latent-heat thermal-energy storage (LHTESS) is slightly lower than the that of a still without LHTESS during sunny days. A significant enhancement in productivity with LHTESS (3.4 kg/m^2) was obtained in comparison with the still without LHTESS (2.1 kg/m^2) during a partially cloudy day. Hence, the still with LHTESS is preferable only for cloudy areas. Moreover, the productivity depends on the flow rate: Productivity decreases with increasing flow rate. The maximum total productivity for the lowest possible flow rate (0.055 kg/min) of a still with and without LHTESS are approximately 4.85 and 5.14 kg/m^2 day, respectively, on a sunny day [18].

3.12.3 Concentrator-Coupled Solar Still with Phase-Change Material

A schematic view of concentrator-coupled hemispherical basin solar still with phase-change material (PCM) as a storage medium is presented in Fig. 3.18. Six copper balls, each of diameter 2.8 cm , are painted black. Paraffin wax is filled through a small hole on the top of each ball, and high-temperature rubber cork is used to seal it. PCM balls are located in the basin of saline water of the still. The solar radiation penetrating through the transparent glass cover is absorbed by the PCM and the basin liner. Consequently, the temperature of the PCM balls and the basin liner is enhanced. The basin liner absorbs some part of the energy and transfers it to the basin water through the mode of convective heat transfer; it also transfers energy to the cooler PCM balls through conduction, which heat up the balls. First, the heat in the PCM balls is stored as sensible heat until it reaches its melting point. During this period, thermal energy is stored as sensible heat in the melted PCM. In the afternoon, the still components start cooling down, and the liquid PCM transfers its stored thermal energy to the blackened surface (basin liner); later, the blackened surface transfers heat to the basin water until the PCM becomes completely solidified [19].

During low-intensity as well as off-sunshine hours, the PCM behaves as a significant heat-storage medium for the basin water available in the still. After sunset, potable water can be obtained from the still even with a low depth of basin water. The performance of the system with and without operating the PCM has been

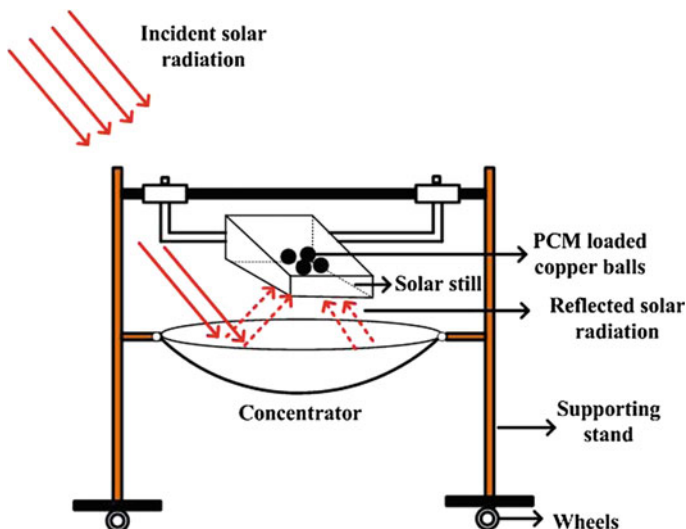


Fig. 3.18 Schematic diagram of concentrator coupled hemispherical basin solar still with phase change material

investigated for Tamilnadu (India) climatic conditions. The enhancement in the temperature of the PCM is due to its energy-absorption capability. It acts as a driving force in the system to enhance the temperature difference between the evaporative surface and the inner surface of the glass cover during off-sunshine hours. At lower water depth in the basin, the PCM becomes more effective during low-sunshine hours. Therefore, the productivity of the still can be significantly improved by integrating PCM in solar still. On a good sunny day, it has been observed that the productivity of a concentrator-coupled single-slope solar still with and without operating the PCM is 4460 and 3520 ml/m² day, respectively.

3.13 Tubular Solar Still

A systematic view of a tubular solar still (TSS) is shown in Fig. 3.19, which describes the pure water-production mechanism. It consists of a blackened rectangular trough inside a transparent tubular cover. In general, two types of mass-transfer mechanism take place inside the TSS (including phase-change process): evaporation and condensation. The process of evaporation takes place from the evaporative surface (water) to the humid air, and condensation occurs from the humid air to the inner surface of the cover. Various types of heat transfer take place inside the TSS: convective and evaporative heat transfer between the water surface and the humid air; heat transfer through condensation from the humid air to the inner glass cover; and radiative heat transfer between the evaporative surface and

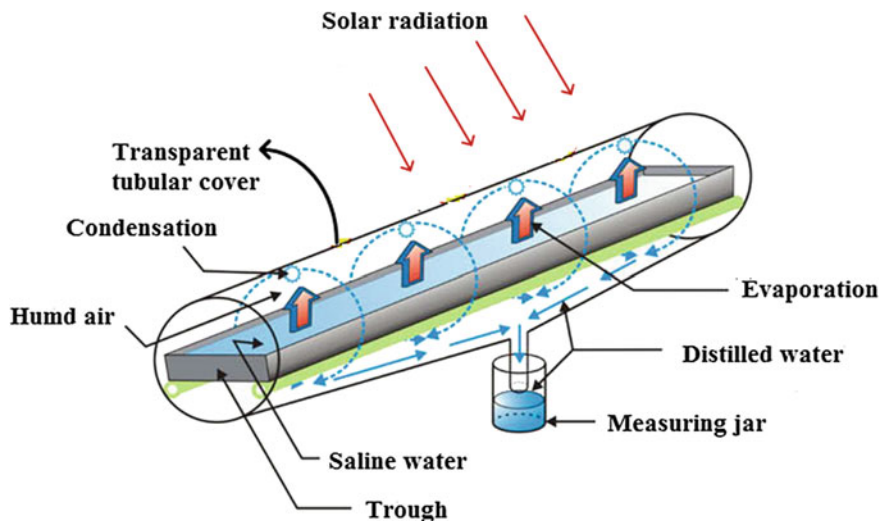


Fig. 3.19 Cross-section view of tubular solar still

the cover, between the cover and the atmosphere, between the humid air and the trough, between the humid air and the cover, and between the trough and the water.

The solar radiation transmitted through the glass cover is mostly absorbed by the saline water in the basin. Consequently, the saline water is heated, and the mechanism of evaporative-heat transfer is initiated. The density of water vapour of the humid air increases associated with the evaporative-heat transfer from the saline-water surface. The water vapour releases its latent heat to the inner surface of the glass cover and condenses there as explained previously. Finally, the condensed water trickles down under the force of gravity at the lower end of the glass cover and is collected through a channel [20].

A tubular solar still shown in Fig. 3.19 based on the new heat- and mass-transfer model by considering the properties of humid air inside the still. Consequently, it delivers new outputs for the system, i.e., water-vapour density, temperature, relative humidity, hourly evaporation flux, and condensation flux in addition to the temperature of the cover and the water. Daily variation of the water-vapour density of humid air and the relative humidity intensely depends on the difference between the rates of evaporation and condensation.

3.14 Tube-Type Networked Solar Still for Desert Technology

Figure 3.20 shows a schematic view of the tube-type networked still. The tubular solar still (TSS) provides more area for convection mechanism over the basin, which controls the circulation of vapour under the basin in comparison with the

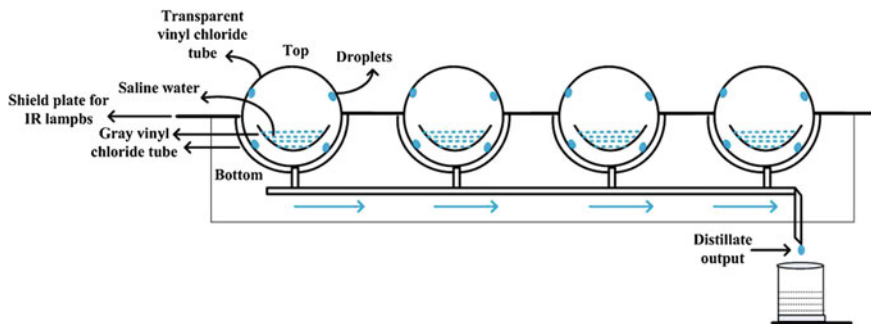


Fig. 3.20 Schematic view of tube-type networked solar still

conventional flat basin. The basin of the TSS minimizes the possibility insulating the still. The outer tube of the still, as a cover, is fabricated with a 2 mm-thick transparent sheet of vinyl chloride and a half-cut vinyl chloride tube (length 110 cm, thickness 0.7 cm, and inner diameter 10 cm) as an underground part. Another gray half-cut vinyl chloride tube (length 100 cm, thickness 0.45 cm, and inner diameter 6.7 cm) is installed as a basin. The inner side is coated with black paint for better absorptivity. To maintain the uniform diffusion gap, the inner half tube is coaxially fixed with the outer tube at both the ends. The water level remains constant with a supply tank. T-type thermocouples are connected to measure temperatures at various places of the still. In laboratory-experiment tests, variable solar-radiation input was provided with 250 W capacities of infrared lamps. The infrared radiation falls only on the upper portion of the tube with the help of shield plate. The water vapour condenses after releasing its latent heat to the tube surface and dribbles down to finally be collected through a channel into a measuring jar. The productivity (yield) and distributions of temperature have been measured for different solar intensities of infrared lamps (200, 400, 600 and 800 W/m²) and water levels in the tube basin (1 and 2 cm) [21].

Figure 3.20 describes the concept of desert plantation. The lower half portion of the system is buried underground. In this process, the fresh water obtained inside the tube is not collected separately in the storage tank but rather flows directly underground through a channel at the lower end of the tube. Therefore, insulation is essential at the lower end of a conventional tube-type still. An air gap between the bottom and basin of the tube of the still allows the underground setting.

3.15 Stand-Alone Point-Focus Parabolic Solar Still

Figure 3.21 depicts an illustrative view of the design of a point-focus parabolic solar still. The system consists of various components including a parabolic-shaped dish concentrator, a double-axis solar-tracking system with a programmable logic

controller (PLC)–built regulator part, double-plate heat exchangers (PHEs), an evaporation chamber (absorber), and a water level–control unit. These different components of the still are balanced on a stand.

The position of the concentrator and the absorber (evaporation chamber) is vital; consequently, the absorber is always located at the focal point of the concentrator, and the inlet of the absorber is directly attached to the supply tank. The water vapour from the absorber plate reaches into the double-plate heat exchanger and condenses, which in turn raises the temperature of the brackish water before entering the absorber plate during circulation. The control unit has been incorporated in the system to maintain the level of the brackish water in the absorber plate.

In detail, the parabolic reflector has a focal length of 0.693 m and an aperture diameter of 2 m. A highly reflective silver-backed piece of glass, of 2 mm thickness is used to cover the reflector (area 3.142 m²). The absorber is made of CK-45 steel alloy mounted at the focal point and has a receiving surface of 0.031 m². The absorber is entirely insulated with 0.02 m-thick rock wool except for the part that is ignited by the concentrated solar radiation. The absorptivity of the bottom side of the absorber is increased by painting it black (chrome). Three different components—a pressure-relief valve, an air vent, and a moisture separator—have been integrated with the fixed absorber. The pressure-relief valve and air vent are placed on the absorber at the top position, and it is unlocked only at a set pressure of approximately 4.5 bar. Therefore, a preferred pressure can be attained inside the absorber. During the period of initial heating, an air vent eliminates the air/dissolved gases in the water. In contrast, a moisture separator is installed between the absorber and the pressure-relief valve. The main function of the moisture separator is to avoid the carry-over of liquid droplets from the steam-relief valve [22].

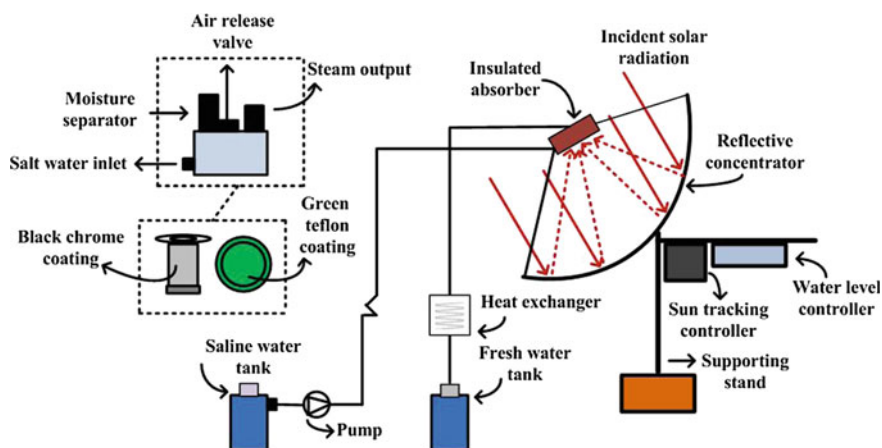


Fig. 3.21 Systematic diagram of stand-alone point-focus parabolic solar still

The Sun-tracking motor works on the implemented functions; therefore, the instructions with respect to the tracking mechanism are pre-stored in the programmable memory of the PLC. The estimated location of the dish tracker is achieved using two DC motors, which help to drive the system. The total heat-transfer area of 0.14 m^2 of the two small-plate heat exchangers (PHEs) is linked to the small circulation pump, which develops the pre-heating thermal-distillation system. Two heat exchangers perform separately in the system such that one heats the feed of brackish water, and the other condenses the water vapours generated by the absorber. The circulating fluid (soft water) between two double-plate heat exchangers lowers sediment creation due to heat-shock reduction. During the first operation period of the system, the dish reflector reflects the incident solar radiations toward the bottom of the absorber situated at the focal point. Consequently, the process of evaporation of brackish water takes place in the absorber through the concentrated solar radiation. The produced steam drifts up and condenses in the PHE after releasing the latent heat of vaporization to the host fluid. Afterward, the brackish water receives the gained heat (steam) of the cold water in the second PHE in order to enhance its temperature before inflowing into the absorber. This cycle repeats until the determined minimum level is not achieved by the feed water in the absorber. Thus, the remaining water (brine) in the absorber is drained through the electric discharge valve, which is connected to the absorber's exit vent. A productivity (yield) of 5.12 kg/day is obtained with maximum solar radiation of 626.8 W/m^2 and absorber wall temperature of 150.7°C for the climatic conditions of Tehran, Iran. The average efficiency evaluated of the system with maximum productivity of 1.2 kg/h is 34.69% .

3.16 Single-Slope Solar Still Integrated with Condenser

In a conventional solar still, solar radiation is transmitted through the top transparent glass cover, and condensation (after releasing of latent heat) of water vapour takes place at the inner surface of the glass cover as explained previously in Sect. 3.2. Consequently, it lowers the overall temperature difference between the water (evaporative) and inner glass surface (condensing). This temperature difference can be improved by separating the condensing surface from the still chamber as illustrated in Fig. 3.22. With this concept, the water vapours are transferred from the solar-still cavity to the integrated condensing chamber where they condense. Very little condensation occurs on the sloped surface. Because the most condensation takes place in the condensing chamber, the temperature difference between the evaporative and condensing surface is enhanced, which causes rapid evaporation and thus produces more distillate output. In this case, the still efficiency is enhanced by 45% . Furthermore, the productivity (yield) can be improved by natural circulation of the vapour as shown in Fig. 3.22b [23].

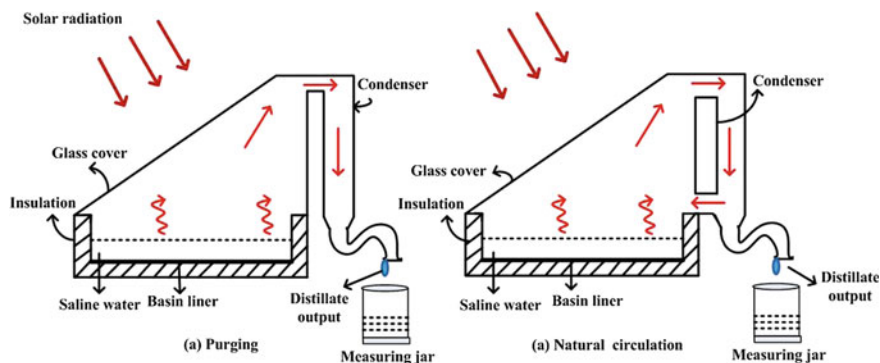


Fig. 3.22 Schematic diagram of single slope solar still integrated with condenser

3.17 Single-Slope Solar Still with Nanofluids

Nanofluids are embryonic fluids and promising thermal-energy carriers in solar thermal applications due to their superior thermo-physical and optical properties. Nanofluids have various features—such as ultrafast heat-transfer capability, lower pumping-power requirement, better stability, superior lubrication, low friction coefficient and erosion, etc.—which efficiently improve system performance. Nanoparticles can be made more attractive as functional materials in comparison with various applications by controlling the frequency (depending on size and shape) across a wide range of wavelengths. A schematic diagram of a conventional single-slope solar still loaded with nanofluid is shown in Fig. 3.23. The working principal of the conventional solar still using water was discussed previously in Sect. 3.2.

The advantage of incorporating metallic nanoparticles is that their plasmon resonance—absorption band arises in the range of the visible and near IR spectrum. The oscillatory motion of nanoparticle electrons is responsible for the light scattering from the nanoparticle surface. Moreover, the energy of incident light is converted to heat after absorption by the nanoparticles. Eventually, the plasmon resonance of nanoparticles has high absorption modes in the ultraviolet and infrared spectral regions. Consequently, nanofluids openly absorb the penetrated solar irradiation because of tuning between the spectrum of optical absorption (nanofluids) and solar irradiation. At high concentration, the assisting metallic nanoparticles spread more (greater surface area) in the given basin, and the nanofluid/heat exchanger volume raises the nanofluid temperature.

Therefore, due to matching between its optical-absorption spectrum and the solar-radiation spectrum, mixed metallic nanoparticles in the base fluid absorb the solar radiation directly. In a solar still, each assisting individual nanoparticles's temperature enhances after the direct absorption of solar radiation and hence increases the thermal conductivity, which in turn raises the temperature of the basin fluid. In addition to this, basin liner also transfer thermal energy to the fluid (base

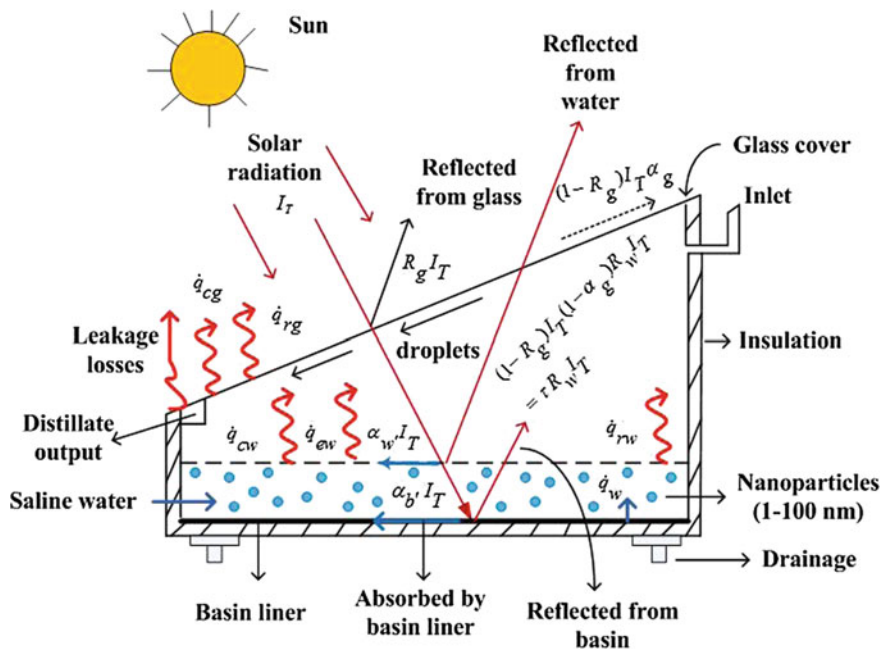


Fig. 3.23 Illustrative view of single slope solar still with nanofluid

fluid/nanofluid). Therefore, the mutual effect of the basin liner and the assisting metallic nanoparticles elevates the temperature of the basin fluid (base fluid/nanofluid) mass, which ultimately enhances the internal heat-transfer rates and hence the productivity (yield) of the still. Thermo-physical properties (conductivity, specific heat, density, and viscosity) of different water-based nanofluids are presented in Appendix E.

Problems and descriptive questions

3.1 Discuss the following in brief with systematic diagrams:

- Single-slope solar still
- Asymmetric solar still
- Spherical solar still
- Conical solar still.

3.2 Explain the stepped solar still integrated with internal and external reflectors.

3.3 Explain the process of the networked solar still for desert technology.

3.4 How is the single-slope solar still integrated with an external condenser is more efficient than the conventional solar still? Explain with an illustrative diagram.

3.5 What is the role of the porous-type wick or jute cloth in an inclined solar still with a bottom reflector. Discuss in detail.

- 3.6 Explain the concave wick-type solar still with a systematic diagram.
- 3.7 What is the working mechanism of phase-changing material (PCM) in a solar still? Explain the following solar stills built-in phase-change material (PCM):
- (a) Conventional solar still
 - (b) Cascade weir-type solar still.
- 3.8 Explain the concept and working of a single-slope solar still with nanofluids.

Objective questions

- 3.1 The basic concept of solar distillation is based on:
- (a) Hydrological cycle
 - (b) Filtration technique
 - (c) Artificial technology
 - (d) None of these.
- 3.2 During a water cycle, which of the following process takes place for the production of pure water?
- (a) Condensation
 - (b) Evaporation
 - (c) Distillation
 - (d) None of these.
- 3.3 The productivity (yield) of the solar still can be enhanced by:
- (a) Cooling of the glass cover
 - (b) Heating of the glass cover
 - (c) Heating of the basin water
 - (d) None of these.
- 3.4 The productivity (yield) of the solar still is a function of:
- (a) Water depth in the basin
 - (b) Area of the still
 - (c) Facing the still
 - (d) Climatic conditions
 - (e) All of these.
- 3.5 The temperature difference among which of the following components acts as a driving force for enhanced productivity (yield) of the still?
- (a) Water and inner condensing surface
 - (b) Water and basin liner
 - (c) Outer condensing surface and ambient
 - (d) All of these.

- 3.6 An asymmetric double-effect solar still consists of:
- (a) Double basins and a single glass cover
 - (b) A single basin and double glass covers
 - (c) Double basins and double glass covers
 - (d) None of these.
- 3.7 The productivity (yield) of a spherical solar still is higher with:
- (a) Low thickness of LDPE
 - (b) High thickness of LDPE
 - (c) Independent on thickness of LDPE.
- 3.8 Which of the following is cost-effective combination in the design of V-shape solar still for rural arid regions?
- (a) CGTCC with air flow
 - (b) CGTCC without air flow
 - (c) Both (a) and (b)
 - (d) None of these.
- 3.9 Which of the following is a cost-effective combination in the design of a V-shape solar still for windy areas?
- (a) CGTCC without a fan
 - (b) CGTCC with a fan
 - (c) Both (a) and (b)
 - (d) None of these.
- 3.10 In a solar still, the porous multi-wick or jute cloth acts a:
- (a) Capillary
 - (b) Absorber
 - (c) Both (a) and (b)
 - (d) None of these.
- 3.11 The choice of PCM depends on:
- (a) Maximum temperature of the basin water
 - (b) Climatic conditions
 - (c) Area of the basin
 - (d) None of these.
- 3.12 Productivity of the still with LHTESS is slightly lower than productivity with LHTESS for:
- (a) Partially cloudy
 - (b) Cloudy conditions
 - (c) Sunny conditions
 - (d) For all conditions.

- 3.13 Which of the following fact is responsible for the fast evaporation in a solar still with condenser?
- Little condensation occurs at the inner surface of the glass cover
 - High condensation occurs at the inner surface of the glass cover
 - Enhancement in still area
 - None of these.
- 3.14 The plasmon resonance–absorption band of metallic nanoparticles arises in the range of
- Visible and far infra-red spectrum
 - Visible and near infra-red spectrum
 - Ultraviolet and far infra-red spectrum
 - Ultraviolet and near infra-red spectrum.
- 3.15 Metallic nanoparticles absorb solar radiation:
- Directly
 - Indirectly.

Answers

- 3.1 (a) 3.2 (b) 3.3 (a) and (c) 3.4 (e) 3.5 (a) 3.6 (b)
 3.7 (a) 3.8 (b) 3.9 (a) 3.10 (c) 3.11 (a) 3.12 (c)
 3.13 (a) 3.14 (b) 3.15 (a)

References

- G.N. Tiwari, R.K. Mishra, *Advanced Renewable Energy Sources* (RSC Publishing Cambridge, UK, 2012)
- A. Trad, A. Kaabi, Effect of orientation on the performance of a symmetric solar still with a double effect solar still (comparison study). *Desalination* **329**, 68–77 (2013)
- T. Arunkumar, R. Jayaprakash, D. Denkenberger, A. Ahsan, M.S. Okundamiya, S. Kumar, H. Tanaka, H.S. Aybar, An experimental study on a hemispherical solar still. *Desalination* **286**, 342–348 (2012)
- R. Jayaprakash, K. Perumal, T. Arunkumar, S. Kumar, B. Selvakumar, Design and performance analysis of low cost solar still using transparent LDPE cover, *J. Environ. Res. Dev.* **4** (2009)
- R. Sathyamurthy, H.J. Kennady, P.K. Nagarajan, A. Ahsan, Factors affecting the performance of triangular pyramid solar still. *Desalination* **344**, 383–390 (2014)
- T. Rajaseenivasan, K.K. Murugavel, Theoretical and experimental investigation on double basin double slope solar still. *Desalination* **319**, 25–32 (2013)
- P.U. Suneesh, R. Jayaprakash, T. Arunkumar, D. Denkenberger, Effect of air flow on “V” type solar still with cotton gauze cooling. *Desalination* **337**, 1–5 (2014)
- H.E. Gad, S.S. El-Din, A.A. Hussien, K. Ramzy, Thermal analysis of a conical solar still performance: an experimental study. *Sol. Energy* **122**, 900–909 (2015)
- G.N. Tiwari, *Solar Energy: Fundamentals, Designs, Modeling and Applications* (Narosa Publishing House New Delhi, 2002)

10. A.E. Kabeel, Performance of solar still with a concave wick evaporation surface. *Energy* **34**, 1504–1509 (2009)
11. H.S. Aybar, F. Egelioglu, U. Atikol, An experimental study on an inclined solar water distillation system. *Desalination* **180**, 285–289 (2005)
12. H. Tanaka, Tilted wick solar still with flat plate bottom reflector. *Desalination* **273**, 405–413 (2011)
13. A.S. Abdullah, Improving the performance of stepped solar still. *Desalination* **319**, 60–65 (2013)
14. A.E. Kabeel, A. Khalil, Z.M. Omara, M.M. Younes, Theoretical and experimental parametric study of modified stepped solar still. *Desalination* **289**, 12–20 (2012)
15. T. Hiroshi, Tilted wick solar still with external flat plate reflector: optimum inclination of still and reflector. *Desalination* **249**, 411–415 (2009)
16. H. Tanaka, Tilted wick solar still with flat plate bottom reflector. *Desalination* **273**, 405–413 (2015)
17. O. Ansari, M. Asbik, A. Bah, A. Arbaoui, A. Khmou, Desalination of the brackish water using a passive solar still with a heat energy storage system, *Desalination* **324**, 10–20 (2013)
18. F.T. Farshad, M. Dashtban, M. Hamid, Experimental investigation of a weir-type cascade solar still with built-in latent heat thermal energy storage system. *Desalination* **260**, 248–253 (2010)
19. T. Arunkumar, D. Denkenberger, A. Ahsan, R. Jayaprakash, The augmentation of distillate yield by using concentrator coupled solar still with phase change material. *Desalination* **314**, 189–192 (2013)
20. A. Ahsan, T. Fukuhara, Mass and heat transfer model of tubular solar still. *Sol. Energy* **84**, 1147–1156 (2010)
21. K. Murase, H. Tobata, M. Ishikawa, S. Toyama, Experimental and numerical analysis of a tube-type networked solar still for desert technology. *Desalination* **190**, 137–146 (2006)
22. S. Gorjian, B. Ghobadian, T.T. Hashjin, A. Banakar, Experimental performance evaluation of a stand-alone point-focus parabolic solar still. *Desalination* **352**, 1–17 (2014)
23. H.E.S. Fath, S.M. Elsherbiny, Effect of adding a passive condenser on solar still performance. *Energy Conserv. Manage.* **34**, 63–73 (1993)

Chapter 4

Solar Collectors

4.1 Introduction

A flat-plate collector (FPC) is a device to collect solar energy and transform it into thermal energy (low-grade energy) by using water as a working fluid. It has many applications in medium-temperature range ($\cong 100\text{ }^{\circ}\text{C}$) from domestic to pre-heating to industrial sectors. The hot water available from flat-plate collectors (FPCs) can also be used to conserve fossil fuel. It can provide a medium-temperature range $150\text{ }^{\circ}\text{C}$ with a working fluid under steady-state conditions. However, for a temperature range of $>150\text{ }^{\circ}\text{C}$, the design of the FPC must be changed.

For a greater operating temperature range ($\geq 300\text{ }^{\circ}\text{C}$) of solar thermal-energy applications in the industrial sector, the beam radiation of solar energy is concentrated at a low surface area of the receiver. This is referred to as a “concentrating system” and can be used for power generation with high-temperature boiling fluids as medium. Solar-power generation is economical for higher-capacity plants ($\geq 1\text{ MW}$) with grid power in a dust-free region for less frequent cleaning of the reflecting sheet. It has been observed that all solar-thermal devices give better thermal performance under a forced mode of operation due to lower temperature; hence, a photovoltaic thermal (PVT) system is essentially required in all solar-thermal systems.

In a flat-plate collector (FPC) and solar concentrator, there are two thermal losses from the absorber/receiver to the glazing cover as discussed later in the text.

(a) The rate of convective-heat transfer

The rate of convective-heat transfer depends on the temperature-dependent physical properties of enclosed air between the absorber/receiver and the glazing cover. If enclosed air between the absorber/receiver and the glazing cover is evacuated to provide a vacuum, then the rate of convective-heat transfer is suppressed to a lower value, and hence the upward rate of heat loss is minimized to have a maximum absorber/receiver temperature. In a glazed flat absorber/receiver

surface of an FPC or solar concentrator, it is difficult to have vacuum; also in addition, it is not practical for a greater surface of the absorber/receiver. Due to such a limitation, a vacuum is created inside the co-axial glazed conductive tube absorber/receiver. The co-axial glazed conductive tube absorber/receiver is known as an “evacuated tubular absorber/receiver.”

(b) The rate of radiative-heat transfer

The rate of radiative heat transfer depends on the emissivity (ϵ) of the blackened surface of the absorber/receiver. This can be achieved easily for a smaller surface of absorber/receiver. It is also durable for a longer period compared with an FPC. The previous condition is achieved in an evacuated tubular collector (ETC). There are only the two following differences:

- (i) Only beam radiation is used in a solar concentrator due to application of the optical property.
- (ii) Total radiation is used in an evacuated tubular solar collector (ETSC).

An evacuated tubular solar collector (ETSC) is another device to collect solar energy for thermal application in a temperature range between 100 and 300 °C. In this case, an ETSC can be used for indirect space heating and crop-drying through a heat-exchanger. The ETSC can also be used for the pre-heating of working fluid for lower-capacity power generation.

4.2 Classification of Solar Collectors

The absorber plate is the most essential part of the collector. The liquid or air that flows through the duct or pipe, which is in thermal contact along with the absorber plate, transfers heat to the plate. The solar radiation penetrates through the glazing, and the maximum portion of it is absorbed by the collector plate, with minimum heat loss to the atmosphere, and flows downward through the back of the casing. The collector plate transfers the reserved heat to the fluid or air.

Basically, materials of greater conductance—such as copper, aluminum, and steel—have been used for constructing absorber plates. The surface of the plate is coated to enhance the absorptivity (minimize the emissivity) and ultimately to obtain the required range of temperature. It is important to choose the selective surface for the collector surface for a temperature that is much greater than the ambient-air temperature. Usually the plate is coated black for a domestic water-heating system. The fluid circulating through a network of tubes, which are in good thermal contact with the plate, extracts the absorbed energy of the plate. The collector is maintained at a precise angle (depending on the location) to retrieve the maximum solar radiation. Losses are minimized by insulating the bottom and sides of the collector.

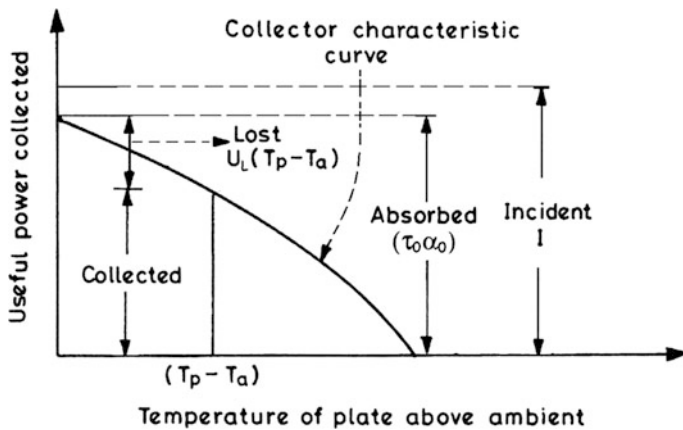


Fig. 4.1 Collector characteristics curve [1]

Under steady-state conditions, the rate of energy absorbed by the plate per unit area should be equal to the sum of the useful energy $\dot{q}_u$ transferred to the fluid and the energy lost ($\dot{q}_L$) by the plate to the surrounding. Thus,

$$\begin{aligned}\dot{q}_{ab} &= (\tau_0 \alpha_0) I(t) \text{ and } \dot{q}_L = U_L (T_p - T_a) \\ \dot{q}_{ab} &= \dot{q}_L + \dot{q}_u\end{aligned}$$

where τ_0 is the transmissivity of the glazing surface; α_0 is the absorptivity; $I(t)$ is the incident solar radiation in the plane of the absorber (W/m^2); T_p and T_a are the plate and ambient temperature ($^\circ\text{C}$), respectively; and U_L is the heat-loss coefficient for the collector ($\text{W/m}^2 \text{ } ^\circ\text{C}$).

As shown in Fig. 4.1, the useful energy increases with a decrease in the temperature difference. The collector performance critically depends on its thermal loss to the surroundings. In general, heat loss depends on the temperature difference between the plate and the ambient such that the useful-energy output is lower for greater losses. Consequently, different varieties of collectors have been designed for different ranges of temperature difference to reduce $\dot{q}_L$ and optimize $\dot{q}_u$ in attempts to decrease $\dot{q}_L$ which further decreases.

On the basis of shape, collectors are generally divided into two categories viz. flat-plate collectors (FPC) and evacuated tubular collectors (ETC), which are discussed in detail in the next sections.

4.3 Photovoltaic Thermal Flat-Plate Collector (PVT-FPC)

The schematic view of the flat-plate collector partially covered with a semi-transparent PV module is presented in Fig. 4.2. A flat-plate collector is designed for operation in low (ambient $60\text{ }^\circ\text{C}$) or medium-temperature ranges

(ambient 100 °C). For a PV area equal to zero, a PVT collector becomes a conventional FPC. The collector absorbs the maximum solar energy (beam and diffuse radiation) and becomes heated, and it later transfers that heat to a stream of liquid or gas. It is generally implanted over the roof top of any structure [1]. The Sun-tracking is not required for it, and it needs little maintenance. A cross-sectional view of a flat-plate collector is shown in Fig. 4.3.

A conventional flat-plate collector (FPC) generally consists of the following components:

- (a) **Glazing:** This is transparent material for the short-wavelength range (0.23–2.6 μm) and opaque for the long-wavelength range (≥ 2.6 μm). The number of transparent materials can be greater than one.
- (b) **Tubes and fins:** The fluid passes through tubes and fins for conducting or directing the heat transfer from the absorber to the flowing fluid.
- (c) **Absorber plate:** This is a blackened conducting flat plate, corrugated or grooved, with tubes or fins for the absorption of short-wavelength solar radiation.
- (d) **Header or manifolds:** There are two headers viz. a lower header that allows the fluid to pass through and an upper header to discharge hot water after heating.
- (e) **Insulation:** This is a non-conducting material at the bottom of the tubes or fins to minimize heat loss.
- (f) **Container or casing:** This covers and protects the various components from dust and moisture, etc.
- (g) **PV module:** A PV module consists of many PV cells wired in parallel to increase current and in series to produce greater voltage. For large power production, 36-cell modules are the industry standard. The module is enclosed in tempered glass (or some other transparent material) on the front surface and has protective and waterproof material on the back surface. The edges are sealed for weatherproofing, and often an aluminum frame holds everything

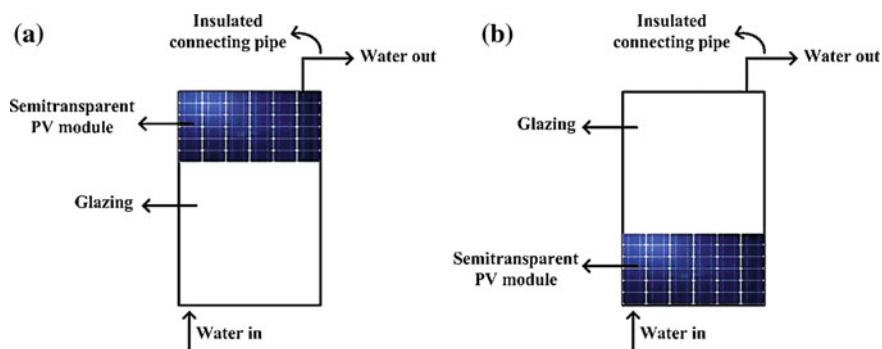
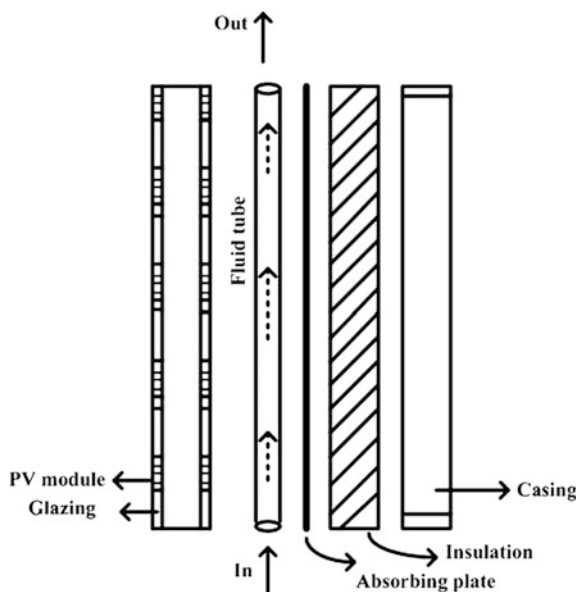


Fig. 4.2 a Upper portion and b lower portion of flat plate collector partially covered with semitransparent PV module

Fig. 4.3 Exposed cross-section through double-glazed flat plate collector



together in a mountable unit. A junction box, or wire leads, is provided at back of the module for electrical connections.

It is important to mention that the area of the glass cover and that of the absorber is equal. Under the scope of this book, we will discuss photovoltaic thermal flat-plate collectors (PVT-FPC) and concentrators (PVT-CPC) in detail.

4.3.1 *Types of PVT Flat-Plate Collectors (PVT-FPC)*

The performance of flat-plate collectors depends on the heat loss by convection. The performance can be improved by incorporating double glazing, but this decreases the solar radiation reaching the absorber plate due to double reflection. Therefore, the use of single glazing gives better efficiency compared with the double glazing for the low-temperature requirement (minimum loss). In contrast, the use of double glazing in the case of higher temperature difference is preferable for enhanced performance.

On the basis of use or consumption, flat-plate collectors are basically divided into two categories (a) water or liquid heaters and (b) air heaters. Sub-division of these collectors is shown below:

Following are the conditions in which different types of flat-plate collectors are used for water-heating purposes:

- (a) **Full pipe-type and fin type:** These collectors are used where both the wetted area and the water capacity are comparatively low: It is used for high-temperature domestic water heating. The fin should be made of highly conducting material, i.e., copper or aluminum.
- (b) **Full water sandwich-type:** These collectors are used where both the wetted area and the water capacity are high: Because the thermal conduction is only across the skin thickness (short distance), materials of low conductivity may be employed; both plastic and steel have been used. This type of collector is commonly used for heating swimming pools with plastic panels.
- (c) **Semi sandwich-type:** These collectors are generally made of material having medium conductivity such as steel.

4.3.2 *Combination of PVT-FPC*

A large array of flat-plate collectors (FPC) can be formed in the following ways:

- (i) **Parallel connection:** A parallel connection is made by connecting the upper and lower headers of each flat-plate collector to increase the water volume to be heated. This combination makes a row, and the whole unit can be referred as “one module.” The mass-flow rate in each FPC is the total mass-flow rate divided by the number of FPC, and the outlet-water temperature is same at the outlet of each FPC. These FPC modules can be operated under different modes of operation, i.e., natural as well as forced mode.
- (ii) **Series connection:** In this case, the outlet of one row of FPCs (the first module) is connected with the inlet to a second row of FPCs (the second module) and so on. The mass-flow rates in such cases are same for all rows. The outlet temperature depends on the number of row of FPCs connected in series. Such series-connected FPC modules can only be operated in forced mode.
- (iii) **Mixed combination of connection:** In this case, the first FPCs are connected in parallel for a given capacity of hot water to make one row (one module), and such modules formed are connected in series to increase the temperature as per requirement. This design is generally referred to as “arrays.” Here, the FPC arrays will only operate in forced mode.

4.3.3 *Optimum Inclination of the Flat-Plate Collector*

Solar radiation varies with (i) inclination of the surface for a given latitude, (ii) orientation, (iii) time of the day, and (iv) day of the year. Hence, there should be an optimum inclination to receive maximum solar radiation. The rule of thumb rule

for Indian climatic conditions was prepared on the basis of a literature survey. Accordingly, an optimum inclination of the surfaces of FPC receiving maximum radiation is given by the following:

$$\beta_{\text{optimum}} = \phi \pm 15^\circ$$

where a positive sign refers to winter conditions, and a negative sign refers to summer conditions.

Because the design of an FPC is made from a water-heating point of view during the winter, the optimum inclination of a collector for the region around Delhi is $28^\circ 35' + 15 = 43^\circ 35' \approx 45^\circ$. The surface should face north in the Southern Hemisphere due to the motion of the Sun. For year round performance, the optimum tilt is 0.9 times the latitude of the location.

4.3.4 Effect of Dust in a Flat-Plate Collector

Dust deposited on the top transparent cover decreases the transmittance of incident solar radiation, which eventually increases scattering losses. It critically affects the performance of the FPC. The deposition of dust basically depends on different factors such as weather conditions of the place, nature of the soil of the place, type of cover, angle of incidence, etc. Therefore, it cannot be generalized due to its dependency on various fluctuating parameters. For the northern region of India, it was reported that transmittance of glass cover is decreased by 8–10% for an inclined surface at 45° .

4.3.5 N-Photovoltaic Thermal Flat-Plate Collector (N-PVT-FPC)

The conventional flat-plate collector requires an external source of electrical energy for forced-mode operation. This requirement of electrical energy can be fulfilled by using grid electricity. However, in a PVT flat-plate water collector, the electrical energy needed for forced-mode operation is supplied from the renewable-energy source such as a PV module of an integrated system [2].

Hence, a photovoltaic thermal (PVT) water-collector system gives electrical as well as thermal energy with enhanced electrical power. Basically, the integration of a semitransparent PV module with a conventional solar water collector in a complete single unit presents PVT technology or a hybrid-PVT concept. In this case, approximately 15–20% of the incident solar radiation is converted into electrical energy by the semi-transparent PV. The rest of the incident solar radiation, approximately >80%, is absorbed by the absorber plate of the collector as well as

the PV module and thus generates thermal energy. The water flowing along the absorber plate in the pipe/duct acts as a thermal-energy carrier such that it extracts or harness the thermal energy generated from the system. The electrical efficiency of the system is decreased due to heating of the PV module. However, thermal-energy extraction by the water/air decreases the temperature, which in turn makes the system highly efficient.

The electrical efficiency (η_{ec}) of a photovoltaic (PV) module as a function of temperature is given by the following:

$$\eta_{ec} = \eta_0[1 - \beta_0(T_c - 298)] \quad (4.3.1)$$

where η_0 is the electrical efficiency of the solar cell under standard test conditions (STC) [solar flux of 1000 W/m^2 and surrounding temperature of 25°C]; β_0 is the silicon-efficiency temperature coefficient (0.0045 or 0.0064 K^{-1}); and T_c is the solar-cell temperature (K).

It is clear that the operating temperature of the PV module determines the electrical efficiency of the photovoltaic (PV) module. It would be improved by decreasing the operating temperature of the PV module. Apart from the increased electrical efficiency of a PV module, additional thermal energy is also available if thermal energy is collected properly by using fluid (water) or air. Such a system is known as a “photovoltaic thermal (PVT) system.”

Under transient conditions, Jones and Underwood analyzed the temperature profiles of a photovoltaic (PV) module. They perceived that the module temperature varies from 27 to 52°C corresponding to an ambient-air temperature of 24.5°C , and it depends on the incident solar radiation. Moreover, they determined that the electrical performance of the PV module intensely depends on (a) the packing factor of the module, (b) the module temperature, and (c) the ohmic losses. Consequently, a greater value of packing factor and a lower value of module temperature enhance the electrical performance of the photovoltaic thermal flat-plate collector (PVT-FPC).

Shyam et al. [2] analytically analyzed the performance of partially covered N-PVT water collectors connected in series for the month January under New Delhi (India) climatic conditions. They studied two different arrangements viz. a PV module coupled at the lower portion (case A) and PV module coupled at the upper portion (case B) of the collectors as discussed later in the text.

Case A: *Semitransparent PV module at inlet portion of a PVT water collector*

In this case, a semitransparent PV module is integrated at the lower portion of a conventional flat-plate collector as shown in Fig. 4.4a. Moreover, Fig. 4.4b, c, respectively, represent the side and front views of the flow pattern in the PVT water collector. The area of the semitransparent PV module is opted for depending on the desired requirement of electrical/thermal energy from the PVT system. The energy balance for different parts of the PVT-FPC is given as follows:

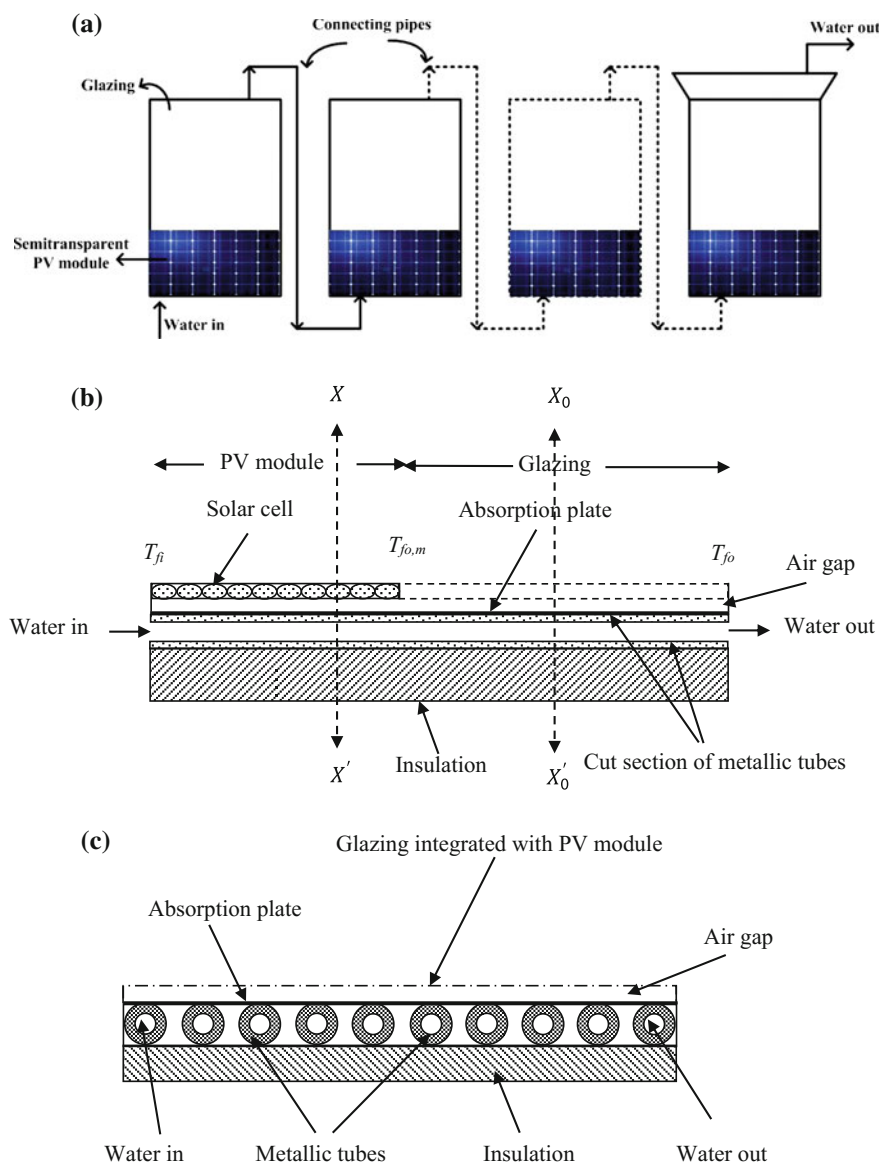


Fig. 4.4 a Series connection of N-Flat plate collectors with partially covered semitransparent photovoltaic module (*lower portion*). b Side view of flow pattern in PVT water collector (module at *lower portion*). c Front view of flow pattern in PVT water collector

The energy-balance equations have been written for quasi steady-state one-dimensional heat conduction and neglecting ohmic losses.

(a) Energy balance for a solar cell of a semitransparent PV module

The energy balance for a small elementary portion (Wdx) of a solar cell can be expressed as follows:

$$\alpha_c \tau_g \beta_c I(t) Wdx = U_{tc,a} (T_c - T_a) Wdx + U_{tc,p} (T_c - T_p) Wdx + \eta_c \tau_g \beta_c I(t) Wdx \quad (4.3.2)$$

where α_c solar-cell absorptivity; τ_g glass transmissivity (PV module); $I(t)$ solar intensity (W/m^2); Wdx elementary section; η_c solar-cell electrical efficiency; β_c packing factor of the solar cell; $U_{tc,a}$ overall heat-transfer coefficient from the solar cell to the ambient through the glass cover ($W/m^2 \text{ } ^\circ C$); $U_{tc,p}$; overall heat-transfer coefficient from the solar cell to the blackened absorber plate through the glass cover and air gap ($W/m^2 \text{ } ^\circ C$); T_c solar-cell temperature ($^\circ C$); T_a ambient temperature ($^\circ C$); T_p blackened absorber-plate temperature ($^\circ C$); and $\eta_m (= \eta_c \tau_g \beta_c)$ is module efficiency.

From the previous equation, the expression of the cell temperature can be obtained as follows:

$$T_c = \frac{(\alpha\tau)_{l,eff} I(t) + U_{tc,a} T_a + U_{tc,p} T_p}{U_{tc,a} + U_{tc,p}} \quad (4.3.3)$$

where $(\alpha\tau)_{l,eff} = (\alpha_c \tau_g \beta - \eta_c \tau_g \beta)$; $U_{tc,a} = \left[\frac{1}{h_0} + \frac{L_g}{K_g} \right]^{-1}$; $U_{tc,p} = \left[\frac{1}{h_i} + \frac{L_g}{K_g} \right]^{-1}$ $h_0 = 5.7 + 3.8V$; $V = 1 \text{ m/s}$; $h_i = 5.7 \text{ W/m}^2 \text{ K}$ h_i is the heat transfer coefficient for space between the glazing and absorption plate ($W/m^2 \text{ } ^\circ C$). h_0 is the heat transfer coefficient from top of PVT water collector to the ambient ($W/m^2 \text{ } ^\circ C$); L_g is the thickness of the glass (mm); and K_g is the thermal conductivity of the glass ($W/m \text{ } ^\circ C$).

(b) Energy balance for a blackened absorber plate below the PV module

$$\begin{aligned} \alpha_p (1 - \beta_c) \tau_g^2 I(t) Wdx + U_{tc,p} (T_c - T_p) Wdx \\ = F' h_{pf} (T_p - T_f) Wdx + U_{tp,a} (T_p - T_a) Wdx \end{aligned} \quad (4.3.4)$$

where α_p is the absorptivity of the blackened plate; F' is the collector-efficiency factor; h_{pf} is the conductive heat-transfer coefficient from the absorber plate to the flowing fluid ($W/m^2 \text{ } ^\circ C$); $U_{tp,a}$ overall heat-transfer coefficient from the absorber plate to the ambient ($W/m^2 \text{ } ^\circ C$); and T_f is the temperature of the fluid ($^\circ C$).

From Eqs. (4.3.3) and (4.3.4), the expression of the plate temperature can be obtained as follows:

$$T_p = \frac{[(\alpha\tau)_{2,\text{eff}} + \text{PF}_1(\alpha\tau)_{1,\text{eff}}]I(t) + U_{L2}T_a + h_{\text{pf}}T_f}{(U_{L2} + h_{\text{pf}})} \quad (4.3.5)$$

where $(\alpha\tau)_{2,\text{eff}} = \alpha_p(1 - \beta)\tau_g^2$; $U_{\text{tp},a} = \left[\frac{1}{U_{\text{tc},a}} + \frac{1}{U_{\text{tc},p}}\right]^{-1} + \left[\frac{L_i}{K_i} + \frac{1}{h_i} + \frac{1}{h_{\text{pf}}}\right]^{-1}$
 $h'_i = 2.8 + 3V'$; $V' = 1 \text{ m/s}$; $U_{L1} = \frac{U_{\text{tc},p}U_{\text{tc},a}}{U_{\text{tc},p} + U_{\text{tc},a}}$; $U_{L2} = U_{L1} + U_{\text{tp},a}$; $\text{PF}_1 = \frac{U_{\text{tc},p}}{U_{\text{tc},p} + U_{\text{tc},a}}$;
 $\text{PF}_1 = \frac{U_{\text{tc},p}}{U_{\text{tc},p} + U_{\text{tc},a}}$.

PF_1 can be referred to as the “first penalty factor” for the absorber plate due to the semi-transparent PV module; U_{L1} is an overall heat-transfer coefficient from the blackened surface to the ambient through the glass of the PV module ($\text{W/m}^2 \text{ }^\circ\text{C}$); and h'_i is the heat-transfer coefficient from the bottom of PVT water collector to the ambient ($\text{W/m}^2 \text{ }^\circ\text{C}$).

(c) Energy balance for water flowing through an absorber pipe below the semitransparent PV module

The flow pattern of water through the riser below the absorber is shown in Fig. 4.6. The energy balance of water flowing through the riser (Fig. 4.4a) is given as

$$\dot{m}_f C_f \frac{dT_f}{dx} dx = F' h_{\text{pf}} (T_p - T_f) W dx \quad (4.3.6)$$

where F' is the collector-efficiency factor calculated by following Duffie and Beckman [1] and Tiwari [3]; $\dot{m}_f$ is the mass flow rate of water (kg/s), C_f is the specific heat of water (J/kg K).

According to Dubey and Tiwari [4], for an N -identical PVT water collector, the outlet-water temperature at the end of the N -th PVT water collector ($T_{\text{fo}N}$) is given by the following:

$$T_{\text{fo}N} = \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^N}{1 - K_k} \right) I(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^N}{1 - K_k} \right) T_a + K_k^N T_{fi} \quad (4.3.7)$$

$$\begin{aligned}
(AF_R(\alpha\tau))_1 &= \left[A_c F_{Rc}(\alpha\tau)_{c,\text{eff}} + PF_2(\alpha\tau)_{m,\text{eff}} A_m F_{Rm} \left(1 - \frac{A_c F_{Rc} U_{L,c}}{\dot{m}_f C_f} \right) \right] \\
(\alpha\tau)_{m,\text{eff}} &= \left[(\alpha\tau)_{2,\text{eff}} + PF_1(\alpha\tau)_{1,\text{eff}} \right]; (\alpha\tau)_{c,\text{eff}} = PF_c \alpha_p \tau_g \\
(AF_R U_L)_1 &= \left[A_c F_{Rc} U_{L,c} + A_m F_{Rm} U_{L,m} \left(1 - \frac{A_c F_{Rc} U_{L,c}}{\dot{m}_f C_f} \right) \right]; K_k = \left(1 - \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right) \\
A_c F_{Rc} &= \frac{\dot{m}_f C_f}{U_{L,c}} \left[1 - \exp \left(\frac{-F' A_c U_{L,c}}{\dot{m}_f C_f} \right) \right]; A_m F_{Rm} = \frac{\dot{m}_f C_f}{U_{L,m}} \left[1 - \exp \left(\frac{-F' A_m U_{L,m}}{\dot{m}_f C_f} \right) \right] \\
U_{L,m} &= \frac{h_{pf} U_{L2}}{F' h_{pf} + U_{L2}}; U_{L,c} = \frac{h_{pf} U_{tp,a}}{F' h_{pf} + U_{tp,a}}; PF_2 = \frac{h_{pf}}{F' h_{pf} + U_{L2}}; PF_c = \frac{h_{pf}}{F' h_{pf} + U_{tp,a}}
\end{aligned}$$

where PF_2 is the second penalty factor due to the absorber below the PV module; PF_c is the penalty factor due to the absorption plate for the portion covered by glazing; $(\alpha\tau)_{m,\text{eff}}$ is the effective absorptivity-transmissivity of the PV module; $U_{L,m}$ is an overall heat-transfer coefficient from the fluid to the ambient through the absorber and the PV module ($\text{W/m}^2 \text{ } ^\circ\text{C}$); $U_{L,c}$ is an overall heat-transfer coefficient from the glazing to the ambient ($\text{W/m}^2 \text{ } ^\circ\text{C}$); $A_m (= WL_m)$ is area of the PV module (m^2); and $A_c (= WL_c)$ is area of the glazing (m^2).

The analytical expression for the temperature-dependent electrical efficiency of solar cells of the N th PVT water collector can be derived using following relation [5]:

$$\eta_{cN} = \eta_0 [1 - \beta_0 (\bar{T}_{cN} - T_0)] \quad (4.3.8)$$

where η_0 is the efficiency under standard test conditions, i.e., at $I(t) = 1000 \text{ W/m}^2$ and $T_0 = 25 \text{ } ^\circ\text{C}$, and $\bar{T}_{cN}$ is the average solar-cell temperature of the N th PVT water collector ($^\circ\text{C}$).

To determine $\bar{T}_{cN}$, one needs the average plate temperature ($\bar{T}_{pN}$) of the N th PVT water collector and the average water temperature ($\bar{T}_{fN}$) of the N th PVT water collector.

The average water temperature below the portion covered by the PV module for N th PVT water collector can be found as follows:

$$\bar{T}_{fN} = \frac{T_{fomN} + T_{foN-1}}{2} \quad (4.3.9)$$

where T_{fomN} and T_{foN-1} are the temperature at the end of the PV module of the N th PVT water collector and the temperature at the end of the $(N-1)$ th PVT water collector, respectively. For N -identical PVT water collectors, the temperature at the end of the portion covered by the PV module of the N th PVT water collector can be found as follows:

$$T_{\text{fom}N} = \left[(AF_R(\alpha\tau))_{m1} + K_m(AF_R(\alpha\tau))_1 \left(\frac{1 - K_k^{N-1}}{1 - K_k} \right) \right] \frac{I(t)}{\dot{m}_f C_f} + \left[(AF_R U_L)_{m1} + K_m(AF_R U_L)_1 \left(\frac{1 - K_k^{N-1}}{1 - K_k} \right) \right] \frac{T_a}{\dot{m}_f C_f} + K_m K_k^{N-1} T_{fi} \quad (4.3.10)$$

where

$$(AF_R(\alpha\tau))_{m1} = PF_2(\alpha\tau)_{m,\text{eff}} A_m F_{Rm}, \quad (AF_R U_L)_{m1} = A_m F_{Rm} U_{L,m}; \quad K_m = \left[1 - \frac{(AF_R U_L)_{m1}}{\dot{m}_f C_f} \right]$$

From Eqs. (4.3.3), (4.3.5), (4.3.7), (4.3.9), and (4.3.10), one can obtain the following:

$$\begin{aligned} \bar{T}_{cN} = & \frac{1}{(U_{\text{ic},a} + U_{\text{ic},p})} \left[\left[(\alpha\tau)_{1,\text{eff}} + \frac{U_{\text{ic},p}}{U_{L2} + F'h_{\text{pf}}} \left\{ (\alpha\tau)_{2,\text{eff}} + PF_1(\alpha\tau)_{1,\text{eff}} \right\} \right. \right. \\ & + \frac{U_{\text{ic},p} F' h_{\text{pf}}}{2\dot{m}_f C_f (U_{L2} + F'h_{\text{pf}})} \left\{ (AF_R(\alpha\tau))_{m1} + (1 + K_m)(AF_R(\alpha\tau))_1 \left(\frac{1 - K_k^{N-1}}{1 - K_k} \right) \right\} \left. \right] I(t) \\ & + \left[U_{\text{ic},a} + \frac{U_{\text{ic},p} U_{L2}}{U_{L2} + F'h_{\text{pf}}} + \frac{U_{\text{ic},p} F' h_{\text{pf}}}{2\dot{m}_f C_f (U_{L2} + F'h_{\text{pf}})} \left\{ (AF_R U_L)_{m1} + (1 + K_m)(AF_R U_L)_1 \left(\frac{1 - K_k^{N-1}}{1 - K_k} \right) \right\} \right] T_a \\ & + \left[\frac{U_{\text{ic},p} F' h_{\text{pf}}}{2(U_{L2} + F'h_{\text{pf}})} ((1 + K_m) K_k^{N-1}) T_{fi} \right] \end{aligned} \quad (4.3.11)$$

From Eqs. (4.3.8) and (4.3.11), one can obtain the following:

$$\eta_{cN} = \frac{\eta_0 \left[1 - \beta_0 \frac{1}{U_{\text{ic},a} + U_{\text{ic},p}} \left[\left[\alpha_c \tau_g \beta + \frac{U_{\text{ic},p}}{U_{L2} + F'h_{\text{pf}}} \left\{ (\alpha\tau)_{2,\text{eff}} + PF_1 \alpha_c \tau_g \beta \right\} + \frac{U_{\text{ic},p} F' h_{\text{pf}}}{2\dot{m}_f C_f (U_{L2} + F'h_{\text{pf}})} \right. \right. \right. \right. \left. \left. \left\{ PF_2(\alpha\tau)_{2,\text{eff}} + PF_2 PF_1 \alpha_c \tau_g \beta \right\} A_m F_{Rm} + (1 + K_m) \right. \right. \right. \left. \left. \left\{ A_c F_{Rc}(\alpha\tau)_{c,\text{eff}} + \left\{ PF_2(\alpha\tau)_{2,\text{eff}} + PF_2 PF_1 \alpha_c \tau_g \beta \right\} A_m F_{Rm} \left(1 - \frac{A_c F_{Rc} U_{L,c}}{\dot{m}_f C_f} \right) \right\} \left(\frac{1 - K_k^{N-1}}{1 - K_k} \right) \right\} \right] I(t) \right. \right. \left. \left. + \left[U_{\text{ic},a} + \frac{U_{\text{ic},p} U_{L2}}{U_{L2} + F'h_{\text{pf}}} + \frac{U_{\text{ic},p} F' h_{\text{pf}}}{2\dot{m}_f C_f (U_{L2} + F'h_{\text{pf}})} \left\{ (AF_R U_L)_{m1} + (1 + K_m)(AF_R U_L)_1 \left(\frac{1 - K_k^{N-1}}{1 - K_k} \right) \right\} \right] T_a \right. \right. \left. \left. + \left[\frac{U_{\text{ic},p} F' h_{\text{pf}} (1 + K_m)}{2(U_{L2} + F'h_{\text{pf}})} K_k^{N-1} \right] T_{fi} \right] \right] - T_0 \right] \left[1 - \frac{\eta_0 \beta_0 I(t)}{(U_{\text{ic},a} + U_{\text{ic},p})} \left[\tau_g \beta + \frac{U_{\text{ic},p}}{U_{L2} + F'h_{\text{pf}}} PF_1 \tau_g \beta + \frac{U_{\text{ic},p} F' h_{\text{pf}}}{2\dot{m}_f C_f (U_{L2} + F'h_{\text{pf}})} PF_2 PF_1 \tau_g \beta A_m F_{Rm} \left\{ 1 + (1 + K_m) \left(1 - \frac{A_c F_{Rc} U_{L,c}}{\dot{m}_f C_f} \right) \left(\frac{1 - K_k^{N-1}}{1 - K_k} \right) \right\} \right] \right] \right] \quad (4.3.12)$$

Finally, the temperature-dependent electrical efficiency of a PV module of the N th PVT water collector is obtained as follows:

$$\eta_{mN} = \tau_g \beta \eta_{cN} \quad (4.3.13)$$

The rate of useful electrical-energy gain from N -identical PVT water collectors is calculated by the following formula:

$$\dot{Q}_{uel,N} = A_m I(t) \sum_1^N \eta_{mN} \quad (4.3.14)$$

According to Mishra and Tiwari [6], the power required to pump the fluid is 0.8 W for a head of 1.2 m and a 75% pump efficiency. The electrical output from the PVT collectors is on the order of kWh; hence, the pumping power was neglected in the present study. The rate of useful thermal-energy gain from N -identical PVT water collectors is computed using the following relation:

$$\dot{Q}_{uth,N} = \dot{m}_f C_f (T_{foN} - T_{fi}) \quad (4.3.15)$$

On substituting the value of T_{foN} from Eq. (4.3.7) into Eq. (4.3.15), one can obtain the following:

$$\dot{Q}_{uth,N} = N(A_c + A_m) \left[(\alpha\tau)_{\text{eff},N} I(t) - U_{L,N} (T_{fi} - T_a) \right] \quad (4.3.16)$$

where

- $A_m = WL_m$ Area of the module (m^2);
- $A_c = WL_c$ Area of the glazing (m^2)
- W Width of PVT water collector (m)
- L_m Length of PVT water collector covered by module (m)
- L_c Length of PVT water collector covered by glazing (m).

The instantaneous thermal efficiency of the N th PVT water collector is given as follows:

$$\eta_{\text{ith},N} = \frac{\dot{Q}_{uth,N}}{N(A_c + A_m)I(t)} = \left[(\alpha\tau)_{\text{eff},N} - U_{L,N} \frac{(T_{fi} - T_a)}{I(t)} \right] \quad (4.3.17)$$

where $(\alpha\tau)_{\text{eff},N} = \frac{(AF_R(\alpha\tau))_1}{(A_c + A_m)} \left[\frac{1 - (1 - K_{k,A})^N}{NK_{k,A}} \right]$; $U_{L,N} = \frac{(AF_R U_L)_1}{(A_c + A_m)} \left[\frac{1 - (1 - K_{k,A})^N}{NK_{k,A}} \right]$; $K_{k,A} = \left[\frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right]$

Case B: *Semitransparent PV module at the outlet portion of a PVT water collector*

The upper portion of a conventional flat-plate collector partially covered with a semitransparent PV module is depicted in Fig. 4.5a. The flow pattern in a PVT water collector (side view) is also shown in Fig. 4.5b.

In this case, the glazing is at the inlet of the PVT water collector, and the PV module is at the far end from the inlet of PVT water collector. The temperature at the end of the portion covered with glazing can be given as follows [1, 3]:

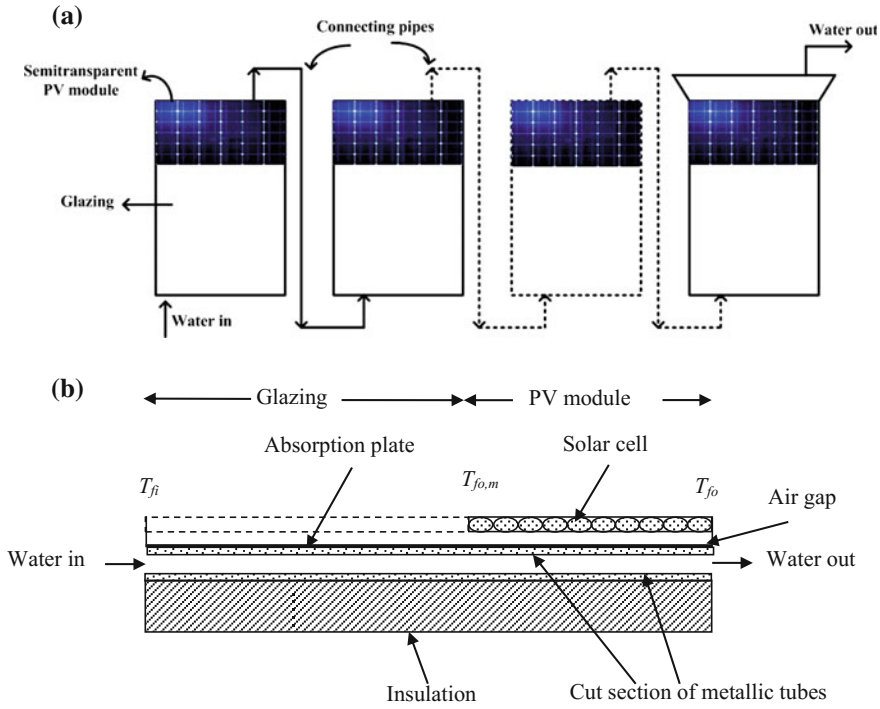


Fig. 4.5 **a** Series connection of N-Flat plate collectors partially covered with semitransparent photovoltaic module (*upper portion*). **b** Side view of flow pattern in PVT water collector (module at *upper portion*)

$$T_{fo1} = \left[\frac{(\alpha\tau)_{c,eff} I(t)}{U_{L,c}} + T_a \right] \left[1 - \exp\left(\frac{-F' A_c U_{L,c}}{\dot{m}_f C_f} \right) \right] + T_{fi} \exp\left(\frac{F' A_c U_{L,c}}{\dot{m}_f C_f} \right) \quad (4.3.18)$$

Again, using Eqs. (4.3.2), (4.3.3), and (4.3.6) with the boundary conditions at $x = 0$, $T_f = T_{fo1}$ and at $x = L_m$, $T_f = T_{fo1}$ —and following the same procedure as in case A—the outlet temperature at the end of the N th PVT water collector can be found as follows:

$$T_{foN} = \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^N}{1 - K_k} \right) I(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^N}{1 - K_k} \right) T_a + K_k^N T_{fi} \quad (4.3.19)$$

where $(AF_R(\alpha\tau))_1 = \left[A_m F_{Rm} PF_2(\alpha\tau)_{m,eff} + (\alpha\tau)_{c,eff} A_c F_{Rc} \left(1 - \frac{A_m F_{Rm} U_{L,m}}{\dot{m}_f C_f} \right) \right]$ and $(AF_R U_L)_1 = \left[A_m F_{Rm} U_{L,m} + A_c F_{Rc} U_{L,c} \left(1 - \frac{A_m F_{Rm} U_{L,m}}{\dot{m}_f C_f} \right) \right]$; $K_k = \left(1 - \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right)$

One can obtain the temperature at the end of the portion covered by glazing in the N th PVT water collector for N -identical PVT water collectors as follows:

$$T_{\text{foc}N} = \left[(AF_R(\alpha\tau))_{c1} + K_c(AF_R(\alpha\tau))_1 \left(\frac{1 - K_k^{N-1}}{1 - K_k} \right) \right] \frac{I(t)}{\dot{m}_f C_f} + \left[(AF_R U_L)_{c1} + K_c(AF_R U_L)_1 \left(\frac{1 - K_k^{N-1}}{1 - K_k} \right) \right] \frac{T_a}{\dot{m}_f C_f} + K_c K_k^{N-1} T_{fi} \quad (4.3.20)$$

where $(AF_R(\alpha\tau))_{c1} = (\alpha\tau)_{c,\text{eff}} A_c F_{Rc}$, $(AF_R U_L)_{c1} = A_c F_{Rc} U_{L,c}$ and $K_c = \left[1 - \frac{(AF_R U_L)_{c1}}{\dot{m}_f C_f} \right]$.

The average water temperature below the portion covered by the PV module for the N th PVT water collector in this case is determined using following relation:

$$\bar{T}_{fN} = \frac{T_{\text{foc}N} + T_{\text{fo}N}}{2} \quad (4.3.21)$$

where $T_{\text{foc}N}$ and $T_{\text{fo}N}$, respectively, are the temperature at the end of glazing and the end of N th PVT water collector.

From Eqs. (4.3.3), (4.3.5), (4.3.19), (4.3.20), and (4.3.21), one can obtain the following:

$$\begin{aligned} \bar{T}_{cN} = & \frac{1}{(U_{\text{tc},a} + U_{\text{tc},p})} \left[\left[(\alpha\tau)_{1,\text{eff}} + \frac{U_{\text{tc},p}}{U_{L2} + F'h_{\text{pf}}} \left\{ (\alpha\tau)_{2,\text{eff}} + \text{PF}_1 (\alpha\tau)_{1,\text{eff}} \right\} \right. \right. \\ & + \frac{U_{\text{tc},p} F' h_{\text{pf}}}{2\dot{m}_f C_f (U_{L2} + F'h_{\text{pf}})} \left\{ (AF_R(\alpha\tau))_{c1} \right. \\ & + (AF_R(\alpha\tau))_1 \left(\frac{K_c(1 - K_k^{N-1}) + (1 - K_k^N)}{1 - K_k} \right) \left. \right\} \left. \right] I(t) \\ & + \left[U_{\text{tc},a} + \frac{U_{\text{tc},p} U_{L2}}{U_{L2} + F'h_{\text{pf}}} + \frac{U_{\text{tc},p} F' h_{\text{pf}}}{2\dot{m}_f C_f (U_{L2} + F'h_{\text{pf}})} \right. \\ & \times \left\{ (AF_R U_L)_{c1} + (AF_R U_L)_1 \left(\frac{K_c(1 - K_k^{N-1}) + (1 - K_k^N)}{1 - K_k} \right) \right\} \left. \right] T_a \\ & + \left[\frac{U_{\text{tc},p} F' h_{\text{pf}}}{2(U_{L2} + F'h_{\text{pf}})} (K_c + K_k) K_k^{N-1} \right] T_{fi} \end{aligned} \quad (4.3.22)$$

From Eqs. (4.3.8) and (4.3.22), one can obtain the temperature-dependent electrical efficiency of the solar cells of the N th PVT water collector as follows:

$$\begin{aligned}
& \eta_{cN} \\
&= \frac{\eta_0 \left[1 - \beta_0 \left[\frac{1}{U_{w,a} + U_{w,p}} \left[\left\{ \alpha_c \tau_g \beta + \frac{U_{w,p}}{U_{12} + F' h_{pf}} \left\{ (\alpha \tau)_{2,eff} + PF_1 \alpha_c \tau_g \beta \right\} + \frac{U_{w,p} F' h_{pf}}{2 m_i C_i (U_{12} + F' h_{pf})} \right\} \right. \right. \right. \\
& \quad \left. \left. \left. \left\{ (AF_R (\alpha \tau))_{c1} + \left\{ PF_2 (\alpha \tau)_{2,eff} + PF_2 PF_1 \alpha_c \tau_g \beta \right\} A_m F_{Rm} \right\} \left(\frac{K_c (1 - K_k^{N-1}) + (1 - K_k^N)}{1 - K_k} \right) \right\} I(t) \right. \right. \right. \\
& \quad \left. \left. \left. + \left[U_{w,a} + \frac{U_{w,p} U_{12}}{U_{12} + F' h_{pf}} + \frac{U_{w,p} F' h_{pf}}{2 m_i C_i (U_{12} + F' h_{pf})} \left\{ (AF_R U_L)_{c1} + (AF_R U_L)_1 \left(\frac{K_c (1 - K_k^{N-1}) + (1 - K_k^N)}{1 - K_k} \right) \right\} \right] T_a \right. \right. \right. \\
& \quad \left. \left. \left. + \left[\frac{U_{w,p} F' h_{pf} (K_c + K_k)}{2 (U_{12} + F' h_{pf})} K_k^{N-1} \right] T_{fi} \right\} \right] - T_0 \right]}{\left[1 - \frac{\eta_0 \beta_0 I(t)}{(U_{w,a} + U_{w,p})} \left[\tau_g \beta + \frac{U_{w,p}}{U_{12} + F' h_{pf}} PF_1 \tau_g \beta + \frac{U_{w,p} F' h_{pf}}{2 m_i C_i (U_{12} + F' h_{pf})} PF_2 PF_1 \tau_g \beta A_m F_{Rm} \left(\frac{K_c (1 - K_k^{N-1}) + (1 - K_k^N)}{1 - K_k} \right) \right] \right]} \quad (4.3.23)
\end{aligned}$$

The temperature-dependent electrical efficiency of a PV module of the N th PVT water collector can be obtained using Eq. (4.3.13) on substituting the value of η_{cN} from Eq. (4.3.23) for case B.

The rate of useful electrical-energy gain is computed by Eq. (4.3.14) using the value of η_{mN} for case B. The rate of useful thermal-energy gain and instantaneous thermal efficiency of the N th PVT water collector are evaluated using Eqs. (4.3.16) and (4.3.17), respectively; for this, the value of T_{foN} is taken for case B from Eq. (4.3.19).

The hourly variation of solar-cell temperature for the two cases is shown in Fig. 4.6. The solar-cell temperature is greater for the arrangement in which a semitransparent PV module is integrated on the upper portion of a flat-plate collector. This occurs due to pre-heating of the water from the lower portion. This decreases the temperature difference between the water and the solar-cell temperature resulting less heat transfer from the module to the water. Basically, solar-cell electrical efficiency is decreased due to high solar-cell temperature (Fig. 4.7).

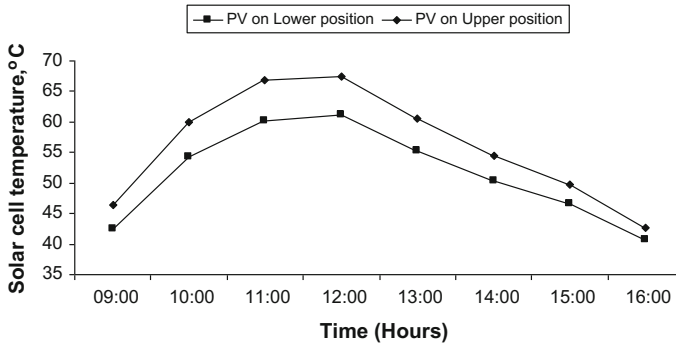


Fig. 4.6 Hourly variation of solar cell temperature for both cases [6]

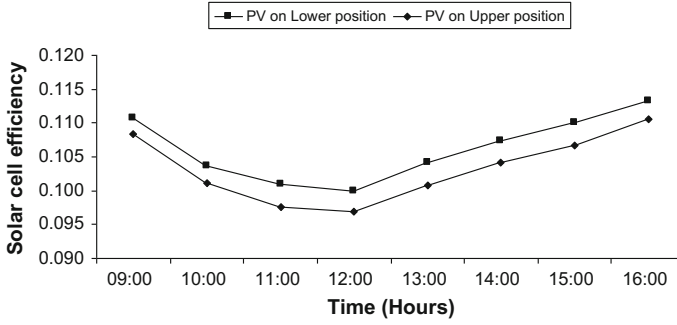


Fig. 4.7 Hourly variation of solar cell efficiency and solar cell temperature for both cases [6]

Limiting cases

Case 1 = All of the PVT water collectors connected in series are fully covered by a PV module ($A_c = 0$). **Case 2** = All of the water collectors connected in series are fully covered by glazing only ($A_m = 0$). The thermal and electrical efficiencies for the limiting cases are obtained by putting $A_c = 0$ (case 1) or $A_m = 0$ (case 2).

Case 1: PVT water collector fully covered by a PV module ($A_c = 0$)

This limiting case is equivalent to N-PVT collectors connected in series and fully covered by a semitransparent PV module. The expressions for the temperature-dependent electrical efficiency and instantaneous thermal efficiency in this limiting case is given as follows:

$$\eta_{CN} = \frac{\left[1 - \beta_0 \left[\frac{1}{U_{ic,a} + U_{ic,p}} + \left[U_{ic,a} + \frac{U_{ic,p}U_{l2}}{U_{l2} + F'h_{pt}} + \frac{U_{ic,p}F'h_{pt}}{2\dot{m}_i C_i (U_{l2} + F'h_{pt})} \left\{ A_m F_{Rm} U_{L,m} \left[1 + (1 + K_m) \left(\frac{1 - K_m^{N-1}}{1 - K_m} \right) \right] \right\} T_a + \left[\frac{U_{ic,p}F'h_{pt}(1 + K_m)}{2(U_{l2} + F'h_{pt})} K_m^{N-1} \right] T_{fi} \right] \right] I(t) \right] - T_0 \right]}{\left[1 - \frac{\eta_0 \beta_0 I(t)}{(U_{ic,a} + U_{ic,p})} \left[\tau_g \beta + \frac{U_{ic,p}}{U_{l2} + F'h_{pt}} PF_1 \tau_g \beta + \frac{U_{ic,p}F'h_{pt}}{2\dot{m}_i C_i (U_{l2} + F'h_{pt})} PF_2 PF_1 \tau_g \beta A_m F_{Rm} \left[1 + (1 + K_m) \left(\frac{1 - K_m^{N-1}}{1 - K_m} \right) \right] \right] \right]} \quad (4.3.24)$$

and

$$\eta_{ith,N} = \frac{\dot{Q}_{uth,N}}{NA_m I(t)} = \left[(\alpha\tau)_{eff,N} - U_{L,N} \frac{(T_{fi} - T_a)}{I(t)} \right] \quad (4.3.25)$$

$$\text{where } (\alpha\tau)_{eff,N} = \frac{PF_2 (\alpha\tau)_{m,eff} F_{Rm}}{N} \left[\frac{1 - (1 - K_{k,A})^N}{K_{k,A}} \right]; U_{L,N} = \frac{F_{Rm} U_{L,m}}{N} \left[\frac{1 - (1 - K_{k,A})^N}{K_{k,A}} \right], K_m = K_{k,A}$$

**Case 2: PVT water collector fully covered by glazing ($A_m = 0$):
Conventional FPC**

This limiting case is similar to that of the conventional flat-plate collector. The expression for instantaneous thermal efficiency is given as follows:

$$\eta_{\text{ith},N} = \frac{\dot{Q}_{\text{uth},N}}{NA_c I(t)} = \left[(\alpha\tau)_{\text{eff},N} - U_{L,N} \frac{(T_{fi} - T_a)}{I(t)} \right] \quad (4.3.26)$$

where

$$\begin{aligned} (\alpha\tau)_{\text{eff},N} &= \frac{F_{Rc}(\alpha\tau)_{c,\text{eff}}}{N} \left[\frac{1 - (1 - K_{k,A})^N}{K_{k,A}} \right]; U_{L,N} \\ &= \frac{F_{Rc}U_{L,c}}{N} \left[\frac{1 - (1 - K_{k,A})^N}{K_{k,A}} \right]; K_{k,A} = \left[\frac{A_c F_{Rc} U_{Lc}}{\dot{m}_f C_f} \right] \end{aligned}$$

Shyam et al. [2] found that the temperature-dependent electrical efficiencies were 10.8% (maximum) and 10.6% (minimum), respectively, for case A, whereas they were 10.4% (maximum) and 10.2% (minimum), respectively, for case B. Consequently, these values clearly specify that case A gives improved performance compared with case B on the basis of electrical energy.

They concluded that the electrical efficiency of series-connected N-PVT water collectors in case (A) is found greater than that in case (B) for a given mass-flow rate and number of PVT collectors. The hourly variation of temperature-dependent electrical efficiency for different numbers of collectors connected in series (mass-flow rate of water was kept constant, i.e., $\dot{m} = 0.04$ kg/s) is presented in Fig. 4.8. With increasing number of collectors, the solar-cell temperature increases and hence the solar-cell electrical efficiency decreases.

Figure 4.9a, b represent the variation of maximum solar-cell temperatures $\bar{T}_{cN,\text{max}}$ and temperature-dependent electrical efficiencies with number of collectors

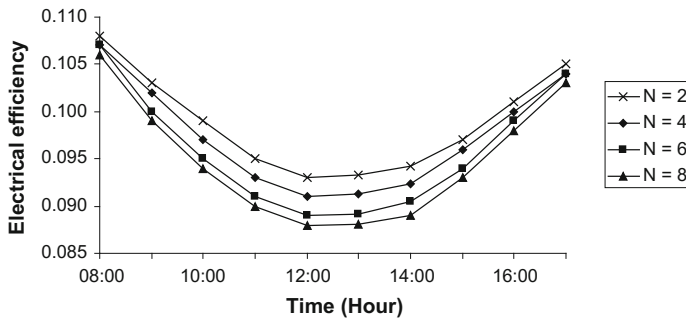


Fig. 4.8 Hourly variation of temperature dependent electrical efficiency by varying the number of collectors at constant flow rate ($\dot{m} = 0.04$ kg/s) [6]

for both cases (upper and lower portion covered partially) at mass-flow rates 0.01 and 0.08 kg/s, respectively. It can be inferred from the figures that $\bar{T}_{cN,\max}$ increases with an increase in the number of collectors for both cases. The temperature-dependent electrical efficiency decreases, as expected, due to the hindrance effect at higher temperature. It was perceived that $\bar{T}_{cN,\max}$ is greater for case B (upper portion covered), which is credited to the fact that the PV module is at the outlet of the PVT water collector, which also receives thermal energy from the hot water below the absorber plate in addition to the energy absorbed from solar radiation.

The hourly variation of outlet-water temperature for both cases A and B (lower and upper portion with a PV) at 0.04 kg/s mass-flow rate and five series-connected PVT water collectors is shown in Fig. 4.10. The solar intensity and ambient

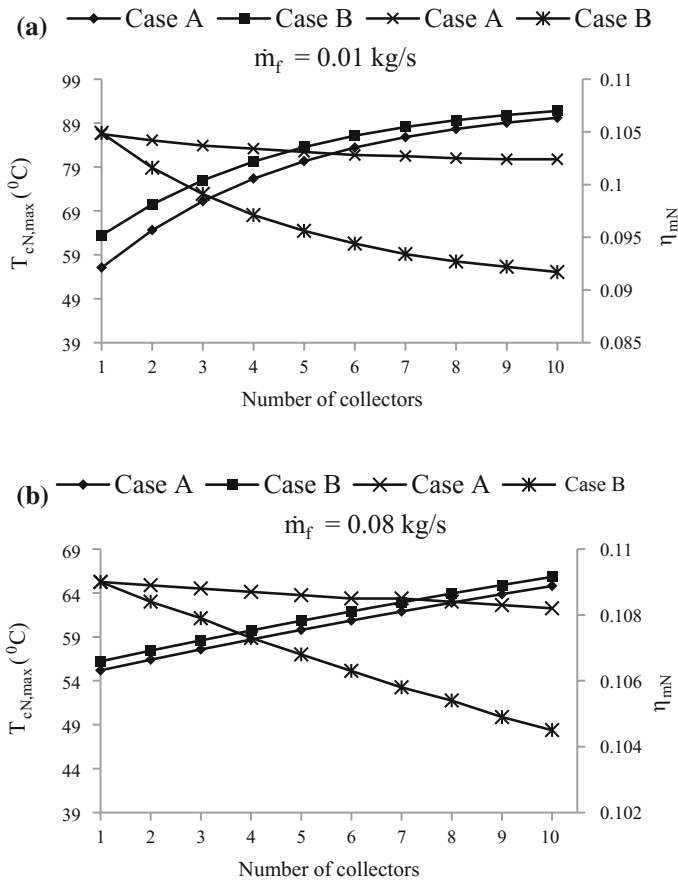


Fig. 4.9 Variation of solar cell temperature and temperature dependent electrical efficiency of N th PVT water collectors with number of collectors connected in series at mass flow rate **a** 0.01 kg/s and **b** 0.08 kg/s [2]

temperature enhance the outlet-water temperature up until the afternoon hours, and then the outlet water temperature starts decreasing after approximately 2 pm. As explained previously, the outlet-water temperature in case B has a lower value than that of case A.

Furthermore, Fig. 4.11 shows the hourly variation of solar-cell temperature and temperature-dependent electrical efficiency for mass-flow rate 0.04 kg/s and five series-connected PVT water collectors. The solar-cell temperature was found to be greater in case B compared with case A, which implies that the temperature-dependent electrical efficiency is greater for case A as expected. The maximum outlet-water temperature $T_{foN,max}$ was observed to be 62.0 and 61.1 °C for cases A and case B, respectively, for the same configuration (mass-flow rate of 0.04 kg/s and $N = 10$ series-connected PVT water collectors). In contrast, the solar-cell temperature $\bar{T}_{cN,max}$ was found to be 72.1 and 73.7 °C, respectively, for cases A and B. The temperature difference between the outlet and the solar-cell temperature for cases A and B decreases on further increasing the number of collectors. In the case of closed loop, there is not much difference regarding thermal and electrical performance with the PV module located either at the top or the bottom of the collector.

Example 4.1 Calculate the outlet-water temperature and rate of useful thermal energy of three photovoltaic thermal collectors (PVT-FPC) connected in series (case A) for a mass-flow rate ($\dot{m}_f$) of 0.01 kg/s. Use the following design and climatic parameters:

$$\begin{aligned} A_c &= 1.395 \text{ m}^2, A_m = 0.605 \text{ m}^2, C_f = 4179 \text{ J/Kg K}, T_a = 25 \text{ }^\circ\text{C}, \\ T_w &= 28 \text{ }^\circ\text{C}, I(t) = 500 \text{ W/m}^2, \tau_g = 0.95, \alpha_c = 0.9, \alpha_p = 0.80, \\ \beta &= 0.89, \eta_c = 0.15, h_{pf} = 100 \text{ W/m}^2, L_g = 0.003 \text{ m}, \\ K_g &= 0.816 \text{ W/m K}, L_i = 0.1 \text{ m}, K_i = 0.166 \text{ W/m K}, \end{aligned}$$

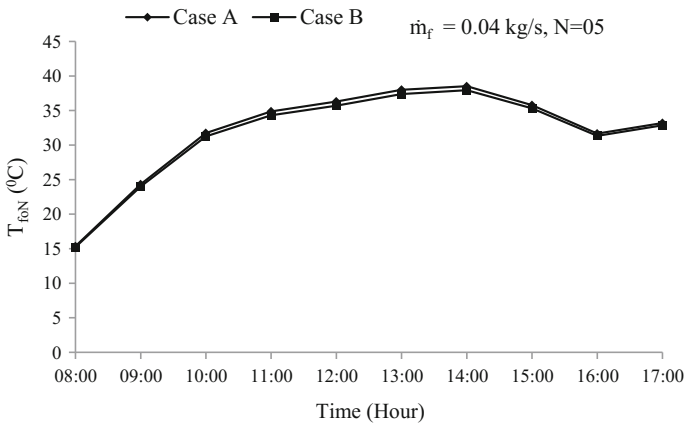


Fig. 4.10 Hourly variation of outlet water temperature at mass flow rate 0.04 kg/s for five PVT water collectors connected in series [2]

$L_p = 0.002 \text{ m}$, $K_p = 64 \text{ W/m K}$, $h'_i = 5.8 \text{ W/m}^2 \text{ K}$, $h_i = 5.7 \text{ W/m}^2 \text{ K}$,
 $F' = 0.968$, $h_0 = 9.5 \text{ W/m}^2$, $F' = 0.968$, Inclination = 30°

Solution

(a) From Eq. (4.3.7),

$$T_{foN} = \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^N}{1 - K_k} \right) I_c(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^N}{1 - K_k} \right) T_a + K_k^N T_{fi} \quad (i)$$

where

$$\begin{aligned} (AF_R(\alpha\tau))_1 &= \left[A_c F_{Rc}(\alpha\tau)_{c,\text{eff}} + \text{PF}_2(\alpha\tau)_{m,\text{eff}} A_m F_{Rm} \left(1 - \frac{A_c F_{Rc} U_{L,c}}{\dot{m}_f C_f} \right) \right] \\ U_{tc,a} &= \left[\frac{1}{h_0} + \frac{L_g}{K_g} \right]^{-1} = 9.20 \text{ W/m}^2 \text{ K}, U_{tc,p} = \left[\frac{1}{h_i} + \frac{L_g}{K_g} \right]^{-1} = 5.58 \text{ W/m}^2 \text{ K}, \\ U_{tp,a} &= \left[\frac{1}{U_{tc,a}} + \frac{1}{U_{tc,p}} \right]^{-1} + \left[\frac{L_i}{K_i} + \frac{1}{h'_i} + \frac{1}{h_{pf}} \right]^{-1} = 4.74 \text{ W/m}^2 \text{ K}, \\ U_{L,c} &= \frac{h_{pf} U_{tp,a}}{F' h_{pf} + U_{tp,a}} = 4.52 \text{ W/m}^2 \text{ K} \\ A_c F_{Rc} &= \frac{\dot{m}_f C_f}{U_{L,c}} \left[1 - \exp \left(\frac{-F' A_c U_{L,c}}{\dot{m}_f C_f} \right) \right] = 9.26 [1 - \exp(-0.146)] = 1.29 \\ \text{PF}_c &= \frac{h_{pf}}{F' h_{pf} + U_{tp,a}} = 0.955, (\alpha\tau)_{c,\text{eff}} = \text{PF}_c \alpha_p \tau_g = (0.955) \times 0.80 \times 0.95 = 0.722 \\ U_{L1} &= \frac{U_{tc,p} U_{tc,a}}{U_{tc,p} + U_{tc,a}} = 3.47 \text{ W/m}^2 \text{ K}, U_{L2} = U_{L1} + U_{tp,a} = 8.21 \text{ W/m}^2 \text{ K} \\ \text{PF}_2 &= \frac{h_{pf}}{F' h_{pf} + U_{L2}} = 0.927 \\ (\alpha\tau)_{2,\text{eff}} &= \alpha_p (1 - \beta) \tau_g^2 = 0.079, \text{PF}_1 = \frac{U_{tc,p}}{U_{tc,p} + U_{tc,a}} = 0.378 \\ (\alpha\tau)_{1,\text{eff}} &= (\alpha_c \tau_g \beta - \eta_c \tau_g \beta) = 0.634 \\ (\alpha\tau)_{m,\text{eff}} &= [(\alpha\tau)_{2,\text{eff}} + \text{PF}_1 (\alpha\tau)_{1,\text{eff}}] = 0.3186 \\ U_{L,m} &= \frac{h_{pf} U_{L2}}{F' h_{pf} + U_{L2}} = 7.58 \text{ W/m}^2 \text{ K} \\ A_m F_{Rm} &= \frac{\dot{m}_f C_f}{U_{L,m}} \left[1 - \exp \left(\frac{-F' A_m U_{L,m}}{\dot{m}_f C_f} \right) \right] = (5.51)(1 - \exp(-0.11)) = 0.523 \end{aligned} \quad (ii)$$

On substituting terms $A_c F_{Rc}(\alpha\tau)_{c,\text{eff}}$, $\text{PF}_2(\alpha\tau)_{m,\text{eff}}$ and $A_m F_R$ in (ii), one can obtain the following:

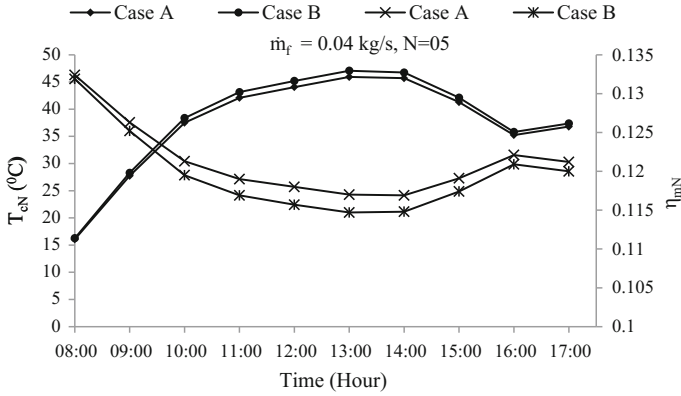


Fig. 4.11 Hourly variation of solar cell temperature and temperature dependent electrical efficiency at mass flow rate 0.04 kg/s for five PVT water collectors connected in series [2]

$$\begin{aligned}
 (AF_R(\alpha\tau))_1 &= (0.931 + 0.132) = 1.063 \\
 (AF_R U_L)_1 &= \left[(A_c F_{Rc}) U_{L,c} + (A_m F_{Rm}) U_{L,m} \left(1 - \frac{(A_c F_{Rc}) U_{L,c}}{\dot{m}_f C_f} \right) \right] \\
 &= 5.83 + 3.96 \times (0.86) = 9.23 \\
 K_k &= \left(1 - \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right) = 0.780
 \end{aligned}$$

Hence, from Eq. (i), for three identical PVT water collectors the outlet-water temperature at the end of the third PVT water collector is as follows:

$$\begin{aligned}
 T_{fo3} &= \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^3}{1 - K_k} \right) I_c(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^3}{1 - K_k} \right) T_a + K_k^3 T_{fi} \\
 &= 29.76 + 13.14 + 13.32 \\
 T_{fo3} &= 56.2^\circ \text{C}
 \end{aligned}$$

(b) From Eq. (4.3.16), the rate of useful thermal energy is expressed as follows:

$$\begin{aligned}
 \dot{Q}_{\text{uth},N} &= N(A_c + A_m) \left[(\alpha\tau)_{\text{eff},N} I_c(t) - U_{L,N} (T_{fi} - T_a) \right] \\
 K_{k,A} &= \left[\frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right] = 0.22, \quad (\alpha\tau)_{\text{eff},3} = \frac{(AF_R(\alpha\tau))_1}{(A_c + A_m)} \left[\frac{1 - (1 - K_{k,A})^3}{N K_{k,A}} \right] \\
 &= 0.531 \times 0.797 = 0.423 \\
 U_{L,3} &= \frac{(AF_R U_L)_1}{(A_c + A_m)} \left[\frac{1 - (1 - K_{k,A})^3}{N K_{k,A}} \right] = 4.6 \times 0.797 = 3.67
 \end{aligned} \tag{iii}$$

Therefore, from Eq. (iii), the rate of useful thermal energy is as follows:

$$\dot{Q}_{uth,3} = 3(A_c + A_m) \left[(\alpha\tau)_{\text{eff},3} I_c(t) - U_{L,3}(T_{fi} - T_a) \right] = 6[211.5 - 3.65 \times (28 - 25)]$$

$$\dot{Q}_{uth,3} = 1.203 \text{ kWh}$$

Example 4.2 Calculate the outlet-water temperature and the rate of useful thermal energy of three photovoltaic thermal flat-plate collectors (PVT-FPC) connected in series (case A) for a mass-flow rate ($\dot{m}_f$) of 0.1 kg/s. Use the design and climatic parameters given in Example 4.1.

Solution

$$T_{foN} = \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^N}{1 - K_k} \right) I_c(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^N}{1 - K_k} \right) T_a + K_k^N T_{fi} \quad (\text{i})$$

$$(AF_R(\alpha\tau))_1 = \left[A_c F_{Rc} (\alpha\tau)_{c,\text{eff}} + PF_2 (\alpha\tau)_{m,\text{eff}} A_m F_{Rm} \left(1 - \frac{A_c F_{Rc} U_{L,c}}{\dot{m}_f C_f} \right) \right]$$

$$U_{tc,a} = \left[\frac{1}{h_0} + \frac{L_g}{K_g} \right]^{-1} = 9.20 \text{ W/m}^2 \text{ K}, U_{tc,p} = \left[\frac{1}{h_i} + \frac{L_g}{K_g} \right]^{-1} = 5.58 \text{ W/m}^2 \text{ K},$$

$$U_{tp,a} = \left[\frac{1}{U_{tc,a}} + \frac{1}{U_{tc,p}} \right]^{-1} + \left[\frac{L_i}{K_i} + \frac{1}{h_i} + \frac{1}{h_{pf}} \right]^{-1} = 4.74 \text{ W/m}^2 \text{ K}, U_{L,c}$$

$$= \frac{h_{pf} U_{tp,a}}{F' h_{pf} + U_{tp,a}} = 4.52 \text{ W/m}^2 \text{ K}$$

$$A_c F_{Rc} = \frac{\dot{m}_f C_f}{U_{L,c}} \left[1 - \exp \left(\frac{-F' A_c U_{L,c}}{\dot{m}_f C_f} \right) \right] = 92.5 [1 - \exp(-0.0146)] = 1.34$$

$$PF_c = \frac{h_{pf}}{F' h_{pf} + U_{tp,a}} = 0.955, (\alpha\tau)_{c,\text{eff}} = PF_c \alpha_p \tau_g = (0.955) \times 0.80 \times 0.95 = 0.722$$

$$U_{L1} = \frac{U_{tc,p} U_{tc,a}}{U_{tc,p} + U_{tc,a}} = 3.47 \text{ W/m}^2 \text{ K}, U_{L2} = U_{L1} + U_{tp,a} = 8.21 \text{ W/m}^2 \text{ K}$$

$$PF_2 = \frac{h_{pf}}{F' h_{pf} + U_{L2}} = 0.927$$

$$(\alpha\tau)_{2,\text{eff}} = \alpha_p (1 - \beta) \tau_g^2 = 0.079, PF_1 = \frac{U_{tc,p}}{U_{tc,p} + U_{tc,a}} = 0.378$$

$$(\alpha\tau)_{1,\text{eff}} = (\alpha_c \tau_g \beta - \eta_c \tau_g \beta) = 0.634$$

$$(\alpha\tau)_{m,\text{eff}} = \left[(\alpha\tau)_{2,\text{eff}} + PF_1 (\alpha\tau)_{1,\text{eff}} \right] = 0.318$$

$$U_{L,m} = \frac{h_{pf} U_{L2}}{F' h_{pf} + U_{L2}} = 7.58 \text{ W/m}^2 \text{ K}$$

$$A_m F_{Rm} = \frac{\dot{m}_f C_f}{U_{L,m}} \left[1 - \exp \left(\frac{-F' A_m U_{L,m}}{\dot{m}_f C_f} \right) \right] = (55.1)(1 - \exp(-0.011)) = 0.6$$

(ii)

On substituting terms $A_c F_{Rc}(\alpha\tau)_{c,\text{eff}}$, PF_2 , $(\alpha\tau)_{m,\text{eff}}$ and $A_m F_R$ in (ii), one can obtain the following:

$$(AF_R(\alpha\tau))_1 = 1.14, (AF_R U_L)_1 = \left[(A_c F_{Rc}) U_{L,c} + (A_m F_{Rm}) U_{L,m} \left(1 - \frac{(A_c F_{Rc}) U_{L,c}}{\dot{m}_f C_f} \right) \right] = 10.5$$

$$K_k = \left(1 - \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right) = 0.975$$

Hence, from Eq. (i), for three identical PVT water collectors the outlet-water temperature at the end of the third PVT water collector is as follows:

$$T_{f03} = \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^3}{1 - K_k} \right) I_c(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^3}{1 - K_k} \right) T_a + K_k^3 T_{fi} = 3.98 + 18.34 + 22.8$$

$$T_{f03} = 45.1^\circ\text{C}$$

(b) The rate of useful thermal energy is as follows:

$$\dot{Q}_{\text{uth},N} = N(A_c + A_m) \left[(\alpha\tau)_{\text{eff},N} I_c(t) - U_{L,N} (T_{fi} - T_a) \right]$$

$$K_{k,A} = \left[\frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right] = 0.025, (\alpha\tau)_{\text{eff},3} = \frac{(AF_R(\alpha\tau))_1}{(A_c + A_m)} \left[\frac{1 - (1 - K_{k,A})^3}{NK_{k,A}} \right] = 0.55$$

$$U_{L,3} = \frac{(AF_R U_L)_1}{(A_c + A_m)} \left[\frac{1 - (1 - K_{k,A})^3}{NK_{k,A}} \right] = 5.1$$

(iii)

Therefore, from Eq. (iii) the rate of useful thermal energy is as follows:

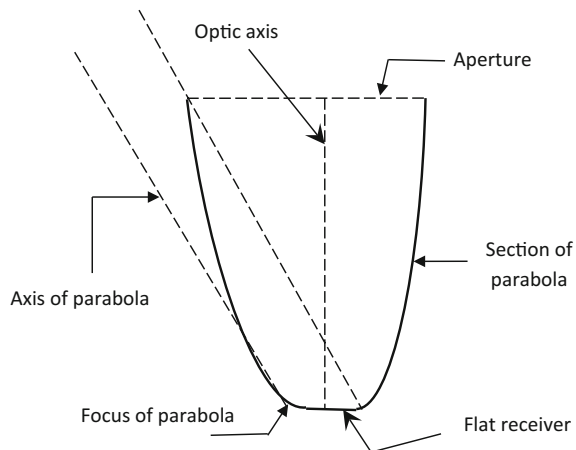
$$\dot{Q}_{\text{uth},3} = 3(A_c + A_m) \left[(\alpha\tau)_{\text{eff},3} I_c(t) - U_{L,3} (T_{fi} - T_a) \right] = 1550 \text{ Wh}$$

$$\dot{Q}_{\text{uth},3} = 1.550 \text{ kWh}$$

4.3.6 Photovoltaic Thermal Compound-Parabolic Concentrator (PVT-CPC)

The compound-parabolic concentrator (CPC) is a non-imaging one with large acceptance angle, and it requires tuning with the Sun. It belongs to a group of concentrators with the highest possible concentration permissible by thermodynamic limit for a given acceptance angle. The CPC comprises two parabolic segments that are oriented in such a way that the focus of one is positioned at the lower

Fig. 4.12 Schematic cross-section of a CPC



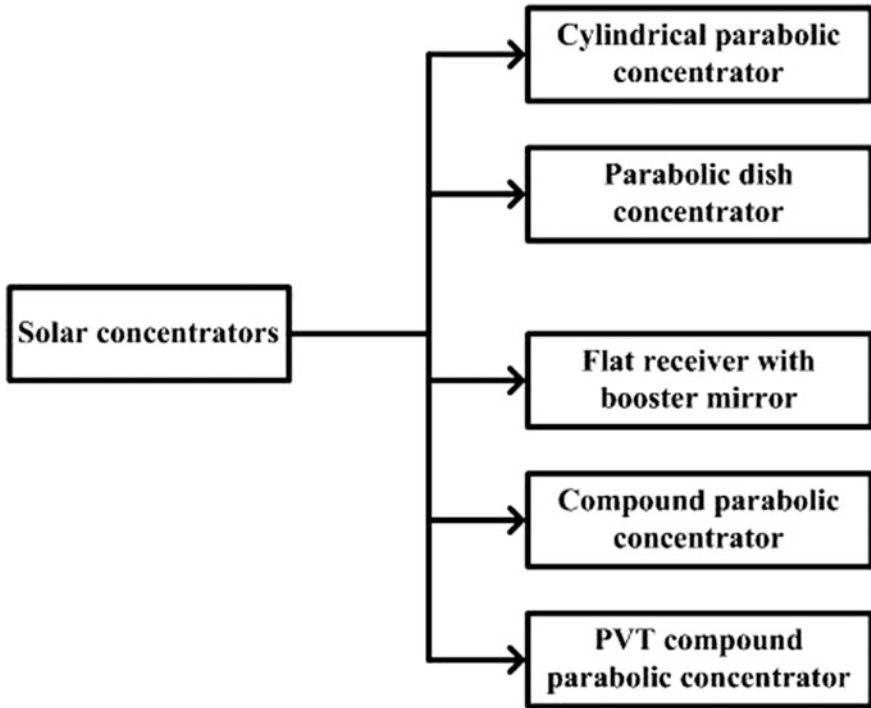
end point of the other and vice versa as shown Fig. 4.12. The axes of the parabolic segments subtend an angle equal to the acceptance angle with the CPC axis, and the slope of the reflector surfaces at the aperture plane is parallel to the CPC axis. The receiver joining the two foci of the reflecting surfaces is parallel to the aperture.

Reflected beam rays are not incident in the central region of the aperture, whereas one or more reflections occur for those near the edges. The number of reflections depends on the beam radiation's incident angle, the collector depth, and the concentration ratio (explained later in the text). The CPC can be trimmed in height to half, without any substantial change in concentration, to minimize the unit cost.

The following modifications in the design of the ideal CPC are essential as has been observed on investigation:

- (i) The incorporation of receiver shapes—such as fins, circular pipes—are intended to improve the optical and thermal performance.
- (ii) A decrease in the CPC height makes the system effective in term of physical performance as well as cost-effectiveness.
- (iii) An asymmetric orientation of source and aperture delivers seasonal varying outputs.
- (iv) Design of CPC as a second stage concentrator.

For the concentration ratio of approximately six, a CPC can be incorporated in a non-tracking mode. It cannot be used for greater concentration ratios due to its larger reflector-surface area. Different solar concentrators are given in a flow chart.



The characteristic parameters (aperture area, acceptance angle, absorber area, geometric concentration ratio, intercept factor, optical efficiency) are given in detail by Mishra and Tiwari [6].

Geometric-concentration ratio (C)

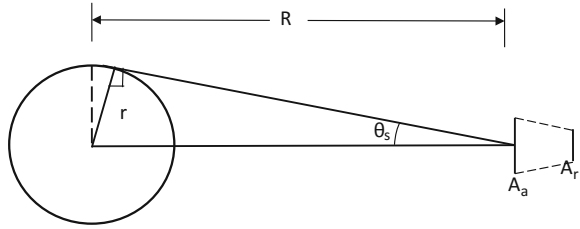
This is defined as the ratio of the collecting aperture-surface area to that of the absorber surface. The value of C varies from unity (flat-plate collector, $C = 1$) to several thousands (parabolic dish).

Let us consider the circular concentrator as shown in Fig. 4.13 with aperture area A_a and receiver area A_r . The half angle made by the Sun (radius r and at a distance R) is θ_s . The beam radiation from the Sun on the aperture (and consequently on receiver) is the fraction of the radiation emitted by the Sun for the perfect concentrator, and it is intercepted by the aperture.

$$Q_{s \rightarrow r} = A_a \frac{r^2}{R^2} \sigma T_s^4$$

A perfect receiver (blackbody) emits radiation in the form of thermal energy equal to $A_r T_r^4$, and a fraction of this, $E_{r \rightarrow s}$ reaches the Sun.

Fig. 4.13 Schematic of sun at T_s at a distance R from a concentrator with aperture area A_a and receiver area A_r



$$Q_{s \rightarrow r} = A_r T_r^4 E_{r-s}$$

Therefore, $A_a \frac{r^2}{R^2} \sigma T_s^4 = A_r T_r^4 E_{r-s}$ when T_r and T_s are the same, $Q_{s \rightarrow r}$ will be equal to $Q_{r \rightarrow s}$ by the second law of thermodynamics.

The maximum possible value of E_{r-s} is unity, and the maximum concentration ratio for circular concentrators is given by the following:

$$\left(\frac{A_a}{A_r} \right)_{\max} = \frac{R^2}{r^2} = \frac{1}{\sin^2 \theta_s} \quad (4.4.27)$$

A similar relation can be obtained for linear concentrators as follows:

$$C = \frac{A_a}{A_{\text{abs}}} \quad (4.4.28)$$

- (a) **Glazed tube type:** In this case, the annular spacing between a selective coated copper tube and a co-axial glazed tube can be evacuated for decreasing the convective heat loss between the annular spaces. Only radiative loss between annular spacing will occur. It is not feasible to integrate a semitransparent photovoltaic module with a glazed receiver/absorber.
- (b) **Parallel flat-plate receiver/absorber:** In such a configuration, it is possible to integrate a semitransparent photovoltaic (PV) module with a glazed receiver/absorber. However, the fluid, other than water flowing between the two parallel receiver/absorber, is not practical due to the high operating temperature ($\approx 300^\circ\text{C}$), which is associated with leakage problems.
- (c) **Tube in plate-type receiver/absorber:** In this case, the operating temperature becomes greater due to the lower heat capacity of the fluid compared with that of the parallel flat-plate absorber. Furthermore, the leakage of the fluid due to high pressure is minimized. Moreover, it is easier to integrate a semitransparent photovoltaic (PV) module with the glazed surface of receiver/absorber such as a PVT-FPC.
- (d) **PV module:** PV modules consist of PV-cell circuits packed in an environmentally protective laminate. They are the fundamental building block of PV systems (as discussed in Sect. 4.3).

4.3.6.1 N-Photovoltaic Thermal Compound-Parabolic Concentrator (N-PVT-CPC)

The series connection of an N-photovoltaic thermal (PVT) compound-parabolic concentrator (CPC) is shown in Fig. 4.14a. The side view of the system is presented in Fig. 4.14b. The inlet for the second PVT-CPC collector is the outlet of the first PVT-CPC collector, and the second PVT-CPC collector outlet is connected to the inlet of the third PVT-CPC collector, and so on [7]. The final outlet-water temperature at the N th PVT-CPC water collector is clearly presented in Fig. 4.14a, b.

Case A: Lower portion of the concentrator partially covered by a semi-transparent PV module (Fig. 4.15a, b)

Energy balances of different portions of the system are given as follows:

(a) Energy balance for a semi-transparent photovoltaic (PV) module

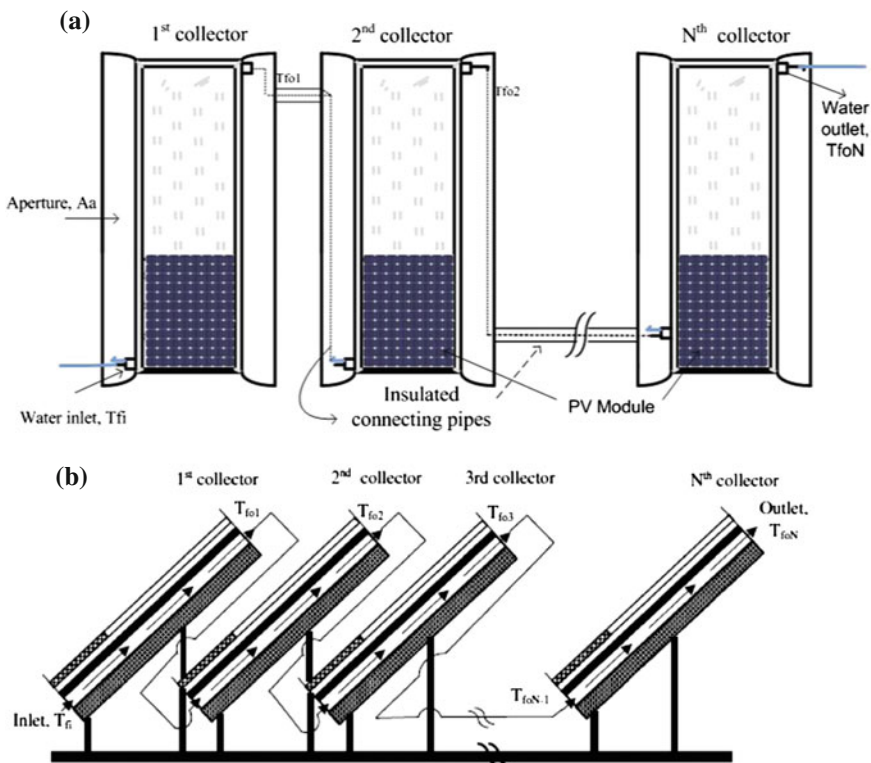


Fig. 4.14 a N-Photovoltaic thermal compound parabolic concentrators connected in series *[7].
b Side view of N-Photovoltaic thermal compound parabolic concentrators connected in series [7]

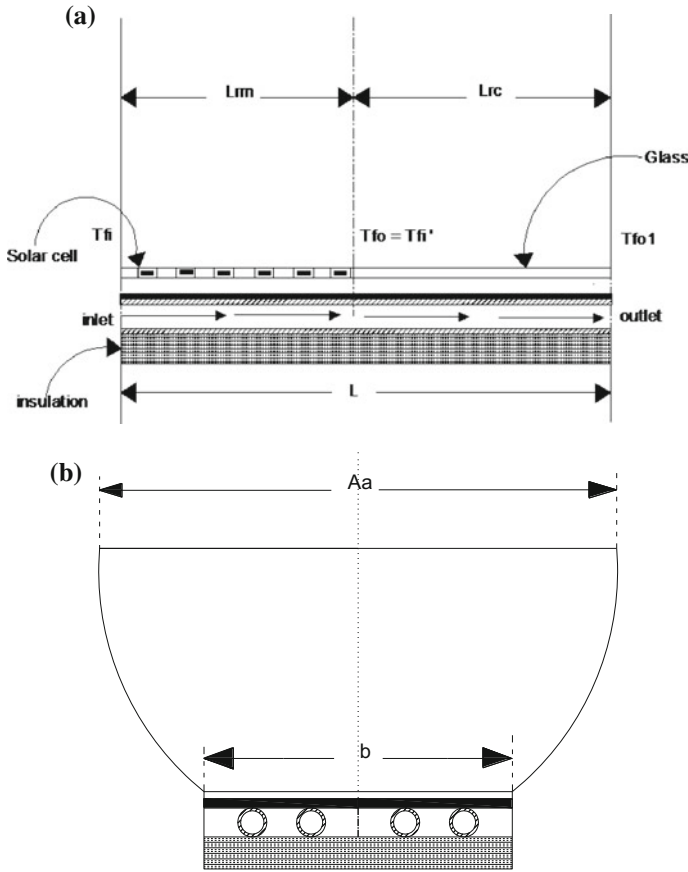


Fig. 4.15 **a** Cross sectional side view of proposed partially covered PVT-CPC water collector. **b** Cut cross-sectional front view of proposed partially covered PVT-CPC water collector

$$\rho \alpha_c \tau_g \beta_c I_b A_{am} = [U_{tc,a}(T_c - T_a) + U_{tc,p}(T_c - T_p)] A_{rm} + \rho \eta_m I_b A_{am} \quad (4.4.29)$$

where α_c solar-cell absorptivity; τ_g glass transmissivity (PV module); $I_b(t)$ beam radiation (W/m^2); β_c packing factor of the solar cell; $U_{tc,a}$ overall heat-transfer coefficient from the solar cell to the ambient through the glass cover ($\text{W/m}^2 \text{ } ^\circ\text{C}$); $U_{tc,p}$ overall heat-transfer coefficient from the solar cell to the blackened absorber plate through the glass cover and air gap ($\text{W/m}^2 \text{ } ^\circ\text{C}$); T_c solar-cell temperature ($^\circ\text{C}$); T_a ambient temperature ($^\circ\text{C}$); T_p blackened absorber plate temperature ($^\circ\text{C}$); $\eta_m (= \eta_c \tau_g \beta_c)$ is the module efficiency; η_c solar-cell electrical efficiency; $A_{rm} (= b L_{rm})$ area of the receiver covered by the PV module (m^2); L_{rm} length of the receiver covered by the PV module (m); $A_{am} (= b_o L_{am})$ area of the aperture covered by the PV module (m^2); L_{am} length of the aperture covered by the PV module (m); b breadth of the receiver (m); and b_o breadth of the aperture (m).

(b) Energy balance for an absorber plate below the PV module

$$\begin{aligned} & \rho\alpha_p\tau_g^2(1-\beta_c)I_bA_{am} + U_{t,cp}[(T_c - T_p)]A_{rm} \\ & = [F'h_{p,f}(T_p - T_f)]A_{rm} + U_{t,pa}[(T_p - T_f)]A_{rm} \end{aligned} \quad (4.4.30)$$

where α_p is the absorptivity of the blackened plate; F' is the collector-efficiency factor; h_{pf} is the conductive heat-transfer coefficient from the absorber plate to the flowing fluid (water) ($W/m^2 \text{ } ^\circ C$); $U_{tp,a}$ overall heat-transfer coefficient from the absorber plate to the ambient ($W/m^2 \text{ } ^\circ C$); $U_{tp,a}$ overall heat-transfer coefficient from the cell to the plate ($W/m^2 \text{ } ^\circ C$); and T_f is the temperature of the fluid ($^\circ C$).

(c) Energy balance for fluid flowing below the absorber

$$\dot{m}_f C_f \frac{dT_f}{dx} = F' [h_{p,f}(T_p - T_f)] b dx \quad (4.4.31)$$

where, and $b dx$ is the elementary section.

From Eqs. (4.4.29) and (4.4.30), the expressions of T_c and T_p can be expressed as follows:

$$T_c = \frac{(\alpha\tau)_{1,eff}I_b + U_{tc,a}T_a + U_{tc,p}T_p}{(U_{tc,a} + U_{tc,p})} \quad (4.4.32)$$

$$T_p = \frac{(\alpha\tau)_{2,eff}I_b + PF_1(\alpha\tau)_{1,eff}I_b + U_{L1}T_a + F'h_{p,f}T_f}{(U_{L1} + F'h_{p,f})} \quad (4.4.33)$$

where

$$(\alpha\tau)_{1,eff} = \rho(\alpha_c\tau_g\beta_c - \eta_m)\frac{A_{am}}{A_{rm}}; (\alpha\tau)_{2,eff} = \rho\alpha_p\tau_g^2(1-\beta_c)\frac{A_{am}}{A_{rm}}$$

$PF_1 = \frac{h_{c,p}}{(U_{tc,a} + h_{c,p})}$ is the first penalty factor due to PV module.

$U_{L1} = \frac{U_{tc,p}U_{tc,a}}{(U_{tc,a} + U_{tc,p})}$ is an overall top heat-transfer coefficient through PV module

from the receiver/absorber to the ambient ($W/m^2 \text{ } ^\circ C$). $U_{tc,a} = \left[\frac{1}{h_0} + \frac{L_g}{K_g} \right]^{-1}$; $U_{tc,p} = \left[\frac{1}{h_i} + \frac{L_g}{K_g} \right]^{-1}$

h_i is the heat transfer coefficient for space between the glazing and absorption plate ($W/m^2 \text{ } ^\circ C$). h_0 is the heat transfer coefficient from top of PVT collector to the ambient ($W/m^2 \text{ } ^\circ C$). L_g is the thickness of the glass (mm), and K_g is the thermal conductivity of the glass ($W/m^2 \text{ } ^\circ C$).

Using Eqs. (4.4.32) and (4.4.33), Eq. (4.4.31) can be re-expressed as follows:

$$\dot{m}_f C_f \frac{dT_f}{dx} = F' \left[PF_2(\alpha\tau)_{m,\text{eff}} I_b - U_{L,m}(T_f - T_a) \right] b dx \quad (4.4.34)$$

where

$$(\alpha\tau)_{m,\text{eff}} = PF_1(\alpha\tau)_{1,\text{eff}} + (\alpha\tau)_{2,\text{eff}}$$

$PF_2 = \frac{F' h_{p,f}}{(U_{L,m} + F' h_{p,f})}$ is the second penalty factor due to the PV module.

$U_{L,m} = \frac{U_{L1} F' h_{p,f}}{(U_{L1} + F' h_{p,f})}$ is an overall top heat-transfer coefficient from the receiver/absorber to the ambient through the PV module ($\text{W/m}^2 \text{ } ^\circ\text{C}$).

Using the initial condition; $T_f = T_{fi}$ at $x = 0$, the solution of Eq. (4.4.34) can be expressed as follows:

$$\frac{T_f - T_a - \left(\frac{PF_2(\alpha\tau)_{m,\text{eff}} I_b}{U_{L,m}} \right)}{T_{fi} - T_a - \left(\frac{PF_2(\alpha\tau)_{m,\text{eff}} I_b}{U_{L,m}} \right)} = \exp \left(- \frac{F' U_{L,m} b x}{\dot{m}_f C_f} \right) \quad (4.4.35)$$

$$T_f = \left[\left(\frac{PF_2(\alpha\tau)_{m,\text{eff}} I_b}{U_{L,m}} \right) + T_a \right] \left\{ 1 - \exp \left(- \frac{F' U_{L,m} b x}{\dot{m}_f C_f} \right) \right\} + T_{fi} \exp \left(- \frac{F' U_{L,m} b x}{\dot{m}_f C_f} \right) \quad (4.4.36)$$

The outlet-fluid temperature at the end of PV module ($T_{fom1} = T_f$ at $x = L_{rm}$) is given by the following:

$$T_{fom1} = \left[\left(\frac{PF_2(\alpha\tau)_{m,\text{eff}} I_b}{U_{L,m}} \right) + T_a \right] \left\{ 1 - \exp \left(- \frac{F' U_{L,m} b L}{\dot{m}_f C_f} \right) \right\} + T_{fi} \exp \left(- \frac{F' U_{L,m} b L}{\dot{m}_f C_f} \right)$$

or

$$T_{fom1} = \left[\left(\frac{PF_2(\alpha\tau)_{m,\text{eff}} I_b}{U_{L,m}} \right) + T_a \right] \left\{ 1 - \exp \left(- \frac{F' U_{L,m} A_{rm}}{\dot{m}_f C_f} \right) \right\} + T_{fi} \exp \left(- \frac{F' U_{L,m} A_{rm}}{\dot{m}_f C_f} \right) \quad (4.4.37)$$

After knowing T_f from Eq. (4.4.36), the outlet-water temperature at the first collector can be expressed as follows:

$$T_{fo1} = \frac{I_b(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \frac{(1 - K_p^N)}{(1 - K_p)} + \frac{T_a(AF_R U_L)_1}{\dot{m}_f C_f} \frac{(1 - K_p^N)}{(1 - K_p)} + T_{fi} K_p^N + T_{fi} \left(1 - \frac{(AF_R U_L)_1}{\dot{m}_f C_f}\right) \quad (4.4.38)$$

This T_{fo1} becomes the inlet for the second PVT-CPC water collector and the outlet of the second PVT-CPC water collector becomes the inlet for the third PVT-CPC water collector, and so on, up to the N th collector (T_{foN}) as explained previously. Therefore, the outlet-fluid temperature at the end of the N th collector's PV module and T_{foN} can be expressed as follows:

$$T_{fomN} = \frac{I_b(AF_R(\alpha\tau))_{mN}}{\dot{m}_f C_f} + \frac{T_a(AF_R U_L)_1}{\dot{m}_f C_f} \frac{(1 - K_p^N)}{(1 - K_p)} + T_{foN-1} K_m \quad (4.4.39)$$

$$T_{foN} = \frac{I_b(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \frac{(1 - K_p^N)}{(1 - K_p)} + \frac{T_a(AF_R U_L)_1}{\dot{m}_f C_f} \frac{(1 - K_p^N)}{(1 - K_p)} + T_{fi} K_m^N \quad (4.4.40)$$

The average fluid temperature can be obtained as follows:

$$\bar{T}_{fN} = \frac{T_{foN-1} + T_{fomN}}{2} \quad (4.4.41)$$

where T_{foN-1} and T_{fomN} are the outlet-water temperature and the temperature at the end of the PV module at the $(N - 1)$ th and N th PVT-CPC water collectors, respectively. From Eq. (4.4.41), one can obtain the expression of average absorber plate temperature ($\bar{T}_{pN}$) as follows:

$$\begin{aligned} \bar{T}_{pN} = & \frac{I_b}{(U_{L2} + F'h_{pf})} \left[(\alpha\tau)_{2,eff} + PF_2(\alpha\tau)_{1,eff} \right. \\ & + \frac{F'h_{pf}}{2\dot{m}_f C_f} \left\{ (AF_R(\alpha\tau))_{m1} + (1 + K_m)(AF_R(\alpha\tau))_1 \frac{(1 - K_k^{N-1})}{(1 - K_k)} \right\} \Big] \\ & + \frac{T_a}{(U_{L2} + F'h_{pf})} \left[U_{L2} + \frac{F'h_{pf}}{2\dot{m}_f C_f} \left\{ (AF_R U_L)_{m1} + (1 + K_m)(AF_R U_L)_1 \frac{(1 - K_k^{N-1})}{(1 - K_k)} \right\} \right] \\ & + \frac{F'h_{pf}}{2(U_{L2} + F'h_{pf})} (1 + K_m) K_k^{N-1} T_{fi} \end{aligned} \quad (4.4.42)$$

The expression of the average solar-cell temperature ($\bar{T}_{cN}$) can be expressed as

$$\bar{T}_{cN} = \frac{(\alpha\tau)_{1,eff} I_b + U_{tc,a} T_a + U_{tc,p} \bar{T}_{pN}}{U_{tc,a} + U_{tc,p}} \quad (4.4.43)$$

Using Eq. (4.4.42), the expression of the average solar-cell temperature ($\bar{T}_{cN}$) can be obtained as follows:

$$\begin{aligned} \bar{T}_{cN} = & \frac{I_b}{U_{tc,p} + U_{tc,a}} \left[(\alpha\tau)_{1,eff} + \frac{U_{tc,p}}{(U_{L2} + F'h_{pf})} \left\{ (\alpha\tau)_{m,eff} \right. \right. \\ & + \left. \frac{F'h_{pf}}{2\dot{m}_f c_f} \left\{ (AF_R U_L)_{m1} + (1 + K_m)(AF_R U_L)_1 \frac{(1 - K_k^{N-1})}{(1 - K_k)} \right\} \right\} \Big] \\ & + \frac{T_a}{U_{tc,p} + U_{tc,a}} \left[U_{tc,a} + \frac{U_{tc,p}}{(U_{L2} + F'h_{pf})} \left\{ U_{L2} + \frac{F'h_{pf}}{2\dot{m}_f c_f} \left\{ (AF_R U_L)_{m1} + \right. \right. \right. \\ & \left. \left. \left. (1 + K_m)(AF_R U_L)_1 \frac{(1 - K_k^{N-1})}{(1 - K_k)} \right\} \right\} \right] \\ & + \left[\frac{U_{tc,p} F' h_{pf}}{2(U_{L2} + F'h_{pf})} (1 + K_m) K_k^{N-1} \right] T_{fi} \end{aligned} \quad (4.4.44)$$

The analytical expression for the temperature-dependent electrical efficiency of solar cells of THE N th PVT-CPC water collector can be obtained from the following equation [5]:

$$\eta_{cN} = \eta_0 [1 - \beta_0 (\bar{T}_{cN} - T_0)] \quad (4.4.45)$$

On substituting Eq. (4.4.44) in the previous equation, one can obtain the following:

$$\begin{aligned} \eta_{cN} = & \left[\eta_0 \left(1 - \beta_0 \frac{1}{U_{tc,p} + U_{tc,a}} \left[\frac{I_b}{U_{tc,p} + U_{tc,a}} \left\{ \frac{\rho\tau_g \alpha_c \beta_c \left(\frac{A_{am}}{A_{rm}} \right) + \frac{U_{tc,p}}{U_{L2} + F'h_{pf}} \left\{ (\alpha\tau)_{2,eff} + PF_1 \rho \alpha_c \tau_g \beta_c \left(\frac{A_{am}}{A_{rm}} \right) + \right. \right. \right. \right. \right. \right. \\ & \left. \left. \left. \frac{U_{tc,p} F' h_{pf}}{2\dot{m}_f c_f (U_{L2} + F'h_{pf})} \left\{ PF_2 (\alpha\tau)_{2,eff} + PF_2 PF_1 \rho \alpha_c \tau_g \beta_c \left(\frac{A_{am}}{A_{rm}} \right) \right\} A_m F_{rm} \right. \right. \right. \right. \\ & \left. \left. \left. + (1 + K_m) \right\} \right\} \right. \\ & \left. \left. \left. \left\{ AF_{rc} (\alpha\tau)_{c,eff} + \left\{ PF_2 (\alpha\tau)_2 + PF_2 PF_1 \rho \alpha_c \tau_g \beta_c \left(\frac{A_{am}}{A_{rm}} \right) \right\} A_m F_{rm} \left(1 - \frac{Ac F_{rc} U_{Lc}}{\dot{m}_f c_f} \right) \right\} \right\} \right. \right. \\ & \left. \left. \left. \left(\frac{1 - K_k^{N-1}}{1 - K_k} \right) \right\} \right. \right. \\ & \left. \left. \left. + T_a \left[U_{tc,a} + \frac{U_{tc,p} U_{L2}}{U_{L2} + F'h_{pf}} + \frac{U_{tc,p} F' h_{pf}}{2\dot{m}_f c_f (U_{L2} + F'h_{pf})} \left\{ (AF_R U_L)_{m1} + (1 + K_m)(AF_R U_L)_1 \left(\frac{1 - K_k^{N-1}}{1 - K_k} \right) \right\} \right] \right. \right. \right. \\ & \left. \left. \left. + T_{fi} \left[\frac{U_{tc,p} F' h_{pf} (1 + K_m) K_k^{N-1}}{2(U_{L2} + F'h_{pf})} \right] \right] \right] \right] \right] - T_0 \end{aligned} \quad (4.4.46)$$

The rate of thermal energy available ($\dot{Q}_{uth,N}$) at the outlet of the N th PVT-CPC water collector is given as follows:

$$\dot{Q}_{\text{uth},N} = \dot{m}_f C_f (T_{\text{fo}N} - T_{\text{fi}}) = A_{\text{rm}} F_{Rm} \left[\text{PF}_2(\alpha\tau)_{m,\text{eff}} I_b - U_{L,m} (T_{\text{fi}} - T_a) \right] \quad (4.4.47)$$

where F_{Rm} is flow-rate factor for a PVT configuration of concentrator, which is given by the following:

$$F_{Rm} = \frac{\dot{m}_f C_f}{U_{L,m} A_{\text{rm}}} \left\{ 1 - \exp \left(- \frac{F' U_{L,m} A_{\text{rm}}}{\dot{m}_f C_f} \right) \right\} \quad (4.4.48)$$

Using Eq. (4.4.46), the temperature-dependent electrical efficiency of PV modules of an N-PVT-PC water collector can be obtained as follows:

$$\eta_{mN} = \tau_g \beta_c \eta_{cN} \quad (4.4.49)$$

Furthermore, the rate of usable electrical-energy gain or exergy from an N-identical PVT-CPC water collector can be evaluated as follows:

$$\dot{Q}_{\text{xel},N} = A_{\text{rm}} I_b \sum_{i=1}^N \eta_{mN} \quad (4.4.50)$$

An overall energy can be obtained as follows:

$$\dot{Q}_{\text{xu},N} = \dot{Q}_{\text{xth},N} + \dot{Q}_{\text{xel},N} \quad (4.4.51)$$

In a similar manner, one can analytically analyse the N th PVT-CPC collector with a partially covered upper portion of a semitransparent PV module (case B).

Limiting cases

Equation (4.4.46) can be discussed for the following limiting conditions:

Case I: For $A_{\text{am}} = A_{\text{rm}}$, $\rho = 1$ and $I_b(t) = I(t)$, Eq. (4.4.46) reduces to the expression derived by Shyam et al. [2] for series-connected N-PVT collectors.

Case II: For $N = 1$, Eq. (4.4.46) is valid for the expression derived by Atheaya et al. [8] for a single (conventional) PVT-CPC water collector.

The hourly variation of outlet-water temperature ($T_{\text{fo}N}$) for a typical day of January and June is shown in Fig. 4.16 for different PVT-CPC water collectors. The water temperature decreases on increasing the number of collectors due to higher heat loss, and it reaches ≤ 100 °C beyond six collectors.

The hourly variation of average solar-cell temperature (T_c) and electric efficiency (η_m) of the PV module for the same months is shown in Fig. 4.17. The decrease in electrical efficiency with an increase in average solar-cell temperature for both months is credited to the fact that the thermal losses are higher at higher temperature. In addition, collisions between electrons in the depletion layer of solar cell also take place at higher operating temperature.

The variation of maximum outlet-water temperature with mass-flow rate for typical days of both months for all of the six collectors is depicted in Fig. 4.18. It

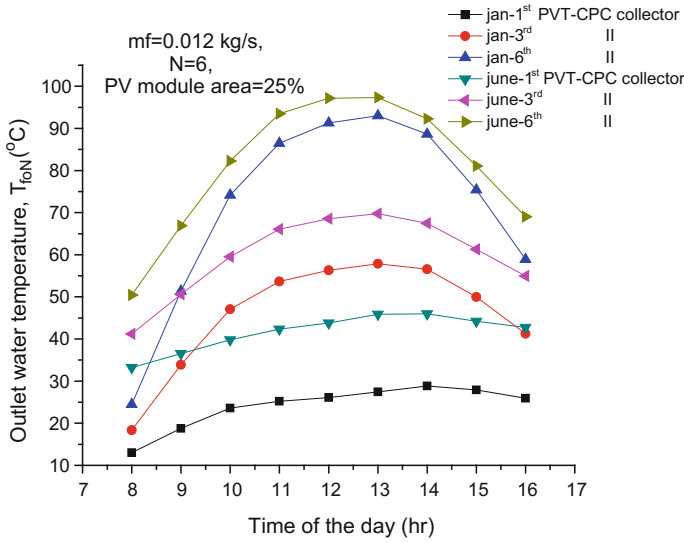


Fig. 4.16 Hourly variation of outlet water temperature, T_{foN} for partially covered N-PVT-CPC water collector for a typical day in month of January and June

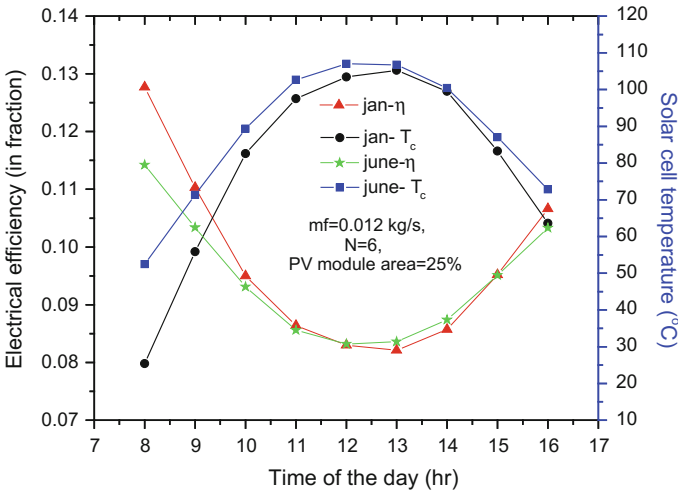


Fig. 4.17 Hourly variation of electrical efficiency and solar cell temperature for partially covered N-PVT-CPC water collector for a typical day in month of June

was observed that the variation decreases with an increase in mass-flow rate. This occurs due to the decrease in thermal losses, which lowers the $(T_{foN})_{max}$. In addition, enhancement in the rate of heat transfer from the absorber plate to the water on increasing the mass-flow rate further lowers the outlet water temperature.

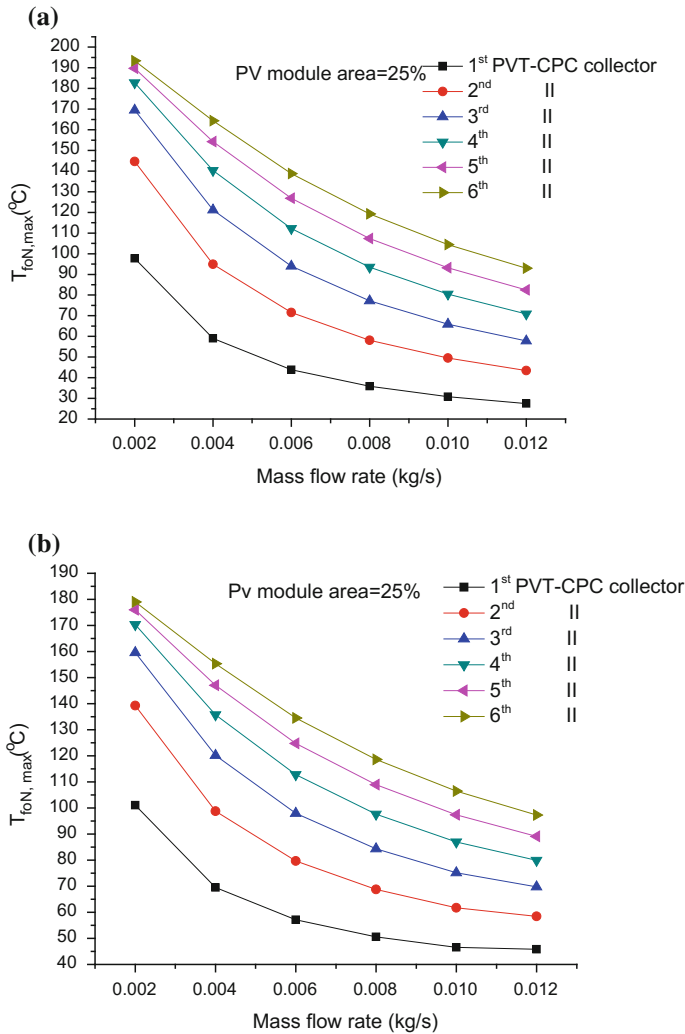


Fig. 4.18 Hourly variation of outlet water temperature, T_{foN} with different values of mass flow rate, for partially covered N-PVT-CPC water collector for a typical day in month of **a** January, and **b** June

A decrease of 101 °C in maximum outlet-water temperature was observed for the range of 0.002–0.012 kg/s mass-flow rate for the given six collectors. This finding suggests that the other fluids with greater boiling temperature can be incorporated for power generation with more series-connected collectors.

The effect of the number of collectors on maximum outlet-water temperature is shown in Fig. 4.19. The $(T_{foN})_{max}$ increases with an increase in the number of collectors for N-PVT collectors connected in series [2]. A boiling temperature of 100 °C was achieved for eight collectors and a 0.012 kg/s mass-flow rate. By

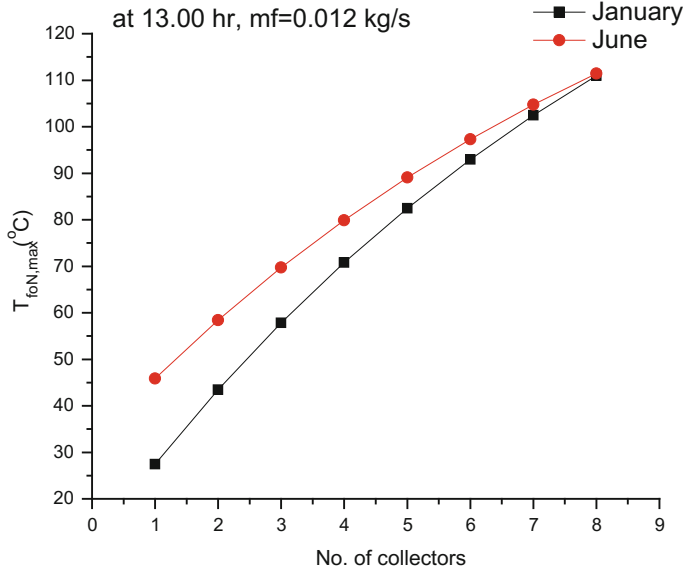


Fig. 4.19 Variation of outlet fluid temperature with varying number of collectors at fixed mass flow rate

incorporating other fluids, this temperature can further be increased on increasing the number of PVT-CPC collectors for power generation.

Example 4.3 Calculate the outlet-water temperature and rate of useful thermal energy of three photovoltaic thermal compound-parabolic concentrators (PVT-CPC) connected in series (case A) for a mass-flow rate ($\dot{m}_f$) of 0.012 kg/s. Use the following design and climatic parameters:

$\frac{A_{rc}}{A_{ac}} = 0.5$, $\frac{A_{am}}{A_{ac}} = 2$, $A_c = 0.75 \text{ m}^2$, $A_m = 0.25 \text{ m}^2$, $A_r = 1 \text{ m}^2$, $A_a = 2 \text{ m}^2$,
 $A_{ac} = 1.5 \text{ m}^2$, $c_f = 4179 \text{ J/kg K}$, $F_{rm} = 0.8110 \text{ m}^2$, $K_g = 0.816 \text{ W/m } ^\circ\text{C}$,
 $L_g = 0.003 \text{ m}$, $K_i = 0.166 \text{ W/m } ^\circ\text{C}$, $L_i = 0.100 \text{ m}$, $K_p = 6 \text{ W/m } ^\circ\text{C}$,
 $L_p = 0.002 \text{ m}$, $U_{L1} = 3.47 \text{ W/m}^2 \text{ } ^\circ\text{C}$, $U_{L,m} = 7.87 \text{ W/m}^2 \text{ } ^\circ\text{C}$, $h_{pf} = 100 \text{ W/m}^2$,
 $h_i = 5.7 \text{ W/m}^2$, $h'_i = 5.8 \text{ W/m}^2$, $h_0 = 9.5 \text{ W/m}^2$, $\rho = 0.84$, $\tau_g = 0.95$, $\alpha_c = 0.9$,
 $\beta_c = 0.89$, $\alpha_p = 0.8$, $I_b = 500 \text{ W/m}^2 \text{ } ^\circ\text{C}$, $F' = 0.968$, $FF = 0.8$, $\eta_c = 0.15$,
Inclination = 30° .

Solution

(a) From Eq. (4.4.40),

$$\begin{aligned}
T_{foN} &= \frac{I_b(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \frac{(1 - K_k^N)}{(1 - K_k)} + \frac{T_a(AF_R U_L)_1}{\dot{m}_f C_f} \frac{(1 - K_k^N)}{(1 - K_k)} + T_{fi} K_k^N \\
U_{tc,a} &= \left[\frac{1}{h_o} + \frac{L_g}{K_g} \right]^{-1} = 9.17 \text{ W/m}^2 \text{ } ^\circ\text{C}; \quad U_{tc,p} = \left[\frac{1}{h_i} + \frac{L_g}{K_g} \right]^{-1} = 5.58 \text{ W/m}^2 \text{ } ^\circ\text{C} \\
U_{tp,a} &= \left[\frac{1}{U_{tc,a}} + \frac{1}{U_{tc,p}} \right]^{-1} + \left[\frac{1}{h_i} + \frac{1}{h_{pf}} + \frac{L_i}{K_i} \right]^{-1} = 4.8 \text{ W/m}^2 \text{ } ^\circ\text{C} \\
U_{L1} &= \frac{U_{tc,p} U_{tc,a}}{U_{tc,p} + U_{tc,a}} = 3.46; \quad U_{L2} = U_{L1} + U_{tp,a} = 8.27 \text{ W/m}^2 \text{ } ^\circ\text{C} \\
U_{L,m} &= \frac{h_{pf} U_{L2}}{F' h_{pf} + U_{L2}} = 7.88; \quad U_{L,c} = \frac{h_{pf} U_{tp,a}}{F' h_{pf} + U_{tp,a}} = 4.72 \\
A_c F_{Rc} &= \frac{\dot{m}_f c_f}{U_{L,c}} \left[1 - \exp\left(\frac{-F' U_{L,c} A_c}{\dot{m}_f c_f}\right) \right] = 10.6(1 - \exp(-0.068)) = 0.70 \\
A_m F_{Rm} &= \frac{\dot{m}_f c_f}{U_{L,m}} \left[1 - \exp\left(\frac{-F' U_{L,m} A_m}{\dot{m}_f c_f}\right) \right] = 6.36(1 - \exp(-0.038)) = 0.24 \\
\therefore (AF_R U_L)_1 &= \left[A_c F_{Rc} U_{L,c} + A_m F_{Rm} U_{L,m} \left(1 - \frac{A_c F_{Rc} U_{L,c}}{\dot{m}_f c_f} \right) \right] = 5.07, \\
K_k &= \left(1 - \frac{(AF_R U_L)_1}{\dot{m}_f c_f} \right) = 0.9 \\
PF_c &= \frac{h_{pf}}{F' h_{pf} + U_{tp,a}} = 0.98, \quad PF_1 = \frac{U_{tc,p}}{U_{tc,p} + U_{tc,a}} = 0.38, \quad PF_2 = \frac{h_{pf}}{F' h_{pf} + U_{L2}} = 0.95 \\
(\alpha\tau)_{1,\text{eff}} &= (\alpha_c - \eta_c) \tau_g \beta_c \frac{A_{am}}{A_{rm}} = 1.27, \quad (\alpha\tau)_{c,\text{eff}} = PF_c \alpha_p \tau_g \frac{A_{rc}}{A_{ac}} = 0.37, \\
(\alpha\tau)_{2,\text{eff}} &= \alpha_p \tau_g^2 (1 - \beta) \frac{A_{am}}{A_{rm}} = 0.11, \quad (\alpha\tau)_{m,\text{eff}} = [(\alpha\tau)_{2,\text{eff}} + PF_1 (\alpha\tau)_{1,\text{eff}}] = 0.59 \\
(AF_R(\alpha\tau))_1 &= \left[A_c F_{Rc} (\alpha\tau)_{c,\text{eff}} + PF_2 (\alpha\tau)_{m,\text{eff}} A_m F_{Rm} \left(1 - \frac{A_c F_{Rc} U_{L,c}}{\dot{m}_f c_f} \right) \right] = 0.38
\end{aligned} \tag{i}$$

Therefore, from Eq. (i), the outlet-water temperature for three identical PVT compound-parabolic concentrators is as follows:

$$\begin{aligned}
T_{fo3} &= \frac{I_b(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \frac{(1 - K_k^3)}{(1 - K_k)} + \frac{T_a(AF_R U_L)_1}{\dot{m}_f C_f} \frac{(1 - K_k^3)}{(1 - K_k)} + T_{fi} K_k^3 \\
&= 10.26 + 6.84 + 20.4 = 37.5
\end{aligned}$$

Hence $T_{fo3} = 37.5 \text{ } ^\circ\text{C}$.

(b) From Eq. (4.4.47), the rate of useful energy or heat transfer is given as follows:

$$\begin{aligned}\dot{Q}_{\text{uth},N} &= (\alpha\tau)_{\text{eff}} I_b - (UA)_{\text{eff}} (T_{fi} - T_a) \\ (\alpha\tau)_{\text{eff}} &= (AF_R(\alpha\tau))_1 \left(\frac{1 - K_K^N}{1 - K_K} \right) = 1.03, (UA)_{\text{eff}} = (A_R F_R U_L)_1 \left(\frac{1 - K_K^N}{1 - K_K} \right) = 13.74\end{aligned}\quad (\text{ii})$$

Therefore, from Eq. (ii), the rate of useful heat output at the third PVT compound parabolic concentrator is as follows:

$$\begin{aligned}\dot{Q}_{\text{uth},N} &= (\alpha\tau)_{\text{eff}} I_b - (UA)_{\text{eff}} (T_{fi} - T_a) = 473.7 \text{ Wh} \\ \dot{Q}_{\text{uth},N} &= 0.437 \text{ kWh.}\end{aligned}$$

4.3.7 Evacuated Tubular Collector

In flat-plate collectors, there are two thermal losses from absorber/receiver to the glazing cover viz. the rate of convective heat transfer and the rate of radiative heat transfer [1, 6]. The convective losses of the collector are the main concern; this can be minimized by using a selective surface, which increases the useful energy. Therefore, it is necessary to fully use the potential of such surfaces for a further decrease in the convective loss. This can be attained by including more glazing covers, but this is done at the cost of low absorption of some incident solar radiation due to an escalation in reflective losses (Fig. 4.1). Different types of evacuated tubular solar collectors are shown below in chart.

This problem can be handled by eliminating the air over the absorbing surface through evacuation. Based on this concept, the University of Sydney developed a collector (Fig. 4.20).

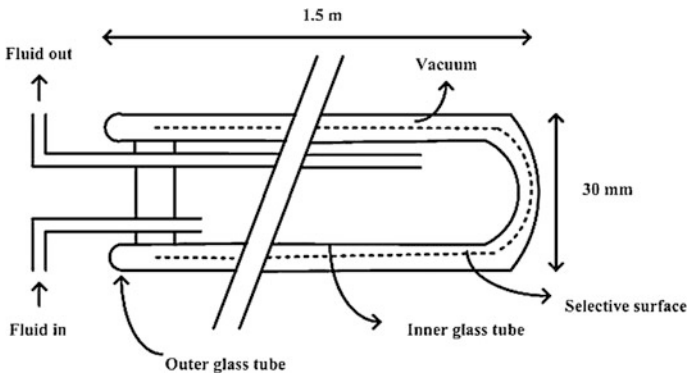


Fig. 4.20 An all-glass evacuated-tube collector module

The simplest modules are made of two connected tubes assembled as shown in Fig. 4.3. The inner side of the inner tube is coated to form a selective surface, which is vacuum-encased ($<10^5$ of atmospheric pressure). The fluid extracts heat and passes in and out at the same end of the inner tube. The requirement of using a cylindrical shape of the collector is one major drawback. It creates a problem due to its difficult arrangement to retrieve the maximum solar radiation. In a commercial unit, reflectors are used behind the tubes to generate the space between the tubes. The solar radiation, which passes through the spacing between the tubes, is reflected by the reflectors onto the back of the tubes. Eventually, at high solar intensity and low extraction temperatures, these collectors are not as proficient as flat-plate collectors. However, the performance is better due to minimum losses at low solar intensity and temperatures $>100^\circ\text{C}$.

A group in School of Physics, University of Sydney, developed a selective surface of sputtered iron/iron carbide on copper, which can be deposited directly onto the glass. They made collectors with a diffuse reflector and increased temperatures $\leq 320^\circ\text{C}$ during the availability of full solar intensity. More than 50% of extraction efficiencies at 100°C can be attained with upgraded reflectors.

Basically, in an evacuated glazed tubular collector, a vacuum is created between the absorber and transparent-glass cover. Many evacuated glazed tubular collectors have been reported in the literature: (i) Solaron collector, (ii) Philips (Germany) collector, (iii) Sanyo evacuated tubular collector, (iv) Corning evacuated tubular collector, (v) Philips (Germany) evacuated tubular collector, (vi) Roberts evacuated tubular collector, (vii) Owens-Illinois (OI) evacuated tubular collector, (viii) General Electric TC-100 evacuated tubular collector, (ix) Gumman evacuated tubular collector, and (x) Corning collector with internal reflector [6].

Mishra et al. [9] analytically studied the performance of evacuated tubular collectors. Coaxial glass tube with an outer diameter of 0.05 m and a length of 1.25 m contains a U-shaped copper tube (fitted inside) as shown in Fig. 4.21a. The selective coating is prepared on the outer surface of the inner tube. The heat transfer between the inner tube and the working fluid flowing through the tubes is improved on including a metal fin at the inner surface of the coaxial tube as shown in Fig. 4.21b. The coaxial tube's annular space is evacuated for lower convective heat loss from the inner tube to the outer tube. The whole ETC assembly is inclined at an angle of approximately 30° (latitude of New Delhi). The outer surface of the tube absorbs the incident solar radiation on the metal fin. This absorbed thermal energy is transferred to the working fluid passing through the U-shaped tube, and it is heated.

The outlet of the first ETC (T_{f01}) is connected to the inlet of the second ETC, and so on, to obtain the desired greater temperature as shown in Fig. 4.22.

The energy balance equation can be given as follows:

$$\alpha\tau^2 I(t)(2R)dx = [F'h_{pf}(T_p - T_f) + U_{t,pa}(T_p - T_a)](2R)dx \quad (4.5.52)$$

where α absorptivity; τ transmissivity; $I(t)$ solar intensity; R outer radius of the glass tube (m); F' collector-efficiency factor; h_{pf} heat-transfer coefficient from the

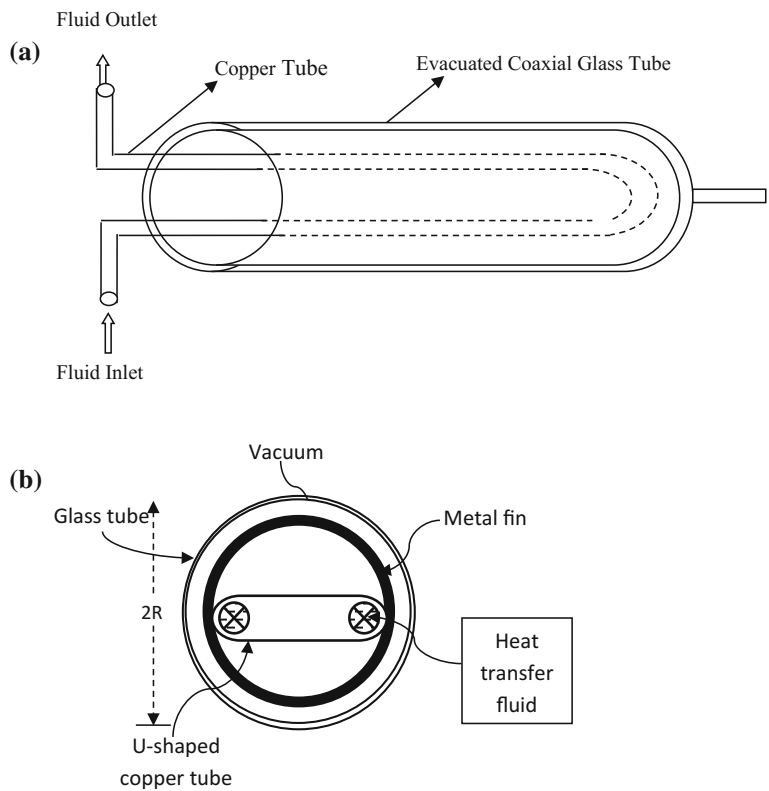


Fig. 4.21 a Elevated view and b cross-section view of evacuated tubular collector

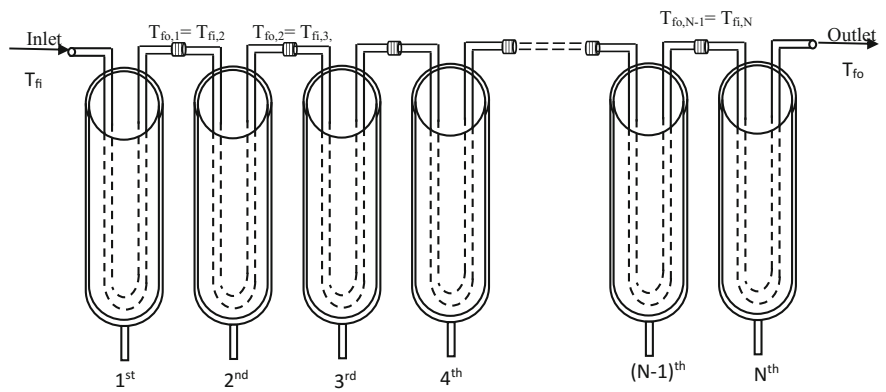


Fig. 4.22 N -Evacuated tubular collectors (ETC) connected in series [9]

blackened plate to the water ($\text{W/m}^2 \text{ } ^\circ\text{C}$); T_p plate temperature ($^\circ\text{C}$); T_f fluid temperature ($^\circ\text{C}$); T_a ambient temperature ($^\circ\text{C}$); and $U_{t,pa}$ overall heat-transfer coefficient from the absorber plate to the ambient through the glass cover ($\text{W/m}^2 \text{ } ^\circ\text{C}$).

$$\dot{m}_f C_f \frac{dT_f}{dx} = F' h_{pf} (T_p - T_f) (2\pi r) dx \quad (4.5.53)$$

where $\dot{m}_f$ mass-flow rate (kg/s); C_f is specific heat of water (J/kg K); and r radius of the U-shaped copper tube (m).

From Eq. (4.5.52),

$$T_p = \frac{\alpha\tau^2 I(t) + F' h_{pf} T_f + U_{t,pa} T_a}{F' h_{pf} + U_{t,pa}} \quad (4.5.54)$$

$$T_p - T_f = \frac{\alpha\tau^2 I(t) - U_{t,pa} (T_f - T_a)}{F' h_{pf} + U_{t,pa}} \quad (4.5.55)$$

$$h_{pf} (T_p - T_f) = \frac{h_{pf}}{F' h_{pf} + U_{t,pa}} \alpha\tau^2 I(t) - \frac{U_{t,pa} h_{pf}}{F' h_{pf} + U_{t,pa}} (T_f - T_a) \quad (4.5.56)$$

$$F' h_{pf} (T_p - T_f) = PF_1 \alpha\tau^2 I(t) - U_L (T_f - T_a) \quad (4.5.57)$$

where

$$PF_1 = \frac{h_{pf}}{F' h_{pf} + U_{t,pa}} \text{ and } U_L = \frac{U_{t,pa} h_{pf}}{F' h_{pf} + U_{t,pa}}$$

Substituting the values from Eq. (4.5.57) in Eq. (4.5.53), one can obtain the following:

$$\dot{m}_f C_f \frac{dT_f}{dx} = (2\pi r) [PF_1 \alpha\tau^2 I(t) - U_L (T_f - T_a)] \quad (4.5.58)$$

On integrating Eq. (4.5.58) under the boundary conditions at $x = 0$; $T_f = T_{fi}$ and at $x = L$; $T_f = T_{fo1}$, one can obtain the following:

$$T_{fo1} = \left[\frac{PF_1 \alpha\tau^2 I(t)}{U_L} + T_a \right] \left[1 - \exp\left(-\frac{2\pi r L U_L}{\dot{m}_f C_f}\right) + T_{fi} \exp\left(-\frac{2\pi r L U_L}{\dot{m}_f C_f}\right) \right] \quad (4.5.59)$$

where T_{fo1} is the outlet temperature from one (the first) collector unit

$$T_{fo1} = \frac{PF_1 \alpha \tau^2 I(t)}{U_L} \times \frac{\dot{m}_f C_f}{U_L} \left[1 - \exp\left(-\frac{2\pi r L U_L}{\dot{m}_f C_f}\right) \right] + \frac{T_a U_L}{\dot{m}_f C_f} \times \frac{\dot{m}_f C_f}{U_L} \left[1 - \exp\left(-\frac{2\pi r L U_L}{\dot{m}_f C_f}\right) \right] + T_{fi} \exp\left(-\frac{2\pi r L U_L}{\dot{m}_f C_f}\right) \quad (4.5.60)$$

Let

$$\frac{\dot{m}_f C_f}{U_L A_R} \left[1 - \exp\left(-\frac{2\pi r L U_L}{\dot{m}_f C_f}\right) \right] = F_R \quad (4.5.61)$$

$$T_{fo1} = (PF_1 \alpha \tau^2 A_R F_R) \left(\frac{I(t)}{\dot{m}_f C_f} \right) + (A_R F_R U_L) \left(\frac{T_a}{\dot{m}_f C_f} \right) + T_{fi} \left(1 - \frac{A_R F_R U_L}{\dot{m}_f C_f} \right) \quad (4.5.62)$$

or

$$T_{fo1} = \frac{(AF_R \alpha \tau)_1}{\dot{m}_f C_f} I(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} T_a + K_K T_{fi} \quad (4.5.63)$$

where $(PF_1 \alpha \tau^2 A_R F_R) = (AF_R \alpha \tau)_1$ and $K_K = 1 - \frac{A_R F_R U_L}{\dot{m}_f C_f}$.

In a similar way,

$$T_{fo2} = \frac{(AF_R \alpha \tau)_1}{\dot{m}_f C_f} I(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} T_a + K_K T_{fo1} \quad (4.5.64)$$

Substituting the value of T_{fo1} from Eq. (4.5.63) into Eq. (4.5.64), one can obtain the following:

$$T_{fo2} = \left[\frac{(AF_R \alpha \tau)_1}{\dot{m}_f C_f} \right] \left[\frac{1 - K_K^2}{1 - K_K} \right] I(t) + \left[\frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right] \left[\frac{1 - K_K^2}{1 - K_K} \right] T_a + K_K^2 T_{fi} \quad (4.5.65)$$

In a similar way, the outlet temperature of the third collector can be obtained as follows:

$$T_{fo2} = \left[\frac{(AF_R \alpha \tau)_1}{\dot{m}_f C_f} \right] \left[\frac{1 - K_K^3}{1 - K_K} \right] I(t) + \left[\frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right] \left[\frac{1 - K_K^3}{1 - K_K} \right] T_a + K_K^3 T_{fi} \quad (4.5.66)$$

In a similar way, the outlet temperature from the N th collector can be obtained as follows:

$$T_{foN} = \left[\frac{(AF_R \alpha \tau)_1}{\dot{m}_f C_f} \right] \left[\frac{1 - K_K^N}{1 - K_K} \right] I(t) + \left[\frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right] \left[\frac{1 - K_K^N}{1 - K_K} \right] T_a + K_K^N T_{fi} \quad (4.5.67)$$

The rate of useful-heat output from an N-ETC connected in series can be given as follows:

$$\begin{aligned}
 \dot{Q}_{u,N} &= \dot{m}_f C_f (T_{foN} - T_{fi}) \\
 &= (AF_R \alpha \tau)_1 \left[\frac{1 - K_K^N}{1 - K_K} \right] I(t) + (AF_R U_L)_1 \left[\frac{1 - K_K^N}{1 - K_K} \right] T_a + (K_K^N - 1) \dot{m}_f C_f T_{fi} \\
 &= (AF_R \alpha \tau)_1 \left[\frac{1 - K_K^N}{1 - K_K} \right] I(t) - \left[(1 - K_K^N) \dot{m}_f C_f T_{fi} - (AF_R U_L)_1 \left[\frac{1 - K_K^N}{1 - K_K} \right] T_a \right]
 \end{aligned} \tag{4.5.68}$$

or

$$\dot{Q}_{u,N} = (\alpha \tau)_{\text{eff}} I(t) - (UA)_{\text{eff}} (T_{fi} - T_a) \tag{4.5.69}$$

After knowing rate of useful thermal-energy gain ($\dot{Q}_{u,N}$) from Eq. (4.5.69), the instantaneous thermal efficiency of an evacuated tubular collector can be defined as follows:

$$\eta_i = \frac{\dot{Q}_{u,N}}{NA_c I(t)} \tag{4.5.70}$$

The hourly variation of the outlet-fluid temperature for a series-connected different number of evacuated tubular collators at a mass-flow rate of 0.002 kg/s is shown in Fig. 4.23. It was perceived that the maximum outlet temperature upturns from 53.91 to 129.23 °C with an increase in the number of collector from $N = 2$ to $N = 6$. The variation of temperature difference between the inlet and outlet with the number of collectors (2–20) and mass-flow rate (0.002, 0.006 and 0.010 kg/s) is shown in Fig. 4.24. For a mass-flow rate of 0.002 kg/s, the temperature difference increases from 55.52 to 133.29 °C as the number of collectors increases from $N = 2$ to $N = 12$. After this value ($N = 12$), it becomes almost constant. Using this curve, the mass-flow rate and the number of collectors can be fixed for a desired temperature difference, which is useful for designing the ETC system for a given capacity. The variation of instantaneous efficiency is presented in Fig. 4.25.

Example 4.4 Calculate the outlet-water temperature and rate of useful thermal energy of three evacuated tubular collectors (ETC) connected in series for a mass-flow rate of ($\dot{m}_f$) of 0.01 kg/s. Use the following design and climatic parameters:

$$\begin{aligned}
 r &= 0.0125 \text{ m}, R = 0.125, L = 2.0 \text{ m}, C_f = 4179 \text{ J/Kg K}, T_a = 25^\circ \text{C}, T_w = 28^\circ \text{C}, I_c(t) = \\
 &500 \text{ W/m}^2, F' = 0.986, h_{pf} = 100 \text{ W/m}^2, L_g = 0.0005 \text{ m}, K_g = 1.09 \text{ W/m K}, U_{t,pa} = \\
 &3.56 \text{ W/m K}^2, \tau = 0.95, \alpha = 0.8, \text{Inclination} = 30^\circ.
 \end{aligned}$$

Solution

(a) From Eq. (4.5.67),

$$\begin{aligned}
 T_{foN} &= \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left(\frac{1 - K_K^N}{1 - K_K} \right) I_c(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left(\frac{1 - K_K^N}{1 - K_K} \right) T_a + T_{fi} K_K^N \\
 U_L &= \frac{h_{pf} U_{t,pa}}{(F' h_{pf} + U_{t,pa})} = 3.48 \text{ W/m}^2 \text{ K} \\
 A_R F_R U_L &= \dot{m}_f C_f \left[1 - \exp \left(-\frac{2\pi r L U_L}{\dot{m}_f C_f} \right) \right] = 41.79 [1 - \exp(-0.013)] = 0.54 \\
 K_K &= 1 - \frac{(A_R F_R U_L)}{\dot{m}_f C_f} = 0.987; (A_R F_R U_L)_1 = (1 - K_K) \dot{m}_f C_f = 0.543 \\
 (PF_1)_{et} &= \frac{h_{pf}}{(F' h_{pf} + U_{t,pa})} = 0.978 \quad \text{and} \quad (AF_R \alpha\tau)_1 = (PF_1)_{et} \alpha\tau^2 A_R F_R = 0.11
 \end{aligned} \tag{i}$$

Hence, from Eq. (i), for three identical evacuated tubular water collectors the outlet-water temperature at the end of the third evacuated tubular water collector is as follows:

$$\begin{aligned}
 T_{fo3} &= \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left(\frac{1 - K_K^3}{1 - K_K} \right) I_c(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left(\frac{1 - K_K^3}{1 - K_K} \right) T_a + T_{fi} K_K^3 \\
 &= 3.83 + 1.062 + 27
 \end{aligned}$$

Therefore, $T_{fo3} = 32^\circ \text{C}$

(b) From Eq. (4.5.68), the rate of useful thermal-energy transfer is as follows:

$$\begin{aligned}
 \dot{Q}_{uth,N} &= (\alpha\tau)_{\text{eff}} I_c(t) - (UA)_{\text{eff}} (T_{fi} - T_a) \\
 (\alpha\tau)_{\text{eff}} &= (AF_R(\alpha\tau))_1 \left(\frac{1 - K_K^3}{1 - K_K} \right) = 0.321 \quad \text{and} \quad (UA)_{\text{eff}} = (A_R F_R U_L)_1 \left(\frac{1 - K_K^3}{1 - K_K} \right) = 1.58
 \end{aligned} \tag{ii}$$

Therefore, from Eq. (ii) $\dot{Q}_{uth,3} = (\alpha\tau)_{\text{eff}} I_c(t) - (UA)_{\text{eff}} (T_{fi} - T_a) = 0.155 \text{ kWh}$

Example 4.5 Calculate the outlet-water temperature and rate of useful thermal energy of three evacuated tubular collectors (ETC) connected in series for a mass-flow rate of ($\dot{m}_f$) of 0.002 kg/s. Use the design and climatic parameters given in Example 4.4.

Solution

$$(a) \quad T_{foN} = \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left(\frac{1 - K_K^N}{1 - K_K} \right) I_c(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left(\frac{1 - K_K^N}{1 - K_K} \right) T_a + T_{fi} K_K^N \quad (i)$$

$$U_L = \frac{h_{pf} U_{t,pa}}{(F' h_{pf} + U_{t,pa})} = 3.48 \text{ W/m}^2 \text{ K}$$

$$A_R F_R U_L = \dot{m}_f C_f \left[1 - \exp \left(- \frac{2\pi r L U_L}{\dot{m}_f C_f} \right) \right] = 8.35 [1 - \exp(-0.065)] = 0.53$$

$$K_K = 1 - \frac{(A_R F_R U_L)}{\dot{m}_f C_f} = 0.94; (A_R F_R U_L)_1 = (1 - K_K) \dot{m}_f C_f = 0.50$$

$$(PF_1)_{et} = \frac{h_{pf}}{(F' h_{pf} + U_{t,pa})} = 0.978$$

$$\text{Therefore; } (AF_R \alpha \tau)_1 = (PF_1)_{et} \alpha \tau^2 A_R F_R = 0.11$$

Hence, from Eq. (i), for three identical evacuated tubular water collectors the outlet-water temperature at the end of the third evacuated tubular water collectors is as follows:

$$\begin{aligned} T_{fo3} &= \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left(\frac{1 - K_K^3}{1 - K_K} \right) I_c(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left(\frac{1 - K_K^3}{1 - K_K} \right) T_a + T_{fi} K_K^3 \\ &= 18.5 + 4.4 + 23.3 \\ T_{fo3} &= 46.1^\circ \text{C} \end{aligned}$$

(b) The rate of useful thermal-energy transfer is as follows:

$$\begin{aligned} \dot{Q}_{uth,N} &= (\alpha\tau)_{\text{eff}} I_c(t) - (UA)_{\text{eff}} (T_{fi} - T_a) \\ (\alpha\tau)_{\text{eff}} &= (AF_R(\alpha\tau))_1 \left(\frac{1 - K_K^3}{1 - K_K} \right) = 0.31 \text{ and } (UA)_{\text{eff}} = (A_R F_R U_L)_1 \left(\frac{1 - K_K^3}{1 - K_K} \right) = 1.4 \end{aligned} \quad (ii)$$

Therefore, from Eq. (ii); $\dot{Q}_{uth,3} = (\alpha\tau)_{\text{eff}} I_c(t) - (UA)_{\text{eff}} (T_{fi} - T_a) = 0.150 \text{ kWh}$
Problems and descriptive questions

- 4.1 Calculate the outlet-water temperature and rate of useful thermal energy of five series-connected photovoltaic thermal flat-plate collectors (PVT-FPCs) for a mass-flow rate ($\dot{m}_f$) of 0.01 kg/s. Use the design and climatic parameters given in Example 5.1.

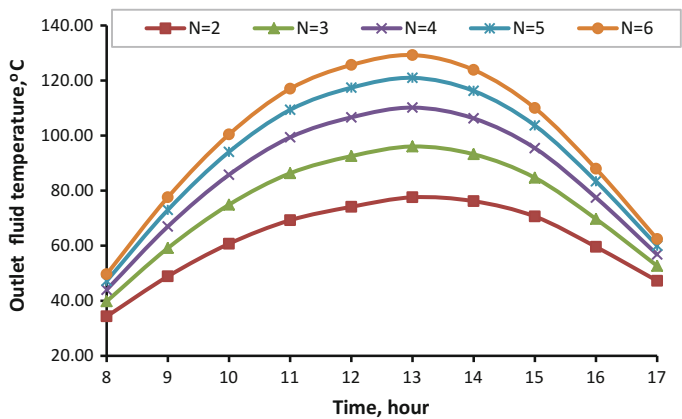


Fig. 4.23 Hourly variation of outlet fluid temperature by varying the number of ETC (N) connected in series ($\dot{m}_f = 0.002$ kg/s)

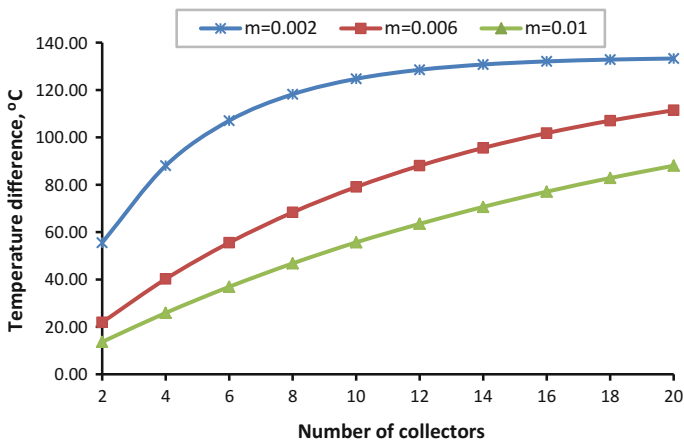


Fig. 4.24 Variation of temperature difference (ΔT , between inlet and outlet) by varying the number of collectors and mass flow rate

- 4.2 Calculate the outlet-water temperature and rate of useful thermal energy of three series-connected photovoltaic thermal compound-parabolic concentrators (PVT-CPCs) connected in series for a mass-flow rate ($\dot{m}_f$) of 0.001 kg/s. Use the design and climatic parameters given in Example 5.3.
- 4.3 Calculate the outlet-water temperature and rate of useful thermal energy of five photovoltaic thermal compound-parabolic concentrators (PVT-CPC)

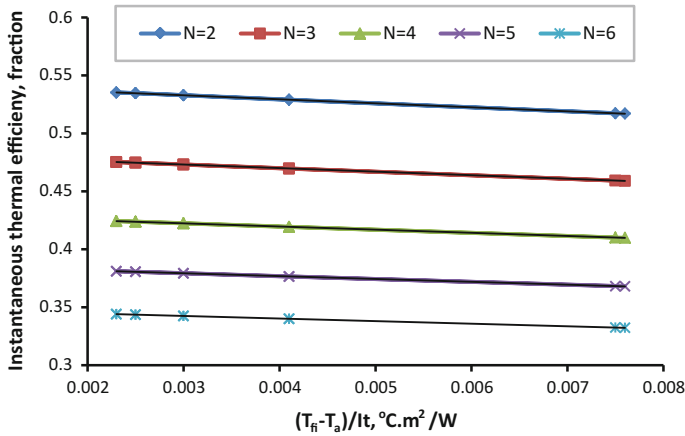


Fig. 4.25 Hourly variation of instantaneous efficiency with reduced temperature $((T_{fi} - T_a)/I(t))$ by varying the N number of ETCs connected in series

connected in series for a mass-flow rate ($\dot{m}_f$) of 0.012 kg/s. Use the design and climatic parameters given in Example 5.3.

- 4.4 Calculate the outlet-water temperature and rate of useful thermal energy of five photovoltaic thermal compound-parabolic concentrators (PVT-CPC) connected in series for a mass-flow rate ($\dot{m}_f$) of 0.05 kg/s. Use the design and climatic parameters given in Example 5.4.
- 4.5 Calculate the outlet-water temperature and rate of useful thermal energy of three photovoltaic thermal compound-parabolic concentrators (PVT-CPC) connected in series for

(a) $\dot{m}_f = 0.002 \text{ kg/s}$, $\frac{A_{pc}}{A_{ac}} = 0$, $\frac{A_{am}}{A_{rm}} = 1.5$

(b) $\dot{m}_f = 0.002 \text{ kg/s}$, $\frac{A_{pc}}{A_{ac}} = 0.7$, $\frac{A_{am}}{A_{rm}} = 0$

Use the rest of the design and climatic parameters given in Example 5.4.

- 4.6 Discuss the following in brief with suitable diagrams:

- (a) Photovoltaic thermal flat-plate collector (PVT-FPC)
- (b) Photovoltaic thermal compound-parabolic concentrator (PVT-CPC)
- (c) Evacuated tubular collector

- 4.7 Derive an expression for the outlet-water temperature at the N th flat-plate collector for the following cases:

- (a) Lower portion of a flat-plate collector covered with a semitransparent PV module
- (b) Upper portion of a flat-plate collector covered with a semitransparent PV module

- 4.8 Discuss the special cases, $A_m = 0$, and $A_c = 0$ for Problem 4.2.
- 4.9 Derive an expression for the outlet-water temperature at the N th compound parabolic concentrator having the lower portion partially covered with a semitransparent PV module.
- 4.10 Derive an expression for the outlet water temperature at the N th evacuated tubular collector.

Objective questions

- 4.1 Window glass transmits the radiation of wavelength between:
 - (a) $0.3 < \lambda < 3 \mu\text{m}$
 - (b) $0 < \lambda < 0.3 \mu\text{m}$
 - (c) $3 < \lambda < 10 \mu\text{m}$
 - (d) None of these
- 4.2 An absorber emits radiation of the wavelength:
 - (a) $0.3 < \lambda < 3 \mu\text{m}$
 - (b) $0 < \lambda < 0.3 \mu\text{m}$
 - (c) $3 < \lambda < 10 \mu\text{m}$
 - (d) None of these
- 4.3 window glass does not allow transmission of the following:
 - (a) Short-wavelength radiation
 - (b) UV radiation
 - (c) Infrared radiation
 - (d) Long-wavelength radiation
- 4.4 The transmittance of window glass depends on the following:
 - (a) Reflectivity
 - (b) Number of glass
 - (c) Incidence angle
 - (d) All of these
- 4.5 The transmittance of window glass is maximum for the following:
 - (a) Zero angle of incidence
 - (b) 90° -angle of incidence
 - (c) Angle of incidence at latitude (ϕ)
 - (d) None of these
- 4.6 The total heat loss (U) in a double-glazed flat-plate collector (FPC) is:
 - (a) Increased
 - (b) Unaffected
 - (c) Decreased
 - (d) None of these

- 4.7 The outlet temperature in a double-glazed FPC:
- (a) Decreases
 - (b) Is unaffected
 - (c) Increases
 - (d) None of these
- 4.8 For natural circulation, flat-plate collectors are connected in:
- (a) Series
 - (b) Parallel
 - (c) series and parallel
 - (d) None of these
- 4.9 For a forced-circulation solar water heater, the flat-plate collectors are connected in:
- (a) Only in parallel
 - (b) Only in series
 - (c) In both series and parallel
 - (d) A combination of all of these
- 4.10 The annually optimum inclination of a flat-plate collector condition is:
- (a) $\phi + 15$ latitude
 - (b) $\phi - 15$
 - (c) ϕ (latitude)
 - (d) none
- 4.11 The optimum inclination of flat-plate collector for summer condition is
- (a) $\phi - 15$
 - (b) $\phi + 15$
 - (c) ϕ (latitude)
 - (d) All of these
- 4.12 The concentration ratio is maximum in the case of:
- (a) A flat-plate collector
 - (b) An air heater
 - (c) An evacuated collector
 - (d) A concentrator
- 4.13 The concentration ratio for a concentrator is:
- (a) >1
 - (b) <1
 - (c) $=1$
 - (d) None of these

- 4.14 The absorber temperature in the case of a concentrator is:
- (a) more than that of a flat-plate collector
 - (b) less than that of flat-plate collector
 - (c) equal to that of a flat-plate collector
 - (d) None of these
- 4.15 The fluid used in a concentrator has a:
- (a) high boiling temperature
 - (b) low boiling temperature
 - (c) less-than-boiling temperature of water
 - (d) equal to the boiling temperature of water
- 4.16 The optical efficiency of a concentrator is:
- (a) Less than thermal efficiency
 - (b) More than thermal efficiency
 - (c) Equal to thermal efficiency
 - (d) None of these
- 4.17 The outlet-fluid temperature of a concentrator is:
- (a) less than that of a flat-plate collector
 - (b) more than that of flat-plate collector
 - (c) equal to that of flat-plate collector
 - (d) None of these
- 4.18 In a concentrator, the use of insulation is negligible compared with
- (a) A flat-plate collector
 - (b) An air heater
 - (c) An evacuated tubular collector
 - (d) All of these
- 4.19 The rate of useful energy is maximum for:
- (a) Without tracking
 - (b) With tracking
 - (c) Horizontal absorber
 - (d) None of these
- 4.20 The absorber of a concentrating collector is:
- (a) Selective
 - (b) Normal
 - (c) Blackened
 - (d) None of these

- 4.21 The convective heat loss between the absorber and glass cover is decreased by:
- (a) Using fins
 - (b) Creating a vacuum
 - (c) Selective coating
 - (d) None of these
- 4.22 The radiative heat loss between the absorber and glass cover is decreased by:
- (a) Using selective coating
 - (b) Using a vacuum
 - (c) Using fins
 - (d) None of these
- 4.23 The vacuum between the absorber and the glass cover can be maintained only in:
- (a) A flat-plate collector
 - (b) A concentrating collector
 - (c) A tubular collector
 - (d) None of these
- 4.24 The outlet-fluid temperature is maximum in:
- (a) A flat-plate collector
 - (b) An evacuated tubular collector
 - (c) a fin-type flat-plate collector
 - (d) None of these
- 4.25 The instantaneous thermal efficiency of an evacuated tubular collector at greater operating temperature is:
- (a) Greater than that of a flat-plate collector
 - (b) Lower than that of a flat-plate collector
 - (c) Equal to that of a flat-plate collector
 - (d) None of these
- 4.26 The absorber temperature in an evacuated tubular collector is:
- (a) lower than that of a concentrating collector
 - (b) greater than that of a unglazed flat-plate collector
 - (c) greater than that of a glazed flat-plate collector
 - (d) All of these

Answers

- 4.1 (a) 4.2 (c) 4.3 (d) 4.4 (d) 4.5 (b) 4.6 (c) 4.7(c) 4.8 (b) 4.9 (d) 4.10 (c) 4.11 (a) 4.12 (d) 4.13(a) 4.14(a) 4.15 (a) 4.16 (b) 4.17 (b) 4.18 (d) 4.19 (b) 4.20 (a) 4.21 (b) 4.22(a) 4.23 (c) 4.24 (b) 4.25 (b) 4.26 (c)

References

1. G.N. Tiwari, *Solar Energy: Fundamentals, Designs, Modeling and Applications* (Narosa Publishing House, New Delhi, 2002)
2. Shyam, G.N. Tiwari, I.M. Al-Helal, Analytical expression of temperature dependent electrical efficiency of N-PVT water collectors connected in series. *Sol. Energy* **114**, 61–76 (2015)
3. J.A. Duffie, W. Beckman, *Solar engineering of thermal processes* (Wiley, New York, 1991)
4. S. Dubey, G.N. Tiwari, Analysis of PV/T flat plate water collectors connected in series. *Sol. Energy* **83**, 1485–1498 (2009)
5. D.L. Evans, Simplified method for predicting PV array output. *Sol. Energy* **27**, 555–560 (1981)
6. G.N. Tiwari, R.K. Mishra, *Advanced Renewable Energy Sources* (RSC Publishing Cambridge, UK, 2012)
7. R. Tripathi, G.N. Tiwari, I.M. Al-Helal, Thermal modelling of N partially covered photovoltaic thermal (PVT)—compound parabolic concentrator (CPC) collectors connected in series. *Sol. Energy* **123**, 174–184 (2016)
8. D. Atheaya, A. Tiwari, G.N. Tiwari, I.M. Al-Helal, Analytical characteristic equation for partially covered photovoltaic thermal (PVT) compound parabolic concentrator (CPC). *Sol. Energy* **111**, 176–185 (2015)
9. R.K. Mishra, V. Garg, G.N. Tiwari, Thermal modeling and development of characteristic equations of evacuated tubular collectors (ETC). *Sol. Energy* **116**, 165–176 (2015)

Chapter 5

Thermal Modeling of Active Solar-Distillation Systems

5.1 Introduction

The efficiency of a solar still can be enhanced with a forced-circulation mode of operation. In this mode, the temperature of water in the still can be increased. Consequently, the temperature difference between the water and the inner surface of the transparent glass cover can be increased, which increases the heat-transfer rate from the water surface.

Soliman [1] suggested the concept of feeding hot water into the basin from a solar-collector panel (high-temperature solar distillation) in 1976. Worldwide, many researchers [2–12] have theoretically and experimentally studied different active solar-distillation systems.

Either a conventional or a non-conventional external source of energy is required to increase the water temperature. The forced mode of operation is achieved by using a pump, which can further run either by a conventional source of energy (electricity) or a non-conventional source of energy (photovoltaic [PV]). Therefore, grid electricity as a power source was supplied for the forced mode in a conventional solar thermal collector. Both electrical and thermal energy, in the case of a hybrid photovoltaic thermal (PVT) system, is generated by the PVT collector itself. However, the photovoltaic (PV) systems convert incident solar radiation into electrical energy, but the thermal energy absorbed has been unexploited [13]. Conventional solar thermal systems can be integrated with the photovoltaic cells/module and PVT systems to maximize the energy gain. Therefore, a solar still integrated with solar thermal technology—e.g., a flat-plate collector (FPC), an evacuated tubular collector (ETC), and a compound parabolic concentrator (CPC)—and photovoltaic technology makes the solar still fully dependent on a renewable source of energy. Integration of a solar still with solar thermal technology and photovoltaic technology to fulfill the external energy requirement makes it a “PVT active solar still.”

The external thermal energy can be feed into the basin of the solar still by integrating different PVT systems. For this chapter, a conventional solar still coupled with (a) PVT flat-plate collectors (FPC), (b) PVT compound parabolic concentrators (CPC), and (c) evacuated tubular collectors (ETC) were studied analytically. Moreover, the expression of basin-water temperature is derived for all of these active solar-distillation systems.

5.2 Solar Still Integrated with *N*-Photovoltaic Thermal Partially Covered Flat-Plate Collectors (N-PVT-FPC)

To determine the performance of a flat-plate collector (FPC), the essential factor is heat loss by convection. As discussed in Chap. 4, the flat-plate collector (FPC) is at the heart of any solar energy-collection system designed for operation in a low or medium temperature range. The main function of the FPC is to convert absorbed solar energy into heat and transfer it into a stream of fluid. The diagram of the system is shown in Fig. 5.1.

The water is circulated through the series-connected *N*-photovoltaic thermal partially covered flat-plate collectors, and its outlet is connected to the single-slope

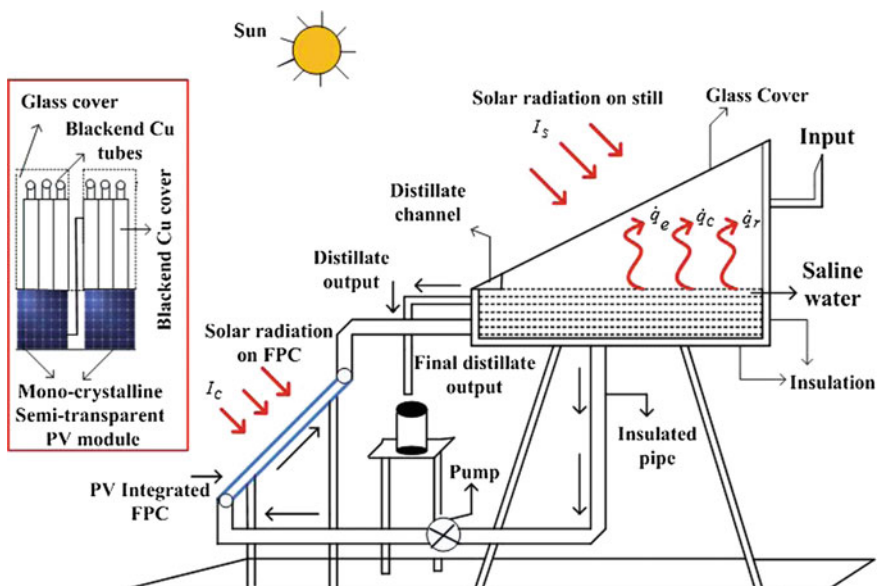


Fig. 5.1 Schematic view of an active solar still coupled with a flat plate collector

solar still. The rate of useful thermal energy ($\dot{Q}_{\text{uth},N}$) of *N*-PVT-FPC collectors (Eq. 4.3.16) is added to the thermal energy of the basin-water mass in the still.

The following assumptions are taken into account in writing the energy balance of an active solar still:

- (a) All processes in the system are in a quasi-steady state.
- (b) There is no temperature stratification between the layers of fluid in the system.
- (c) The heat capacity of the absorbing material, the insulation (bottom and sides), and the top transparent-glass cover is negligible.
- (d) The system is vapor-leakage proof.

The energy-balance equations of different components of an *N*-photovoltaic thermal partially covered flat-plate collector (PVT-FPC) connected in series integrated to a single-slope solar still are as follows:

(a) **Inner glass cover**

$$\alpha'_g I(t) A_g + h_1 (T_w - T_{gi}) A_g = \frac{K_g}{L_g} (T_{gi} - T_{go}) A_g \quad (5.2.1)$$

where α'_g —absorptivity of the glass; $I(t)$ —solar intensity (W/m^2); A_g —area of the glass cover (m^2); $h_1 (=h_{ew} + h_{cw} + h_{rw})$ —total internal heat-transfer coefficient from the water to the glass; h_{ew} , h_{cw} , h_{rw} , respectively, are the evaporative, convective, and radiative heat-transfer coefficients from the water surface; T_w —basin-water temperature ($^{\circ}\text{C}$); T_{gi} —temperature of inner surface of the glass cover ($^{\circ}\text{C}$); T_{go} —temperature of the outer surface of the glass cover ($^{\circ}\text{C}$); K_g —thermal conductivity of the glass cover; and L_g —the thickness of the glass cover (m).

(b) **Outer glass cover**

$$\frac{K_g}{L_g} (T_{gi} - T_{go}) A_g = h_2 (T_{go} - T_a) A_g \quad (5.2.2)$$

where T_a —ambient temperature ($^{\circ}\text{C}$); $h_2 (=h_{cg} + h_{rg})$ —total external heat-transfer coefficient from the glass surface to the ambient; and h_{rg} and h_{cg} are the radiative and convective heat-transfer coefficients, respectively, from the glass surface to the ambient.

(c) **Water mass**

$$\alpha'_w I(t) A_b + h_3 (T_b - T_w) A_b + \dot{Q}_{\text{uth},N} = M_w C_w \frac{dT_w}{dt} + h_1 (T_w - T_{gi}) A_b \quad (5.2.3)$$

where α'_w —absorptivity of water; A_b —basin area of the solar still (m^2); T_b —basin temperature; $h_3 (=h_w)$ —natural convective heat-transfer coefficient from

the basin liner to the water; C_w —specific heat of water; and $J/kg\ K$, M_w —mass of basin water in the solar still (kg).

(d) **Basin liner**

$$\alpha'_b I(t) A_b = h_3 (T_b - T_w) A_b = h_b (T_b - T_a) (A_b + A_s) \quad (5.2.4)$$

where A_s —area of the sides of the solar still (m^2); and h_b is the heat-transfer coefficient of the basin liner.

It can be noted that the above-mentioned energy-balance equations (Eqs. 5.2.1–5.2.4) of active single-slope solar still become the energy-balance equations for a passive single-slope solar still on substituting $\dot{Q}_{\text{uth},N}$ equal to zero.

On solving Eq. (5.2.1) for T_{go} and Eq. (5.2.2) for T_{gi} , one can obtain:

$$T_{go} = \frac{\left[\left(\frac{K_g}{L_g} \right) T_{gi} + h_2 T_a \right]}{\left[\frac{K_g}{L_g} + h_2 \right]} \quad (5.2.5)$$

$$T_{gi} = \frac{\left[\alpha'_g I(t) + h_1 T_w + \left(\frac{K_g}{L_g} \right) T_{go} \right]}{\left[\frac{K_g}{L_g} + h_1 \right]} \quad (5.2.6)$$

On solving Eqs. (5.2.5) and (5.2.6), one can obtain:

$$T_{gi} = \frac{\left[\alpha''_g I(t) + h_1 T_w + T_a U'_{g,a} \right]}{\left[U'_{g,a} + h_1 \right]} \quad (5.2.7)$$

where $\alpha''_g = \alpha'_g \frac{A_g}{A_b}$; $U_{g,a} = \left(\frac{K_g}{L_g} h_2 \right) / \left(\frac{K_g}{L_g} + h_2 \right)$ and $U'_{g,a} = U_{g,a} \left(\frac{L_g}{K_g} \right)$

$$h_1 (T_w - T_{gi}) = \frac{h_1 \left[(T_w - T_a) U'_{g,a} - \alpha''_g I(t) \right]}{\left[h_1 + U'_{g,a} \right]} \quad (5.2.8)$$

$$h_1 (T_w - T_{gi}) = \left[(T_w - T_a) U_{12} - \alpha''_g I(t) C_1 \right]$$

$$C_1 = \frac{h_1}{h_1 + U'_{g,a}} \text{ and } U_{12} = \frac{h_1 U'_{g,a}}{h_1 + U'_{g,a}}$$

Similarly, on solving (5.2.4) for $h_3 (T_b - T_w)$, one can obtain:

$$h_3(T_b - T_w) = C_2 \alpha'_b I(t) + U_{3b}(T_a - T_w) \quad (5.2.9)$$

where $C_2 = \frac{h_3}{h_3 + h'_b}$, $U_{3b} = \frac{h_3 h'_b}{h_3 + h'_b}$, and $h'_b = h_b \left(1 + \frac{A_s}{A_b}\right)$

From Eq. (4.3.16) in Chap. 4, the rate of useful thermal energy of a partially covered N -photovoltaic thermal flat-plate collector (N -PVT-FPC) connected in series is expressed as follows:

$$\dot{Q}_{\text{uth},N} = N(A_c + A_m) \left[(\alpha\tau)_{\text{eff},N} I_c(t) - U_{L,N}(T_{\text{fi}} - T_a) \right] \quad (5.2.10)$$

$$\begin{aligned} (\alpha\tau)_{\text{eff},N} &= \frac{(AF_R(\alpha\tau))_1}{(A_c + A_m)} \left[\frac{1 - (1 - K_{k,A})^N}{NK_{k,A}} \right]; \quad U_{L,N} = \frac{(AF_R U_L)_1}{(A_c + A_m)} \left[\frac{1 - (1 - K_{k,A})^N}{NK_{k,A}} \right]; \\ K_{k,A} &= \left[\frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right] \end{aligned}$$

Therefore, on substituting the values of $\dot{Q}_{\text{uth},N}$, $h_1(T_w - T_{\text{gi}})$, and $h_3(T_b - T_w)$ from Eqs. (5.2.10), (5.2.8), and (5.2.9), respectively, in Eq. (5.2.3) one can obtain:

$$\begin{aligned} &\alpha'_w I(t) A_b + [C_2 \alpha'_b I(t) + U_{3b}(T_a - T_w)] A_b + [N(A_c + A_m) \left[(\alpha\tau)_{\text{eff},N} I_c(t) - U_{L,N}(T_w - T_a) \right]] \\ &= M_w C_w \frac{dT_w}{dt} + [U_{12}(T_w - T_a)] A_b - \alpha''_g I(t) C_1 \\ M_w C_w \frac{dT_w}{dt} &+ [U_{3b} A_b + U_{12} A_b + N(A_c + A_m) U_{L,N}] T_w = [\alpha'_w A_b + C_2 \alpha'_b A_b + \alpha''_g C_1] I(t) \\ &+ [N(A_c + A_m) (\alpha\tau)_{\text{eff},N} I_c(t)] + T_a [U_{3b} A_b + U_{12} A_b + N(A_c + A_m) U_{L,N}] \\ \frac{dT_w}{dt} &+ \left[\frac{U + N(A_c + A_m) U_{L,N}}{M_w C_w} \right] T_w = \frac{[\alpha_{\text{eff}} I(t) + N(A_c + A_m) (\alpha\tau)_{\text{eff},N} I_c(t) + (U + N(A_c + A_m) U_{L,N})]}{M_w C_w} \\ \frac{dT_w}{dt} &+ a T_w = f(t) \end{aligned} \quad (5.2.11)$$

$$\text{where } a = \left[\frac{U + N(A_c + A_m) U_{L,N}}{M_w C_w} \right];$$

$$f(t) = \frac{[\alpha_{\text{eff}} I(t) + N(A_c + A_m) (\alpha\tau)_{\text{eff},N} I_c(t) + (U + N(A_c + A_m) U_{L,N})]}{M_w C_w}$$

$$\alpha_{\text{eff}} = \alpha'_w A_b + C_2 \alpha'_b A_b + \alpha''_g C_1;$$

$$U = U_{3b} A_b + U_{12} A_b (\alpha\tau)_{\text{eff},N} = \frac{(AF_R(\alpha\tau))_1}{(A_c + A_m)} \left[\frac{1 - (1 - K_{k,A})^N}{NK_{k,A}} \right];$$

$$U_{L,N} = \frac{(AF_R U_L)_1}{(A_c + A_m)} \left[\frac{1 - (1 - K_{k,A})^N}{NK_{k,A}} \right]; \quad K_{k,A} = \left[\frac{(AF_R U_L)_1}{\dot{m}_f C_f} \right]$$

Approximate solution for basin-fluid (water) temperature (T_f)

The following assumptions have been made:

- (a) The time interval Δt ($0 < t < \Delta t$) is small.
- (b) The function $f(t)$ is constant, i.e., $f(t) = \overline{f(t)}$ for the time interval Δt .
- (c) “ a ” is constant during the time interval Δt .

The value of h_{1f} can be determined by considering known values of water and glass temperatures at $t = 0$ i.e. $T_f(t = 0) = T_{f0}$ and $T_g(t = 0) = T_{g0}$.

The temperature of the basin water can be obtained by solving the above-mentioned first-order differential equation as follows:

$$T_w = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] + T_{w0} e^{-a\Delta t} \quad (5.2.12)$$

T_{w0} is the basin water temperature at $t = 0$ and $\overline{f(t)}$ is the average value of $f(t)$ for the time interval between 0 and t .

Average temperature of the water can be expressed as follows:

$$\overline{T_f} = \frac{1}{t} \int_0^t T_f dt = \frac{\overline{f(t)}}{a} \left[1 - \frac{(1 - e^{-a\Delta t})}{a} \right] + T_{f0} \frac{(1 - e^{-a\Delta t})}{a} \quad (5.2.12a)$$

The average glass temperature in terms of the water temperature can be obtained from Eq. (5.2.2) as given below:

$$\overline{T_{gi}} = \frac{\alpha_g I(t) + h_{1f} \overline{T_f} + h_{1g} \overline{T_a}}{h_{1f} + h_{1g}} \quad (5.2.12b)$$

The calculated values of T_f and T_g are used to evaluate the internal heat-transfer coefficient h_{1f} . The value of T_f at the end of an interval becomes the initial condition for the next interval and so on. The accuracy of the computation depends on the selected time interval, being high, for a smaller time interval. Usually the time interval taken is 1 h. The rate of evaporative heat loss and the hourly yield (productivity) of the solar still are given as follows:

$$\dot{q}_{ef} = h_{ef} (T_f - T_g) \quad (5.2.12c)$$

$$\dot{m}_{ef} = \frac{h_{ef} (T_f - T_g)}{L} \times 3600 \text{ kg/m}^2 \text{ h} \quad (5.2.12d)$$

where L is the latent heat of vaporization of the water [16].

For water:

$$L = 3.1625 \times 10^6 + [1 - (7.616 \times 10^{-4} \times (T_v))] \quad \text{for } T_v > 70^\circ\text{C} \quad (5.2.12e)$$

$$L = 2.4935$$

$$\times 10^6 [1 - (9.4779 \times 10^{-4} \times (T_v) + 1.3132 \times 10^{-7} \times (T_v^2) - 4.7974 \times 10^{-3} \times (T_v^3))] \\ \text{for } T_v < 70^\circ\text{C} \quad (5.2.12f)$$

where T_v is the vapor temperature.

In similar manner, one can evaluate the expression of the final basin-water temperature for series-connected (i) *N*-flat-plate collectors (FPC) that are fully covered with semitransparent PV modules ($A_C = 0$) as well as (ii) conventional *N*-flat-plate collectors ($A_m = 0$) integrated with a single-slope solar still. The expressions of T_{f0N} and $\dot{Q}_{\text{uth},N}$ to obtain the basin-water temperature for case (i) can be obtained on substituting $A_C = 0$, whereas for case (ii) these can be obtained on substituting $A_m = 0$.

Singh et al. [14] experimentally studied the performance of a single-slope solar still coupled with two partially covered PVT flat-plate collectors (PVT-FPC) and validated the results with thermal modeling of a solar still integrated with *N*-PVT-FPC (as discussed previously). The systematic view of an experimental set-up and a schematic top view of the system are shown in Fig. 5.2a, b, respectively.

The system consists of three main components viz. *N* identical partially covered PVT-CPC collectors (inclination 45°), a single-slope solar still (area $1 \text{ m} \times 1 \text{ m}$; and glass-cover inclination 30°), and a pump driven by a DC motor (18 V, 40 W and 2800 rpm). At the lower side of each flat-plate collector, a PV module having area of $0.55 \text{ m} \times 1.25 \text{ m}$ is fixed. The system was analyzed for the climatic condition of New Delhi (India) for a typical day in February (2014). The hourly variation of basin-water temperature, transparent glass-cover temperature, and yield of the system is presented in Fig. 5.3. The statistical parameters [coefficient of correlation (r) and mean-square percent deviation (e)] were evaluated, and good agreements were found between the experimental and theoretical results. Moreover, it should be pointed out that the yield of the system depends on the temperature difference between the basin water and that of the inner surface of the transparent glass cover; and ultimately it depends on the evaporative heat-transfer coefficient. Even at higher basin-water temperature, a lower yield can be obtained in case of greater ambient temperature because the transparent glass-cover temperature will also be greater, which results a lower temperature difference in the still cavity. The annual productivity was found to vary between 120.29 and 883.55%.

Figure 5.4 presents the characteristic curve of studied active solar still that shows a fair agreement between the experimental and theoretical results. For basin-water temperature, transparent glass-cover temperature, and yield, respectively, the percentage uncertainty was found to be 8.8, 9.8 and 0.73%, which suggests that the errors are within limits.

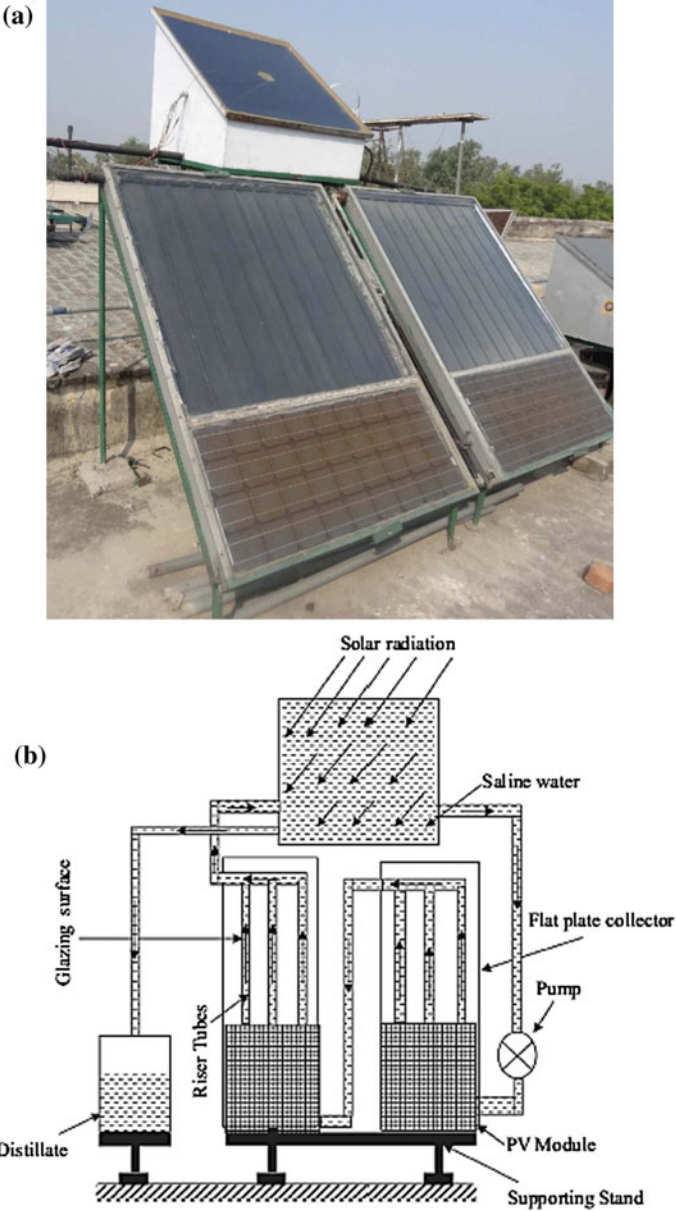


Fig. 5.2 **a** Experimental setup of solar still integrated with two partially covered PVT flat plate collectors. **b** Schematic top view of solar still coupled with partially covered PVT flat plate collectors

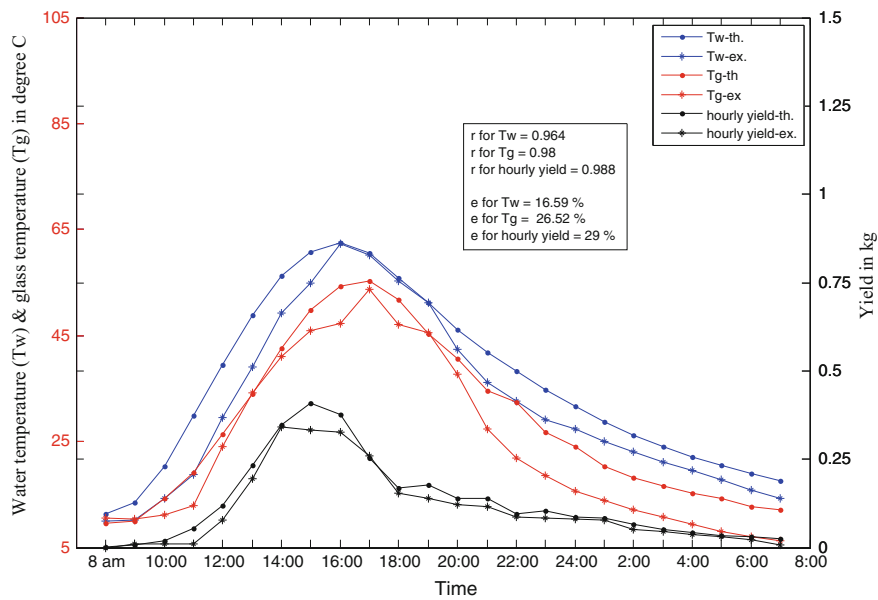


Fig. 5.3 Hourly variation of basin water temperature, toughen glass cover temperature and yield of the system a typical day of the month February (18–19, 2014)

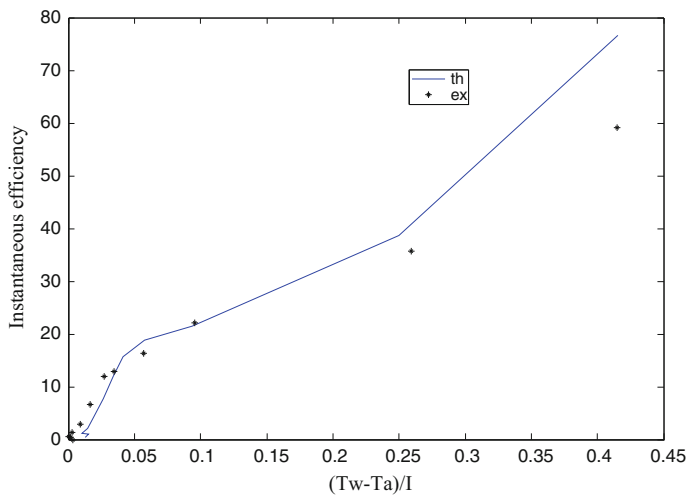


Fig. 5.4 Variation of instantaneous gain energy efficiency (characteristic curve) with reduced temperature of the system a typical day of the month February (18–19, 2014)

5.3 Solar Still Integrated with N-Evacuated Tubular Collectors (N-ETC)

The evacuated tubular collector is discussed in detail in Chap. 4. The outlet of the N evacuated tubular collectors connected in series is coupled to a single-slope solar still in a similar way to that as discussed in Sect. 5.2. The rate of useful thermal energy ($\dot{Q}_{\text{uth},N}$) of N evacuated tubular collectors (Eq. 4.5.69) is added to the thermal energy of basin-water mass in the solar still.

From Eq. (4.5.69) in Chap. 4, the expression of $\dot{Q}_{\text{uth},N}$ is given as follows:

$$\dot{Q}_{\text{uth},N} = (\alpha\tau)_{\text{eff}} I_c(t) - (UA)_{\text{eff}}(T_w - T_a) \quad (5.3.13)$$

where $I_c(t)$ —solar intensity received by the solar collector (W/m^2); T_w —basin-water temperature ($^{\circ}\text{C}$); and T_a —ambient temperature ($^{\circ}\text{C}$).

Where

$$(\alpha\tau)_{\text{eff}} = (AF_R(\alpha\tau))_1 \left(\frac{1 - K_K^N}{1 - K_K} \right) \text{ and } (UA)_{\text{eff}} = (A_R F_R U_L)_1 \left(\frac{1 - K_K^N}{1 - K_K} \right)$$

In similar way, on substituting the values of $\dot{Q}_{\text{uth},N}$, $h_1(T_w - T_{\text{gi}})$, and $h_3(T_b - T_w)$ from (5.2.8), (5.2.9), and (5.3.13) respectively in Eq. (5.2.3), one can obtain:

$$\begin{aligned} & \alpha'_w I(t) A_b + [C_2 \alpha'_b I(t) + U_{3b}(T_a - T_w)] A_b + [(\alpha\tau)_{\text{eff}} I_c(t) - (UA)_{\text{eff}}(T_w - T_a)] \\ & = M_w C_w \frac{dT_w}{dt} + [U_{12}(T_w - T_a)] A_b - \alpha''_g I(t) C_1 \\ & M_w C_w \frac{dT_w}{dt} + [U_{3b} A_b + U_{12} A_b + (UA)_{\text{eff}}] T_w = [\alpha'_w A_b + C_2 \alpha'_b A_b + \alpha''_g C_1] I(t) \\ & \quad + [(\alpha\tau)_{\text{eff}} I_c(t)] + T_a [U_{3b} A_b + U_{12} A_b + (UA)_{\text{eff}}] \\ & \frac{dT_w}{dt} + \left[\frac{U + (UA)_{\text{eff}}}{M_w C_w} \right] T_w = \frac{[\alpha_{\text{eff}} I(t) + (\alpha\tau)_{\text{eff}} I_c(t) + (U + (UA)_{\text{eff}})]}{M_w C_w} \\ & \frac{dT_w}{dt} + a T_w = f(t) \end{aligned} \quad (5.3.14)$$

The temperature of the water can be obtained by solving the above first-order differential equation as given below:

$$T_w = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] + T_{w0} e^{-a\Delta t} \quad (5.3.15)$$

where

$$a = \left[\frac{U + (UA)_{\text{eff}}}{M_w C_w} \right]; \quad f(t) = \frac{[\alpha_{\text{eff}} I(t) + (\alpha \tau)_{\text{eff}} I_c(t) + (U + (UA)_{\text{eff}})]}{M_w C_w}$$

Kumar et al. [15] studied the tube-in-water evacuated tubular collector integrated with a single-slope solar still (ETC-SSSS) under forced mode of operation (Fig. 5.5). The system comprises a number of concentric borosilicate tubes with inclination (45°), a single-slope solar still (area 1 m × 1 m; and glass cover inclination of 15°), and a pump driven by a DC motor. The analysis was performed for the climatic conditions of the New Delhi. The active system was optimized for the mass-flow rate and the basin-water depth; the system performance (daily yield, energy and exergy efficiency, and economic analysis) was also investigated [15].

On changing the mass-flow rate from 0.001 to 0.006 kg/s, the maximum water temperature and productivity was found to be in the range of 83.0–92.6 °C and 2.57–3.47 kg, respectively, under summer climatic conditions. Figure 5.6a shows that the energy and exergy efficiencies increased with an increase of mass-flow rate and showed maximum values (energy 30.02%; exergy 1.75%) at a mass-flow rate of 0.006 kg/s. It was determined that the combination of optimum mass-flow rate of 0.06 kg/s and basin-water depth of 0.03 m produced a daily yield of 3.9 kg/m². The ETC-SSSS in forced-mode of operation performs slightly better than the ETC-SSSS operated in the natural mode of operation (Fig. 5.6b). The annual average yield (263.6 kg/m²) obtained from the hybrid (PVT) active solar still was found to be significantly lower than the yield obtained from the ETC-SSSS system due to greater losses of convection in FPCs. Moreover, the average annual values of

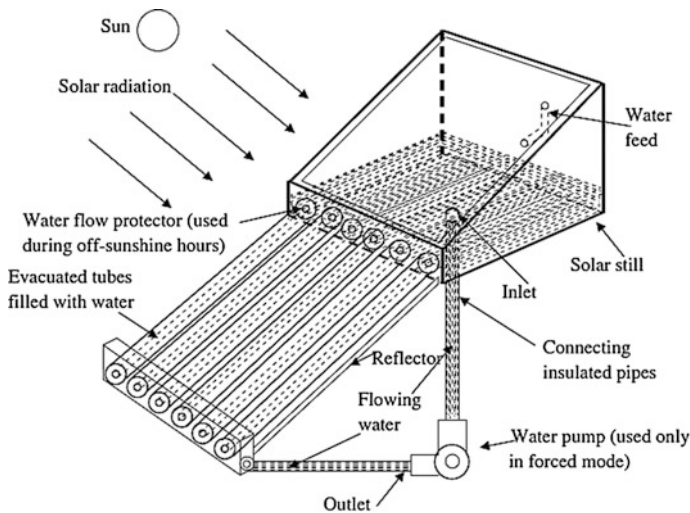


Fig. 5.5 Schematic view of tube-in-water evacuated tubular collector integrated with single slope solar still (ETC-SSSS) in forced mode condition

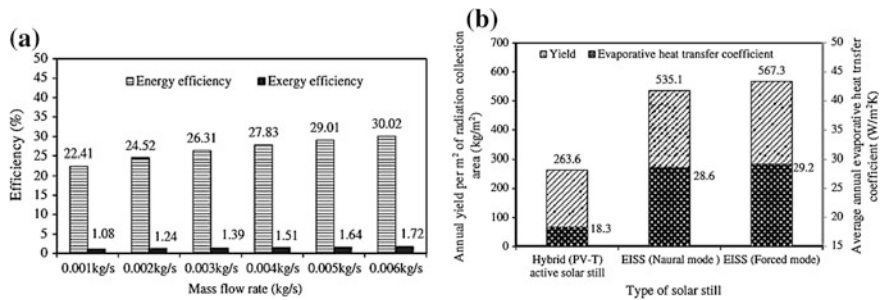
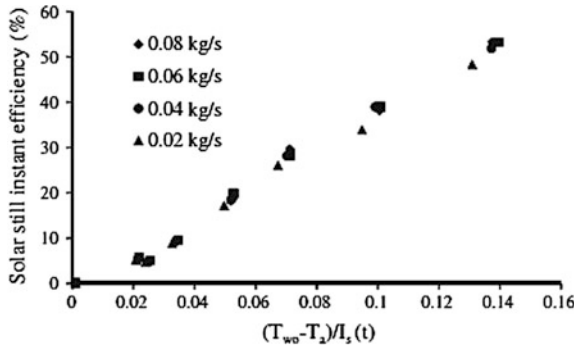


Fig. 5.6 a Variation of energy and exergy efficiency with mass flow rate. b Annual yield and annual average heat transfer coefficient for different systems

Fig. 5.7 Variation of instantaneous efficiency with reduced temperature for active SSSS-ETC system at different mass flow rates and 0.03 kg basin water mass in summer conditions



evaporative HTC of ETC-SSSS (forced mode) were also found to be approximately 1.5 times greater compared with the hybrid (PV/T) active solar still.

Figure 5.7 depicts the variation of instantaneous energy efficiency with decreased temperature of the system at different mass-flow rates and 0.03 kg basin-water mass under summer conditions. It was found to be in the range of 5.4–59.6%. The instantaneous efficiency significantly depends on the single parameter (decreased temperature) for the fixed other parameters of the system.

5.4 Solar Still Integrated with N-Photovoltaic Thermal Compound-Parabolic Concentrator Collectors (N-PVT-CPC)

In this type of active system, external thermal energy is supplied/circulated on integrating the outlet of the series-connected N-photovoltaic thermal compound-parabolic concentrators (N-PVT-CPC) to a conventional single-slope solar still. A schematic

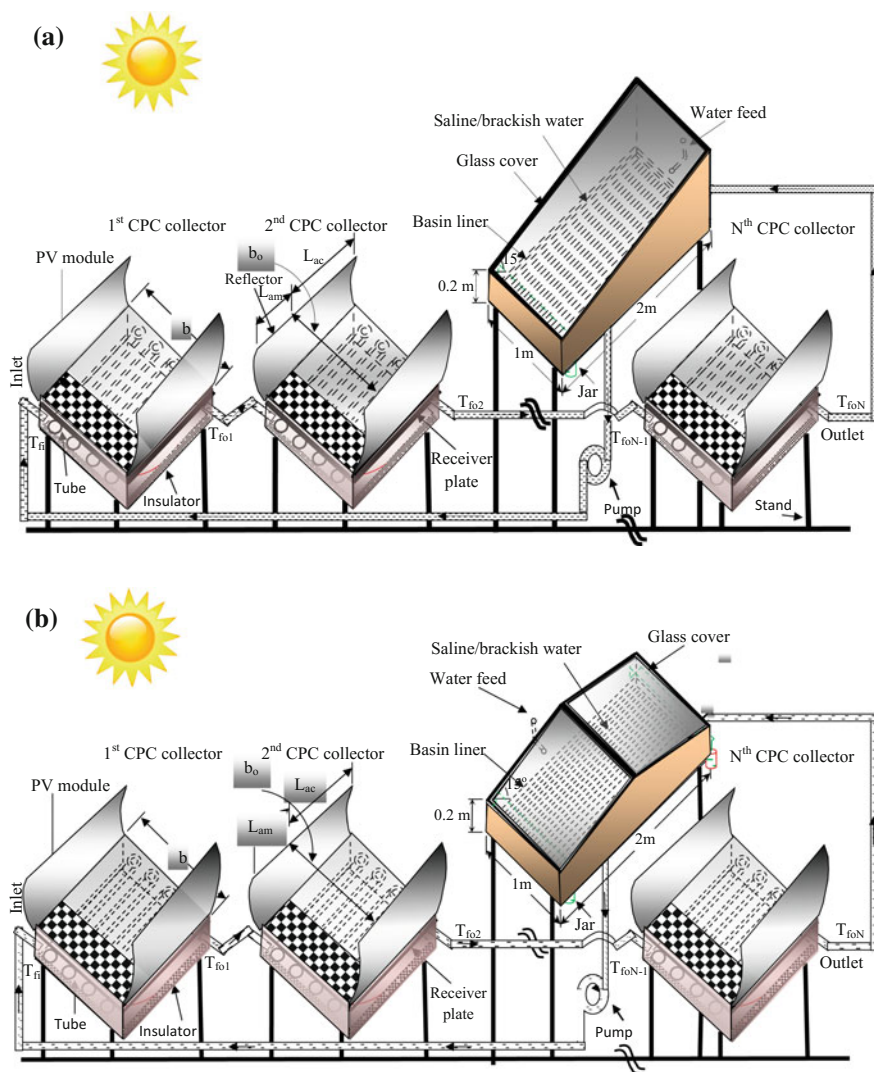


Fig. 5.8 **a** Schematic diagram of single slope active solar still integrated with N-identical partially covered PVT-CPC collectors connected in series. **b** Schematic diagram of double slope active solar still integrated with N partially covered PVT-CPC collectors connected in series

diagram of a single-slope active solar still integrated with N-identical partially covered PVT-CPC collectors connected in series is shown in Fig. 5.8a.

N-identical partially covered PVT-CPC water collectors are in a closed loop with a single-slope active solar still through a pump driven by a DC motor and with insulated pipes. Coated aluminum has been used for the parabolic surface. The parabolic surface reflected the incident beam solar radiation toward the receiver

surface. As explained in Sect. 5.1, a portion of electrical energy generated by a PV module is used to run a DC motor water pump; and the remaining energy is available for other use. The water pump compels the water to circulate under a forced mode of operation by overcoming the pressure decrease in the collectors and the piping arrangement. The radiation directly absorbed by the blackened surface of the collector, the thermal energy convected from the back surface of the PV module, and the solar radiation being transmitted through the non-packing area of the module are used to heat water passing through the pipe in the collector. To transfer the external thermal energy (feed water), the outlet of the N th water collector is integrated into the basin of solar still.

The rate of useful thermal energy of partially covered series-connected N -photovoltaic thermal compound parabolic concentrators (N -PVT-CPCs) is expressed as (Eq. 4.4.47):

$$\dot{Q}_{\text{uth},N} = (\alpha\tau)_{\text{eff}} I_b - (UA)_{\text{eff}} (T_w - T_a) \quad (5.4.16)$$

where $I_b(t)$ beam radiation (W/m^2); T_w basin water temperature ($^{\circ}\text{C}$); and T_a ambient temperature ($^{\circ}\text{C}$).

Where

$$(\alpha\tau)_{\text{eff}} = (AF_R(\alpha\tau))_1 \left(\frac{1 - K_K^N}{1 - K_K} \right) \text{ and } (UA)_{\text{eff}} = (A_R F_R U_L)_1 \left(\frac{1 - K_K^N}{1 - K_K} \right)$$

In a similar way, on substituting the values of $\dot{Q}_{\text{uth},N}$, $h_1(T_w - T_{\text{gi}})$, and $h_3(T_b - T_w)$ from Eqs. (5.4.16), (5.2.8), and (5.2.9), respectively, in Eq. (5.2.3), one can obtain:

$$\begin{aligned} & \alpha'_w I(t) A_b + [C_2 \alpha'_b I(t) + U_{3b}(T_a - T_w)] A_b + [(\alpha\tau)_{\text{eff}} I_b - (UA)_{\text{eff}} (T_w - T_a)] \\ & = M_w C_w \frac{dT_w}{dt} + [U_{12}(T_w - T_a)] A_b - \alpha''_g I(t) C_1 \\ & M_w C_w \frac{dT_w}{dt} + [U_{3b} A_b + U_{12} A_b + (UA)_{\text{eff}}] T_w = [\alpha'_w A_b + C_2 \alpha'_b A_b + \alpha''_g C_1] I(t) \\ & \quad + [(\alpha\tau)_{\text{eff}} I_b] + T_a [(U_{3b} A_b + U_{12} A_b) + (UA)_{\text{eff}}] \\ & \frac{dT_w}{dt} + \left[\frac{U + (UA)_{\text{eff}}}{M_w C_w} \right] T_w = \frac{[\alpha_{\text{eff}} I(t) + (\alpha\tau)_{\text{eff}} I_b + (U + (UA)_{\text{eff}})]}{M_w C_w} \\ & \frac{dT_w}{dt} + a T_w = f(t) \end{aligned} \quad (5.4.17)$$

The solution of the above-mentioned first-order differential equation is given as follows:

$$T_w = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] + T_{w0} e^{-a\Delta t} \quad (5.4.18)$$

$$\text{where } a = \left[\frac{U + (UA)_{\text{eff}}}{M_w C_w} \right]; \quad f(t) = \frac{[z_{\text{eff}} I(t) + (\alpha\tau)_{\text{eff}} I_b + (U + (UA)_{\text{eff}})]}{M_w C_w}$$

In the same manner, one can evaluate the expression of the final basin-water temperature for series-connected (i) series connected N-compound parabolic concentrators (N-CPC) that are fully covered with semitransparent PV modules ($A_{\text{rc}} = 0, A_{\text{ac}} = 0$) as well as (ii) conventional N-compound parabolic concentrators ($A_{\text{am}} = 0, A_{\text{rm}} = 0$) that are integrated with a single-slope solar still.

Similarly, thermal modeling can be performed for a double-slope active solar still integrated with series-connected N-identical partially covered PVT-CPC collectors. The schematic view of the system is depicted in Fig. 5.8b.

Singh and Tiwari [17] analytically analyzed the performance of active single-slope and double-slope solar-distillation systems coupled with series-connected N partially covered compound-parabolic concentrators (N-PVT-CPC). The semi-transparent PV module (area $0.25 \text{ m} \times 1 \text{ m}$; and inclination 30°) was fixed at the lower portion of the CPC collectors (each of area $1 \text{ m} \times 1 \text{ m}$), and the assembly was integrated into the solar still (area of single slope $1 \text{ m} \times 1 \text{ m}$; and double slope $2 \text{ m} \times 1 \text{ m}$) with top transparent glass-cover inclination at 15° . The variation of maximum water temperature values in a PVT-CPC collector of single-slope and double-slope active solar stills with a number of collectors at different mass-flow rates for a typical day of the month June is presented in Fig. 5.9a, b, respectively. It has been observed that water temperature in the collector increases with an increase in the number of collectors and becomes saturated beyond the mass-flow rate of 0.04 kg/s (optimum value), which is due to the fact that water has less time to gain heat in the PVT-CPC water collector. Moreover, the maximum water temperature at the outlet of the N th collector decreases with an increase in mass-flow rate. At the outlet of the seventh collector, an approximate decrease of 40°C maximum outlet water temperature has been observed on increasing the mass-flow rate from 0.01 to 0.04 kg/s . This is credited to the fact that the rate of heat transfer from the absorber plate to the flowing water increases with a mass increase in the flow rate. The water temperature in the PVT-CPC water collector crosses 100°C with an increasing number of collectors greater than seven, and it further decreases for a greater number of collectors due to greater heat losses as expected; hence, the optimum value of number of collectors was found to be seven.

Figure 5.10a presents the variation of daily yield of single-slope and double-slope PVT-CPC active solar stills with a mass-flow rate of seven collectors for a typical day in the months of June and January. It has been observed that the yield of the systems decreases with an increase in mass-flow rate, which is due to low outlet water temperature (external thermal energy) of the collector at greater mass-flow rate; therefore, external thermal energy (feed water) does not increase the basin-water temperature effectively. Hence, the temperature difference between the

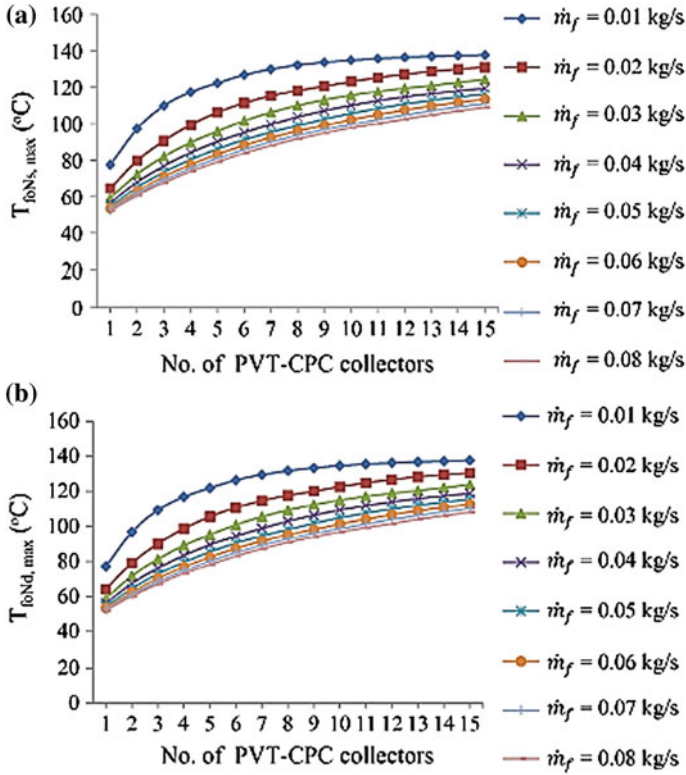


Fig. 5.9 Variation of maximum water temperature in the collector of PVT-CPC of **a** Single slope and **b** Double slope active solar still with number of collectors at different mass flow rates for a typical day of the month June

evaporative surface and the inner surface of the transparent glass cover of the still decreases, which results in a low rate of evaporation, and, ultimately, the system gives a low yield. Figure 5.10b shows the variation of daily yield with basin-water depth at optimized mass-flow rate (0.04 kg/s) and number of collectors (seven). The daily yield decreases with an increase in basin-water depth and then becomes saturated beyond some value. This is credited to the fact that (1) at a greater depth of basin water, any further increase in water temperature is not possible; and (2) an increase in yield at night, due to sensible heat enclosed by the basin-water mass, is balanced by the decrease in yield during the day. Both of the systems performed better in the month of June due to the availability of greater solar radiation in that particular month.

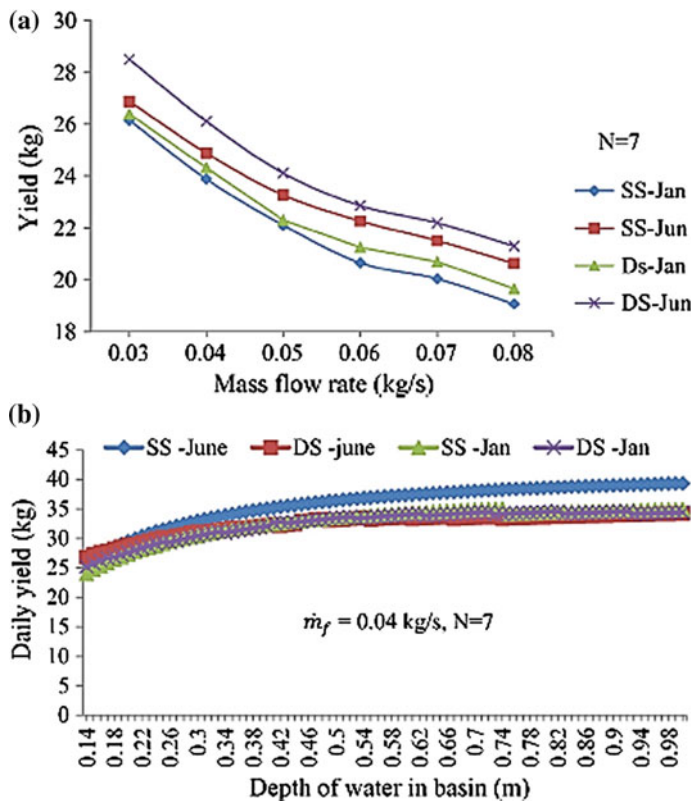


Fig. 5.10 Variation of daily yield of single slope and double slope PVT-CPC active solar still with **a** mass flow rate and **b** basin water depth for a typical day of the month June and January

5.5 Inverted-Absorber Solar Still Integrated with Refrigeration Cycle

A systematic view of an inverted-absorber solar still with refrigeration cycle is illustrated in Fig. 5.11. As the name suggests, the system consists of two main parts viz. an inverted solar still and a refrigeration cycle. An inverted solar still is constructed with a galvanized iron sheet with a thickness of 0.3 in. [18]. The dimension of the solar still is 400 mm × 200 mm. The inverted solar still part is installed under the glass enclosure (1000 mm × 1000 mm), which has a thickness of 0.3 in. Styrofoam as an insulation, with a thickness of 5 cm, was used on both sides of the enclosure. The top portion of the enclosure was executed as a cooling system. For greater absorption of solar radiation, the basin surface is painted black. In addition, for further heating of the basin surface, reflectors (mirrors) are placed under the bottom surface (basin) of the still. Reflected solar radiation from the reflectors concentrates onto the bottom surface of the metallic basin and is gets

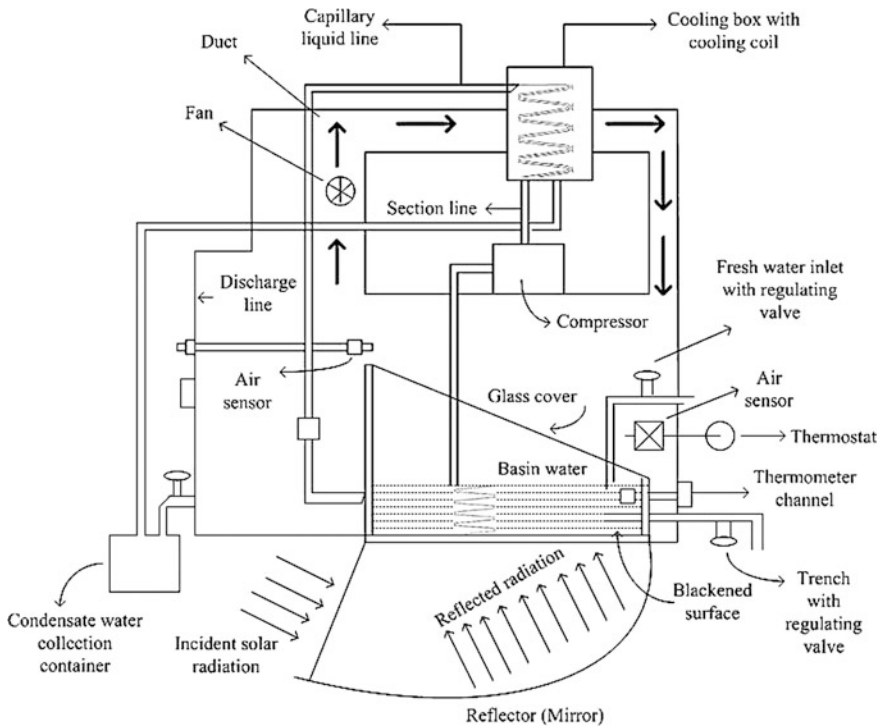


Fig. 5.11 Systematic diagram of inverted absorber solar still integrated with refrigeration cycle [18]

transferred to the contaminated saline water available in the solar still. The temperature of the outer surface the transparent-glass cover is minimized using a uniform flow of cold water over the surface. This increases the temperature difference between the saline water of the still and the inner surface of the top cover, which in turn increases the rate of evaporative heat transfer. For water circulation, a water pump of 0.5 HP is used together with a main water tank, and the thickness of the inlet and the outlet is 0.75 and 0.5 in., respectively [18]. The distilled water is collected through a channel connected at the lower end of the basin.

In contrast, the refrigeration-cycle part of the system comprises of a condenser, an expansion device, and an evaporator 0.25 HP with 134, a refrigerant. Furthermore, an in-line fan with a flexible duct is incorporated to decrease the rapid heating. The use of waste heat from condensation of the refrigerant inside the condenser coil provides extra thermal energy used to vaporize the feed water (saline), which is the first significant effect of the combined system. The second effect of the combined system is that it enhances the rate of condensation by decreasing the temperature of the glass surface. The compressor of the refrigeration

cycle comprises the refrigerant inlet (low side pressure) and outlet line (high side pressure). It forces the refrigerant to flow from the condenser to the evaporator through the condenser coil of the inverted-absorber still. The condenser reject heat to feed saline water of the solar still. The refrigerant turns back to liquid after complete rejection of the heat by condenser.

This rejected heat is used as an extra thermal energy input to increase the rate of the evaporation process in the still. The required energy for evaporation of the refrigerant can be extracted from the air–vapor mixture in the still cavity by using a flexible air duct, and it flows to the evaporator, which performs a heat exchanger. The, the cold air is circulated again in the still cavity below the inner surface of the glass cover. The process of air transport ensures the dissipation of heat from the condensed water and is rapidly removed from the condensing surface. It results in a decrease temperature of the top transparent-glass cover of the still.

5.6 Multi-effect Diffusion Solar Still Integrated with Vacuum Tube Collector and Heat Pipe

Figure 5.12 shows a diagram of the system. The solar heat flowing in the vacuum-tube solar collector by way of a heat pipe (thermosyphon) enhances the temperature of the multi-effect diffusion unit (MDU) [19].

The heat-recovery exchanger is implemented to recover the heat of the distilled water and the hot brine for the purpose of pre-heating the contaminated seawater or saline water.

Design of the Multi-effect Diffusion Unit (MDU)

The normal shape of a wick plate causes contamination of the distilled water and blockage of the heat-conduction path. This is due to deformation of the heating plate and the peel-off of wick material. For this purpose, a bended shape of the wick plate has been taken into account to avoid these problems. Furthermore, this structure increases the strength and polycarbonate (PC). To create a gap between diffusion cells, a silicon rubber spacer is inserted between two vertical parallel plates. For a tight contact with the plate, a tensile force in the wick material can be generated through stretching. Consequently, at a high temperature thermal deformation arises, which generates the problem of contamination and wick peel-off. To avoid thermal deformation, more spacers are required for a wider heating plate [19].

In contrast, a uniform water (inlet) is distributed to all layers of the wick through a 5 cm-thick pulp sponge connected on top of the wicks. The trench that collects the pure distilled water is formed by bending the heating plate. A cotton rope is inserted inside the trench at the lower side. The fresh water flowing to the collector (storage tank) is transported from the trench by way of a capillary mechanism through a cotton rope. This design helps to distinguish the pure water from the

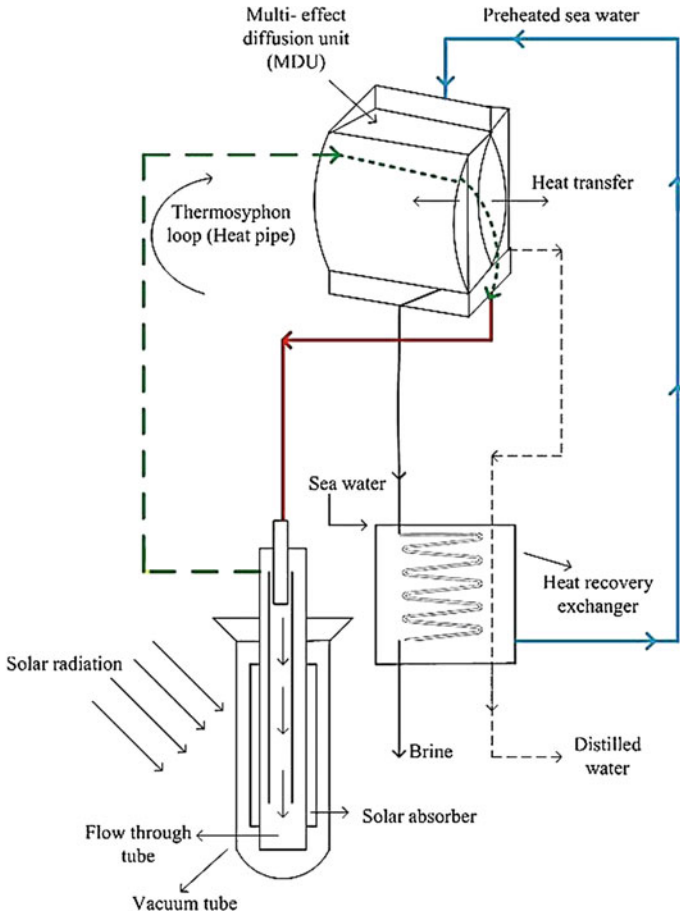


Fig. 5.12 Schematic diagram of multi effect diffusion solar still (MEDSS) [19]

brine. The dissolved gas (oxygen) in pure water may be developed and generate bubbles, which creates the problem of wick peel-off. To avoid wick dry-out and bubble formation in the wick, the flow rate of the water must be controlled through the wick. The MDU is designed in two parts in order to decrease the heat loss. The heat-recovery exchanger preheats the seawater and then feed into the MDU unit from the top side. The effluent and pure water is collected at the bottom in separate collectors. A cover is added to the both sides (front and back) of the MDU to block the sunlight. The reflected light from the front cover is transmitted to the vacuum-tube solar collector, and the openings of the cover provide cooling by way of air ventilation for dissipation of heat from the last cell.

5.7 Multi-effect Active Solar Still: The Effect of the Number of Stages

A systematic diagram of an evaporation chamber comprising four stages and a multi-effect active solar still is presented in Fig. 5.13a, b, respectively. The system contains important components such as an evaporation chamber, a heat exchanger, heat-transfer oil, an electric heater with a PLC, and a circulation pump. The horizontal area of each stage of the multi-stage evaporation chambers is 0.45 m^2 as shown in Fig. 5.5a.

The first stage consists of a rectangular basin with a tilted tray over it, and the basin is filled to a water depth of 1 cm. The current heat exchanger in it is immersed into the brackish water. Water available in all of the four identical trays is filled up to 0.7 cm. The depth of water for the first stage is 3.5 cm and the corresponding depth of the other trays is 2.5 cm. Consequently, all of the four stages of the stills are filled up to water depth of 1.7, 2.4, 3.1, and 3.8 cm, respectively [20]. A collector is placed under each tray, and the distilled water produced by each tray is collected in the evaporation chamber. The collector is tilted and installed behind

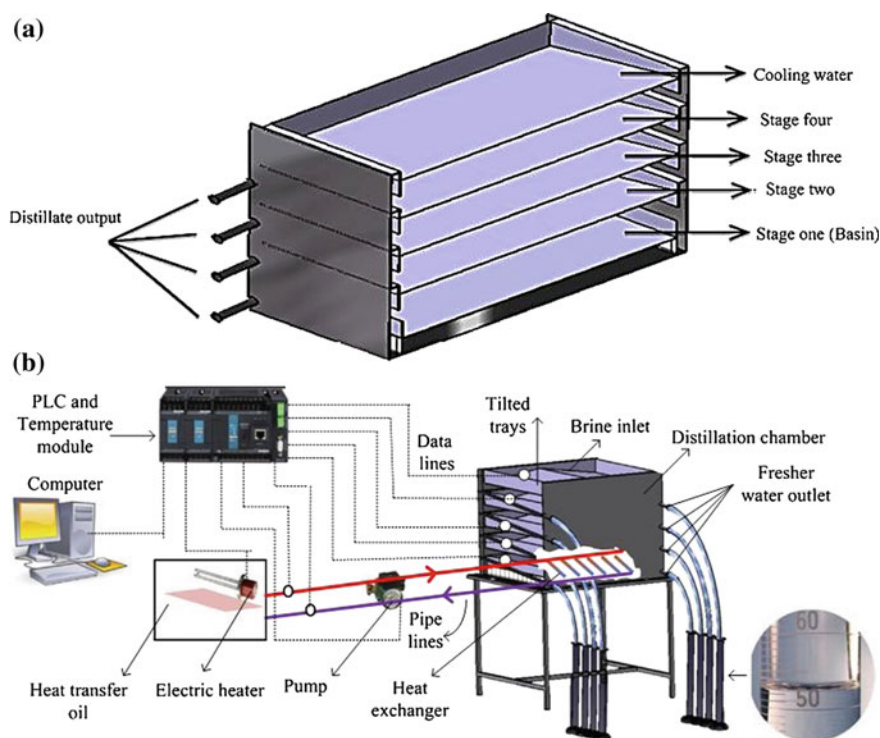


Fig. 5.13 a Scheme of 4-stage evaporation chamber [20]. b Systematic diagram of multi-effect active solar still [20]

Table 5.1 List of materials used in the system

Material	Component
Cover of still	Plexiglass
Heat exchanger	Copper
Insulation of still	Polystyrene
Insulation of electric heater chamber	Polyurethane
Insulation of piping	Rubber
Trays	Aluminum

the lower stage in order to retain the stage height at a minimum. Furthermore, the tray angle is kept at a minimum to lower the water depth in the basin. In each stage, the brackish water is supplied from the top through a tube (vapor leakage), and all of the stages are sealed to avoid vapor leakage. The materials used for the construction of different parts of the system are listed in Table 5.1. The diameter of the heat exchanger, which is constructed from copper pipe, is 12 mm and the length is 2 m. The heat-transfer oil, as a heat-transfer fluid (HTF), is used for energy transfer through the pump circulation.

5.8 Solar Still Integrated with a Solar Pond

In this section, two different systems viz. a solar still integrated with a shallow solar pond and a fin-type solar still integrated with a fin-type mini solar pond are discussed.

5.8.1 Single-Basin Solar Still Integrated with a Shallow Solar Pond

The systematic view of the system of single-basin solar still integrated with a shallow solar pond (SSP) is shown in Fig. 5.14. The system consists of a single-slope solar still assisted by a shallow solar pond. The solar still's basin, with an area of 1 m², is assembled with a galvanized iron sheet having a top transparent glass cover at an angle of 10° with horizontal. Solar radiation penetrates through the transparent-glass cover of the still [21]. The basin surface is painted matte black in order to absorb the maximum solar radiation. Insulation is used in the bottom and sides of the still to minimize heat losses.

The shallow solar pond is fabricated with a galvanized iron sheet. The solar pond and still are placed at the same level as shown in Fig. 5.6. The depth and bottom surface areas of the pond are 0.088 m and 1 m², respectively, which absorb the incident solar radiation. Glass sheets with a thickness of 0.003 m, having a gap of 0.027 m, are used in the solar pond, and it is fully packed with a water to avoid the

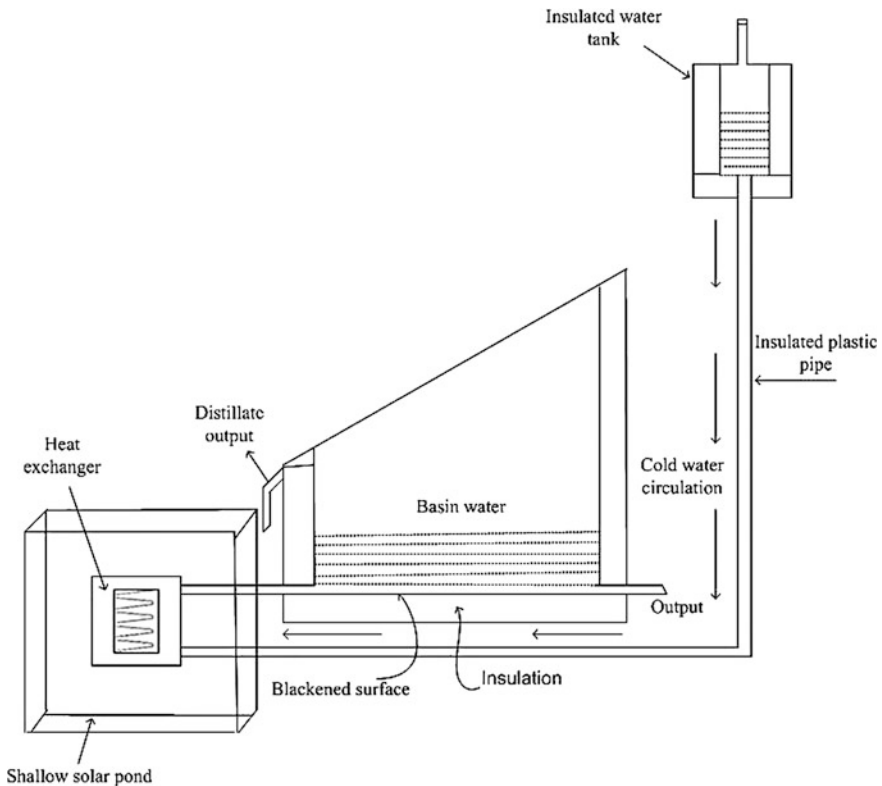


Fig. 5.14 Schematic diagram of a single slope solar still integrated to shallow solar pond

evaporation process. Consequently, the cooling process due to the evaporation of water is prevented. A heat exchanger, made of copper with a length of 5 m and a diameter of 0.001 m, incorporated into the absorber plate of the pond. To extract the heat from the pond under an open cycle, i.e., in a continuous mode, cold water of an insulated tank flowing through the heat exchanger is used as a fluid [21]. An insulated water tank is placed at an upper height to attain the required pressure for water flow. The still is connected to the outlet of the heat exchanger through an insulated pipe to decrease heat loss. At the outlet of the heat exchanger of the shallow solar pond, the hot water is nourished directly into the inlet of the solar still.

5.8.2 *Fin-Type Solar Still Integrated with a Fin-Type Mini Solar Pond*

The basin plate is integrated with rectangular solid fins to increase the surface area of the basin. The convective heat-transfer rate between the basin and water

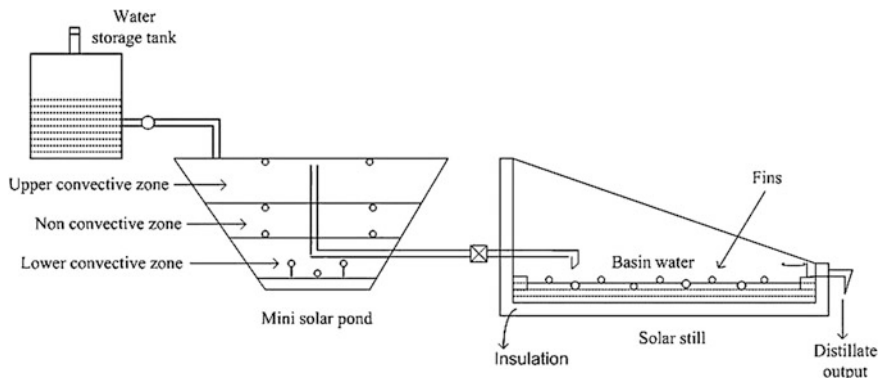


Fig. 5.15 Systematic view of fin type solar still integrated with fin type mini solar pond

increases with increasing surface area of the absorber plate, which in turn increases the temperature of the contaminated saline water. Consequently, it increases the temperature difference between the inner surface of the transparent-glass cover and the saline water in the still; hence, it improves the productivity (yield) of the system [22]. An illustrative view of the system is presented in Fig. 5.15. The heat-storing capacity of the mini solar pond depends on the area of base of the pond. Eventually, it increases with increasing the base area of the solar pond, and it can also be increased by integrating fins. Therefore, the rate of convective heat transfer increases from the lower bottom (basin) of the pond to the lower convective zone (LCZ). Finally, to obtain the highest productivity, the fin-type solar pond is integrated with the fin-type single-slope solar still [22].

5.9 Characteristic Equations of an Active Double-Slope Solar Still Integrated with a Partially Covered N-PVT-FPC

Instantaneous efficiency is the ratio of the rate of evaporative heat transfer to the rate of solar radiation falling on the system [23]. For improvement in the design and performance of solar stills, the concept of efficiency is very important, and interpreting the instantaneous-gain and loss-efficiency curves help to understand the performance of solar stills. Moreover, the characteristic equations can be used for further modifications of the existing design in terms of design, operating parameters, and climatic factors, etc. Tamini [24] made the first attempt to characterize the performance of solar stills, and Boukar and Harmim [25] explicitly explain the characteristic curve for one-sided vertical solar stills.

A characteristic equation for the following two types of active double-slope solar still (DSSS) has been developed:

- (i) active DSSS without operating helically coiled heat exchanger = system (A); and
- (ii) active DSSS operating with helically coiled heat exchanger = system (B).

5.9.1 Active DSSS Without Operating Helically Coiled Heat Exchanger (System A)

A systematic view of active double-slope solar still without operating helically coiled heat exchanger is shown in Fig. 5.16.

The energy balances of the different components of system A are expressed as follows:

(a) East side

$$\begin{aligned} \alpha_g I_{SE} A_{gE} + h_{lf,E} (T_f - T_{giE}) \left(\frac{A_B}{2} \right) - h_{EW} (T_{giE} - T_{giW}) A_{gE} \\ = \left(\frac{K_g}{L_g} \right) (T_{giE} - T_{gOE}) A_{gE} \end{aligned} \quad (5.9.19)$$

where α_g solar energy absorbed by the transparent-glass cover; I_{SE} solar intensity on the east side of the glass cover (W/m^2); A_{gE} surface area of the east side's glass cover (m^2); $h_{lf,E} (= h_{ef,E} + h_{rf,E} + h_{cf,E})$ total internal heat-transfer coefficient on the east side ($\text{W/m}^2 \text{ } ^\circ\text{C}$); $h_{ef,E}$, $h_{rf,E}$, and $h_{cf,E}$ internal evaporative radiative and convective heat-transfer coefficient, respectively, on the east side; $h_{ef,W}$, $h_{rf,W}$, and $h_{cf,W}$ internal evaporative, radiative, and convective

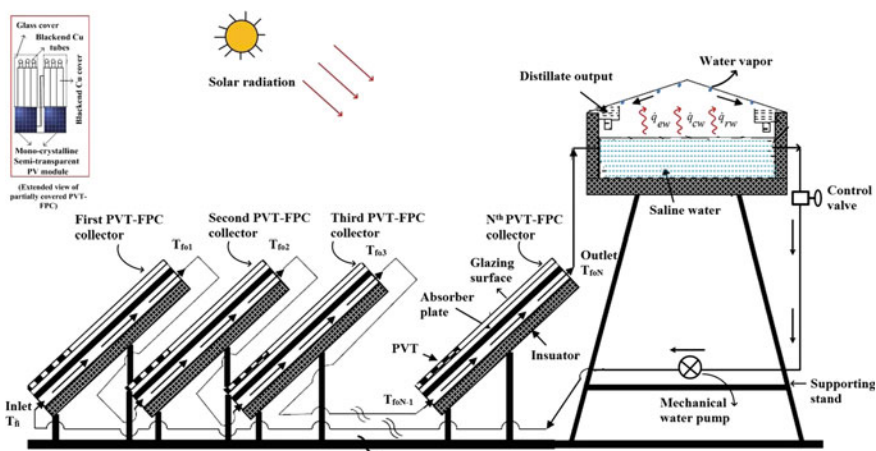


Fig. 5.16 Schematic view of active double slope solar still operating without heat exchanger, system (A)

heat-transfer coefficient on the west side; $h_{1f,w}(=h_{ef,w} + h_{rf,w} + h_{cf,w})$ total internal heat-transfer coefficient on the west side ($\text{W/m}^2 \text{ } ^\circ\text{C}$); h_{EW} internal radiative heat-transfer coefficient between the east and the west glass covers ($\text{W/m}^2 \text{ } ^\circ\text{C}$); K_g thermal conductivity of the glass cover ($\text{W/m}^2 \text{ } ^\circ\text{C}$); L_g thickness of the glass cover (m) T_{goE} temperature of the outer surface of the east-side glass cover ($^\circ\text{C}$); T_{giE} temperature of the inner surface of the east-side glass cover ($^\circ\text{C}$); T_{giW} temperature of the inner surface of the west-side glass cover ($^\circ\text{C}$); and A_B area of the rectangular basin (m^2).

$$\left(\frac{K_g}{L_g}\right)(T_{giE} - T_{goE})A_{gE} = h_{1gE}(T_{goE} - T_a)A_{gE} \quad (5.9.20)$$

where $h_{1gE}(=h_{cg,E} + h_{rg,E})$ total external heat-transfer coefficient from the east-side glass cover to the ambient ($\text{W/m}^2 \text{ } ^\circ\text{C}$); $h_{cg,E}$ external convective heat-transfer coefficient from the east-side glass cover to the ambient ($\text{W/m}^2 \text{ } ^\circ\text{C}$); $h_{rg,E}$ external radiative heat-transfer coefficient from the east-side glass cover to the ambient ($\text{W/m}^2 \text{ } ^\circ\text{C}$); and T_a the ambient temperature ($^\circ\text{C}$).

(b) **West side**

$$\begin{aligned} \alpha_g I_{SW} A_{gW} + h_{1f,w}(T_f - T_{giW})\left(\frac{A_B}{2}\right) - h_{EW}(T_{giE} - T_{giW})A_{gW} \\ = \left(\frac{K_g}{L_g}\right)(T_{giW} - T_{goW})A_{gW} \end{aligned} \quad (5.9.21)$$

where I_{SW} solar intensity on the west side of the glass cover (W/m^2); A_{gW} surface area of the east side's glass cover (m^2); T_f basin fluid (water) temperature ($^\circ\text{C}$); and T_{goW} temperature of the outer surface of the west-side glass cover ($^\circ\text{C}$).

$$\left(\frac{K_g}{L_g}\right)(T_{giW} - T_{goW})A_{gW} = h_{1gW}(T_{goW} - T_a)A_{gW} \quad (5.9.22)$$

where $h_{1gW}(=h_{cg,w} + h_{rg,w})$ total external heat-transfer coefficient from the west-side glass cover to the ambient ($\text{W/m}^2 \text{ } ^\circ\text{C}$); $h_{cg,w}$ external convective heat-transfer coefficient from the west-side glass cover to the ambient ($\text{W/m}^2 \text{ } ^\circ\text{C}$); and $h_{rg,w}$ external radiative heat-transfer coefficient from the west-side glass cover to the ambient ($\text{W/m}^2 \text{ } ^\circ\text{C}$).

On solving Eqs. (5.9.19)–(5.9.22), one can obtain the following:

$$T_{giE} = \frac{[A + T_f B]}{H} \quad (5.9.23)$$

$$T_{giW} = \frac{[A' + T_f B']}{H} \quad (5.9.24)$$

where

$$\begin{aligned} A &= C_1 U_2 + C_2; \quad A' = C'_1 U_1 + C'_2; \quad B = (h_{1fE} U_2 + h_{1fW} h_{EW} A_{gE}) \left(\frac{A_B}{2} \right) \\ B' &= (h_{1fW} U_1 + h_{1fE} h_{EW} A_{gE}) \left(\frac{A_B}{2} \right); \quad H = U_1 U_2 - h_{EW}^2 A_{gE} A_{gW}; \\ C_1 &= \alpha_g I_{SE} A_{gE} + U_{gaE} T_a A_{gE} \quad C_2 = \alpha_g I_{SW} h_{EW} A_{gE} A_{gW} + U_{gaW} T_a h_{EW} A_{gE} A_{gW}; \\ C'_1 &= \alpha_g I_{SW} A_{gE} + U_{gaW} T_a A_{gW} \quad C'_2 = \alpha_g I_{SE} h_{EW} A_{gE} A_{gW} + U_{gaE} T_a h_{EW} A_{gE} A_{gW}; \\ U_1 &= h_{1fE} \left(\frac{A_B}{2} \right) + h_{EW} A_{gE} + U_{gaE} A_{gE} \\ U_2 &= h_{1fW} \left(\frac{A_B}{2} \right) + h_{EW} A_{gW} + U_{gaW} A_{gW}. \end{aligned}$$

(c) **Basin liner**

$$\alpha_b (I_{SE} + I_{SW}) = 2h_{b,f} (T_b - T_f) + 2h_{ba} (T_b - T_a) \quad (5.9.25)$$

where $h_{b,f}$ heat-transfer coefficient from the basin liner to the fluid (water) ($\text{W/m}^2 \text{ } ^\circ\text{C}$); α_b absorptivity of the basin liner; T_b the basin temperature ($^\circ\text{C}$); T_a ambient temperature ($^\circ\text{C}$); T_f (fluid) water temperature ($^\circ\text{C}$); and h_{ba} heat-transfer coefficient from the basin liner and the ambient air ($\text{W/m}^2 \text{ } ^\circ\text{C}$).

(d) **Water mass**

$$\begin{aligned} M_f C_f \frac{dT_f}{dt} &= \alpha_f (I_{SE} + I_{SW}) \left(\frac{A_B}{2} \right) + 2h_{b,f} (T_b - T_f) \left(\frac{A_B}{2} \right) - h_{1f,E} (T_f - T_{giE}) \left(\frac{A_B}{2} \right) \\ &\quad - h_{1f,W} (T_f - T_{giW}) \left(\frac{A_B}{2} \right) + \dot{Q}_{uN} \end{aligned} \quad (5.9.26)$$

where $\dot{Q}_{uN}$ is the useful thermal energy obtained from the N-PVT-FPC given as follows:

$$\dot{Q}_{uN} = N(A_c + A_m) F' \left[(\alpha\tau)_{N,\text{eff}} I_c - U_{LN} (T_f - T_a) \right].$$

where α_f solar energy absorbed by the basin fluid (water); C_f specific heat of the water (J/kg K), M_f mass of the basin fluid (water) (kg); and $I_c(t)$ solar intensity on the FPC (W/m^2).

On solving Eqs. (5.9.25) and (5.9.26) using Eqs. (5.9.23) and (5.9.24), one can obtain the following:

$$\frac{dT_f}{dt} + a_1 T_f = f_1(t) \quad (5.9.27)$$

The solution of the above-mentioned first-order differential can be written as follows:

$$T_f = \frac{\overline{f_1(t)}}{a_1} (1 - e^{-a_1 \Delta t}) + T_{f0} e^{-a_1 \Delta t} \quad (5.9.28)$$

where

$$f_1(t) = \left(\frac{A_b}{2H} \right) \{ [(K_{1E} + \alpha_{fb})I_{SE}(t) + (K_{1W} + \alpha_{wb})I_{SW}(t) + N(A_c + A_m)F'(\alpha\tau)_{N,eff}I_c(t)] + T_a(H_1 + H_2 + H_3 + H_4 + H_5) \} \quad (5.9.29)$$

$$a_1 = \left(\frac{A_b}{2H} \right) [h_{1f,E}(E_1 + E_2) + h_{1f,W}(E'_1 + E'_2) + (U_{ba}A_b + N(A_c + A_m)F'U_{L,N})]$$

$$(\alpha\tau)_{N,eff} = \frac{PF_2(\alpha\tau)_{m,eff}F_{Rm}}{N} \left[\frac{1 - (1 - K_{k,A})^N}{K_{k,A}} \right]; \quad K_{k,A} = \frac{A_m F_{Rm} U_{L,m}}{\dot{m}_f C_f};$$

$$U_{L,N} = \frac{F_{Rm} U_{L,m}}{N} \left[\frac{1 - (1 - K_{k,A})^N}{K_{k,A}} \right]$$

$$\alpha_{fb} = \left(\frac{A_b}{2} \right) (\alpha_f + 2\alpha_b U_{ga});$$

$$K_{1E} = \left[h_{1f,W} \left(\frac{A_b}{2A_{gW}} \right) + h_{EW} \left(1 + \frac{1}{h_{1f,E}} \right) + U_{gaW} \right] A_{gE} A_{gW} \alpha_g h_{1f,E}$$

$$K_{1W} = \left[h_{1f,E} \left(\frac{A_b}{2A_{gE}} \right) + h_{EW} \left(1 + \frac{1}{h_{1f,W}} \right) + U_{gaE} \right] A_{gE} A_{gW} \alpha_g h_{1f,W}$$

$$K'_{1E} = \left[h_{ef,W} \left(\frac{A_b}{2} \right) + h_{EW} \left(1 + \frac{h_{ef,W}}{h_{ef,E}} \right) A_{gW} + U_{gaW} A_{gW} \right] A_{gE} \alpha_g h_{ef,E}$$

$$K'_{1W} = \left[h_{ef,E} \left(\frac{A_b}{2} \right) + h_{EW} \left(1 + \frac{h_{ef,E}}{h_{ef,W}} \right) A_{gE} + U_{gaE} A_{gE} \right] A_{gW} \alpha_g h_{ef,W}$$

$$\begin{aligned}
H_1 &= \left(\frac{A_b}{2} \right) (U_{gaE} A_{gE} + U_{gaW} A_{gW}) h_{1f,E} h_{1f,W} \\
H_2 &= A_{gE} A_{gW} h_{EW} (U_{gaE} h_{1f,E} + U_{gaW} h_{1f,W}) \\
H_3 &= A_{gE} A_{gW} U_{gaE} U_{gaW} (h_{1f,E} + h_{1f,W}) \\
H_4 &= A_{gE} A_{gW} h_{EW} (U_{gaE} h_{1f,W} + U_{gaW} h_{1f,E}); \quad H = U_1 U_2 - h_{EW}^2 A_{gE} A_{gW} \\
E_1 &= U_{gaE} \left[h_{EW} + h_{1f,W} \left(\frac{A_b}{2A_{gW}} \right) \right]; \quad E_2 = U_{gaW} (h_{EW} + U_{gaE}) A_{gE} A_{gW} \\
E'_1 &= U_{gaW} \left[h_{EW} + h_{1f,E} \left(\frac{A_b}{2A_{gE}} \right) \right]; \quad E'_2 = U_{gaE} (h_{EW} + U_{gaW}) A_{gE} A_{gW}
\end{aligned}$$

The instantaneous-gain thermal-energy efficiency ($\eta_{g1,th}$) can be written as follows:

$$\eta_{g1,th} = \frac{[h_{ef,E}(T_f - T_{giE}) + h_{ef,W}(T_f - T_{giW})] A_b}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} \quad (5.9.30)$$

Substituting Eqs. (5.9.23) and (5.9.24) in Eq. (5.9.30), one can obtain the following:

$$\begin{aligned}
\eta_{g1,th} &= \left(\frac{A_b}{H} \right) \left\{ \frac{[h_{ef,E}(H - B) + h_{ef,W}(H - B')]}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} T_f - \frac{[h_{ef,E}(A) + h_{ef,W}(A')]}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} \right\} \\
&= \left(\frac{A_b}{H} \right) \left\{ \frac{\left[h_{ef,E}(E_1 + E_2) A_{gE} + h_{ef,W}(E'_1 + E'_2) A_{gW} \right] \left[\frac{\overline{f_1(t)}}{a_1} (1 - e^{-a_1 \Delta t}) + T_{f0} e^{-a_1 \Delta t} \right]}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} - \frac{[(K'_{IE} I_{SE}(t) + K'_{IW} I_{SW}(t)) + T_a(H_1 + H_2 + H_3 + H_4)]}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} \right\} \quad (5.9.31)
\end{aligned}$$

By substituting the expressions of $f_1(t)$ and a_1 in the above-mentioned equation, one obtains the following:

$$\begin{aligned}
\eta_{g1,th} &= \left(\frac{A_b}{H}\right) \left(\frac{1}{A_{gE}I_{SE}(t) + A_{gW}I_{SW}(t)}\right) \left\{ \left\{ \left[\frac{h_{ef,E}(E_1 + E_2)A_{gE} + h_{ef,W}(E'_1 + E'_2)A_{gW}}{H'_{11} + H''_{22}} \right] [(K_{1E} + \alpha_{fb})I_{SE}(t) \right. \right. \\
&\quad + [(K_{1W} + \alpha_{fb})I_{SW}(t) + N(A_c + A_m)F'(\alpha\tau)_{N,eff}I_c(t)] (1 - e^{-a_1\Delta t}) \left. \left. - (K'_{1E}I_{SE}(t) \right. \right. \\
&\quad + K'_{1W}I_{SW}(t)) \left. \left. + H'_{11}(T_{f0} - T_a)e^{-a_1\Delta t} \right\} \right. \\
&= \left(\frac{A_b}{H}\right) e^{-a_1\Delta t} \left\{ \frac{\left\{ \left\{ Z_{11}[(K_{1E} + \alpha_{fb})I_{SE}(t) + (K_{1W} + \alpha_{fb})I_{SW}(t) + N(A_c + A_m)F'(\alpha\tau)_{N,eff}I_c(t)](e^{a_1\Delta t} - 1) \right\} \right. \right. \\
&\quad \left. \left. - (K'_{1E}I_{SE}(t) + K'_{1W}I_{SW}(t))e^{a_1\Delta t} \right\}}{A_{gE}I_{SE}(t) + A_{gW}I_{SW}(t)} \right. \\
&\quad \left. + \left[\frac{(T_{f0} - T_a)}{A_{gE}I_{SE}(t) + A_{gW}I_{SW}(t)} \right] H'_{11} \right\}.
\end{aligned} \tag{5.9.32}$$

or

$$\eta_{g1,th} = F'_{g1} \left[(\alpha\tau)_{g1,eff} + \frac{(T_{f0} - T_a)}{I(t)} (U_{g1,eff}) \right] \tag{5.9.33}$$

where

$$\begin{aligned}
Z_{11} &= \left[(K_{1E} + \alpha_{fb})I_{SE}(t) + (K_{1W} + \alpha_{fb})I_{SW}(t) + N(A_c + A_m)F'(\alpha\tau)_{N,eff}I_c(t) \right] (e^{a_1\Delta t} - 1) \\
(\alpha\tau)_{g1,eff} &= \frac{- (K'_{1E}I_{SE}(t) + K'_{1W}I_{SW}(t))e^{a_1\Delta t}}{I(t)} \\
U_{g1,eff} &= H'_{11}; F'_{g1} = \left(\frac{A_b}{H}\right) e^{-a_1\Delta t}; \text{ and } Z_{11} = \frac{h_{ef,E}(E_1 + E_2)A_{gE} + h_{ef,W}(E'_1 + E'_2)A_{gW}}{H'_{11} + H''_{22}}; \\
H'_{11} &= H_1 + H_2 + H_3 + H_4; H''_{22} = \frac{2H}{A_b} (U_b A_b + A_c F' U_{L,N}); I(t) = A_{gE}I_{SE}(t) + A_{gW}I_{SW}(t)
\end{aligned}$$

Equation (5.9.33) represents the instantaneous-gain thermal-energy efficiency (characteristic equation) of an active double-slope solar still without an operating helically coiled heat exchanger.

The internal convective and radiative thermal losses from the water (fluid) surface are minimal compared with the heat lost on increasing the basin-water (fluid) temperature (sensible heat). Therefore, the lost thermal-energy efficiency ($\eta_{L1,th}$) of system A can be expressed as follows:

$$\eta_{L1,th} = \frac{M_f C_f (T_f - T_{f0})}{(A_{gE}I_{SE} + A_{gW}I_{SW})} \tag{5.9.34}$$

On substituting T_f from Eq. (5.9.28), one can obtain the following:

$$\begin{aligned}
 \eta_{L1,th} &= \frac{M_f C_f}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} \left[\frac{[(K_{IE} + \alpha_{fb}) I_{SE}(t) + (K_{IW} + \alpha_{fb}) I_{SW}(t) + N(A_c + A_m) F'(\alpha\tau)_{N,eff} I_c(t) + T_a (H'_{11} + H''_{22})] (1 - e^{-a_1 \Delta t})}{H'_{11} + H''_{22}} \right. \\
 &\quad \left. + T_{fo} (e^{-a_1 \Delta t} - 1) \right] \\
 &= \frac{M_f C_f}{(H'_{11} + H''_{22})} \left[\frac{[(K_{IE} + \alpha_{fb}) I_{SE}(t) + (K_{IW} + \alpha_{fb}) I_{SW}(t) + N(A_c + A_m) F'(\alpha\tau)_{N,eff} I_c(t)] (1 - e^{-a_1 \Delta t})}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} \right. \\
 &\quad \left. - (H'_{11} + H''_{22}) (1 - e^{-a_1 \Delta t}) \frac{(T_{fo} - T_a)}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} \right] \\
 \eta_{L1,th} &= F'_{L1} \left[(\alpha\tau)_{L1,eff} - U'_{L1,eff} \frac{(T_{fo} - T_a)}{I(t)} \right]
 \end{aligned} \tag{5.9.35}$$

where

$$\begin{aligned}
 F'_{L1} &= \frac{M_f C_f}{(H'_{11} + H''_{22})}; \quad U'_{L1,eff} = (H'_{11} + H''_{22}) (1 - e^{-a_1 \Delta t}) \\
 (\alpha\tau)_{L1,eff} &= \frac{[(K_{IE} + \alpha_{fb}) I_{SE}(t) + (K_{IW} + \alpha_{fb}) I_{SW}(t) + N(A_c + A_m) F'(\alpha\tau)_{N,eff} I_c(t)] (1 - e^{-a_1 \Delta t})}{I(t)};
 \end{aligned}$$

Equation (5.9.35) represents the instantaneous-loss thermal-energy efficiency (characteristic equation) of an active double-slope solar still without an operating helically coiled heat exchanger.

5.9.2 Operating with a Helically Coiled Heat Exchanger (System B)

External thermal energy from the heat-transfer carrier fluid (water) can be transferred either directly or by way of heat exchangers. Coiled tubes are an effective heat exchanger compared with straight-tube heat exchangers because of their excellent heat-transfer performance, compact size, and the enhanced turbulence. Helically coiled heat exchangers (large heat-transfer area per unit volume) are frequently used and mostly preferred over the straight tubes due to their excellent heat-transfer performance, compact size, and enhanced turbulence, which in turn enhances the heat-transfer coefficient of the tube's internal surface. Apart from using water as a working fluid, some other fluids having a greater boiling temperature compared with water can be used along with a heat exchanger to obtain a

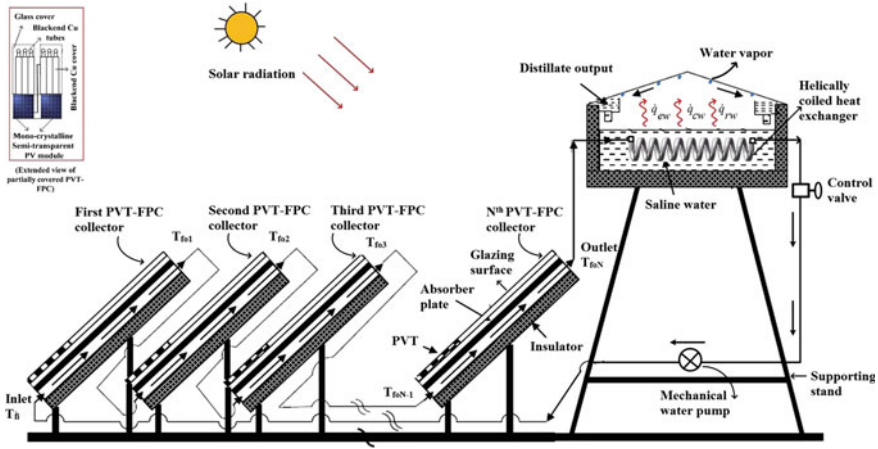


Fig. 5.17 Schematic view of active double slope solar still operating with heat exchanger, system (B)

greater yield. A schematic view of an active DSSS coupled with a helically coiled heat exchanger is shown in Fig. 5.17 (system B).

The energy balance of the heat exchanger immersed in the basin water (fluid) of the solar still can be expressed as follows:

$$\dot{m}_f C_f \frac{dT_f}{dx} dx = -(2\pi r_{11} U)(T_{HE} - T_f) dx \quad (5.9.36)$$

where $U = \left[\frac{1}{h_{bf}} + \left(\frac{r_{11}}{K_1} \right) \log \left(\frac{r_{22}}{r_{11}} \right) + \left(\frac{r_{11}}{r_{22}} \right) \left(\frac{1}{h_{bf}} \right) \right]^{-1}$ where $\dot{m}_f$ —mass-flow rate (kg/s); C_f —specific heat of water (J/kg K); r_{11} —outer diameter of the heat-exchanger tube (mm); r_{22} —inner diameter of the heat-exchanger tube (mm); K_1 —thermal conductivity of the heat exchanger W/m K; h_{bf} —heat-transfer coefficient of the working fluid W/m² K; T_{HE} —temperature of the heat exchanger (°C); and U —heat transfer in heat exchanger.

Boundary conditions: $T_f(x = 0) = T_{foN}$ and $T_f(x = L) = T_{fi}$.

Solving Eq. (5.9.36) using the above-mentioned boundary conditions, one can obtain the following:

$$T_{fi} = T_f \left[1 - \exp \left(-\frac{2\pi r_{11} UL}{\dot{m}_f C_f} \right) \right] + T_{foN} \exp \left(-\frac{2\pi r_{11} UL}{\dot{m}_f C_f} \right) \quad (5.9.37)$$

where L length of the heat exchanger (m).

The rate of useful thermal-energy gain from series-connected N -identical PVT water collectors can be calculated using the following relation:

$$\dot{Q}_{uN} = \dot{m}_f C_f (T_{FoN} - T_{fi}) \quad (5.9.38)$$

From Eq. (4.3.7) of Chap. 4, the outlet-water temperature at the end of the N th PVT water collector is given by the following:

$$T_{foN} = \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^N}{1 - K_k} \right) I_c(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left(\frac{1 - K_k^N}{1 - K_k} \right) T_a + K_k^N T_{fi} \quad (5.9.39)$$

where $I_c(t)$ —solar intensity received by the FPC (W/m^2).

On substituting T_{foN} from Eq. (5.9.39) in Eq. (5.9.36) and rearranging, one can obtain the following:

$$\begin{aligned} T_{FoN} - T_{fi} = & \left(K_k^N - 1 \right) \left(\frac{1 - e^{-z}}{1 - K_k^N e^{-z}} \right) T_f \\ & + \frac{(AF_R(\alpha\tau))_1}{\dot{m}_f C_f} \left[1 + \frac{(K_k^N - 1)e^{-z}}{1 - K_k^N e^{-z}} \right] \left(\frac{1 - K_k^N}{1 - K_k} \right) I_c(t) + \frac{(AF_R U_L)_1}{\dot{m}_f C_f} \left[1 \right. \\ & \left. + \frac{(K_k^N - 1)e^{-z}}{1 - K_k^N e^{-z}} \right] \left(\frac{1 - K_k^N}{1 - K_k} \right) T_a \end{aligned}$$

where $z = \frac{2\pi r_{tu} U_L}{\dot{m}_f C_f}$

Therefore, the rate of useful thermal-energy gain (Eq. 5.9.38) can be expressed as follows:

$$\begin{aligned} \dot{Q}_{uN} = \dot{m}_f C_f \left[\left(K_k^N - 1 \right) \left(\frac{1 - e^{-z}}{1 - K_k^N e^{-z}} \right) T_f + (AF_R(\alpha\tau))_1 \left[1 + \frac{(K_k^N - 1)e^{-z}}{1 - K_k^N e^{-z}} \right] \left(\frac{1 - K_k^N}{1 - K_k} \right) I_c(t) \right. \\ \left. + (AF_R U_L)_1 \left[1 + \frac{(K_k^N - 1)e^{-z}}{1 - K_k^N e^{-z}} \right] \left(\frac{1 - K_k^N}{1 - K_k} \right) T_a \right] \end{aligned} \quad (5.9.40)$$

$$\dot{Q}_{uN} = D_1 T_f + D_2 I_c(t) + D_3 T_a \quad (5.9.41)$$

where

$$D_1 = \dot{m}_f C_f \left[\left(K_k^N - 1 \right) \left(\frac{1 - e^{-z}}{1 - K_k^N e^{-z}} \right) \right]; D_2 = (AF_R(\alpha\tau))_1 \left[1 + \frac{(K_k^N - 1)e^{-z}}{1 - K_k^N e^{-z}} \right] \left(\frac{1 - K_k^N}{1 - K_k} \right); \text{ and}$$

$$D_3 = (AF_R U_L)_1 \left[1 + \frac{(K_k^N - 1)e^{-z}}{1 - K_k^N e^{-z}} \right] \left(\frac{1 - K_k^N}{1 - K_k} \right)$$

The term $(AF_R(\alpha\tau))_1$ is a function of the efficiency of the collector (η_c) [13, 26].

On substituting T_{giE} , T_{giW} , $h_{b,f}(T_b - T_f)$, and $\dot{Q}_{uN}$ from Eqs. (5.9.23) through (5.9.25), and Eq. (5.9.41), respectively, in the water-mass equation (Eq. 5.9.26), one can obtain the following:

$$\begin{aligned} \frac{dT_f}{dt} = & -T_f \left[h_{1f,E} \left(1 - \frac{B}{H} \right) \left(\frac{A_b}{2} \right) + h_{1f,W} \left(1 - \frac{B'}{H} \right) \left(\frac{A_b}{2} \right) + 2U_b \left(\frac{A_b}{2} \right) - D_1 \right] \left(\frac{1}{M_f C_f} \right) + [(\alpha_f \\ & + 2\alpha_b h_1)(I_{SE} + I_{SW}) \left(\frac{A_b}{2} \right) + h_{1f,E} \left(\frac{A}{H} \right) \left(\frac{A_b}{2} \right) + h_{1f,W} \left(\frac{A'}{H} \right) \left(\frac{A_b}{2} \right) + D_2 I_c(t) + \left(2U_b \left(\frac{A_b}{2} \right) \right. \\ & \left. + D_3 \right) T_a] \left(\frac{1}{M_f C_f} \right) \\ \frac{dT_f}{dt} = & -a_2 T_f + f_2(t) \end{aligned} \quad (5.9.42)$$

Or

$$\frac{dT_f}{dt} + a_2 T_f = f_2(t) \quad (5.9.43)$$

where

$$\begin{aligned} a_2 = & \left(\frac{A_b}{2H} \right) (H'_{11} + H''_{33}) \left(\frac{1}{M_f C_f} \right) \\ f_2(t) = & \left(\frac{A_b}{2H} \right) \{ [(\alpha_f + 2\alpha_b h_1)H + K_1 E'] I_{SE}(t) + [(\alpha_f + 2\alpha_b h_1)H + K_1 W'] I_{SW}(t) + D_2 I_c(t) \} \\ & + T_a (H'_{11} + H''_{44}) \left(\frac{1}{M_f C_f} \right) \\ H''_{44} = & U_b A_b + D_3; \end{aligned}$$

Similar to Eq. (5.9.28), the solution of the first-order differential Eq. (5.9.43) can be expressed as follows:

$$T_f = \frac{\overline{f_2(t)}}{a_2} [1 - e^{-a_2 \Delta t}] + T_{f0} e^{-a_2 \Delta t} \quad (5.9.44)$$

On substituting T_{giE} (Eq. 5.9.24), T_{giW} (Eq. 5.9.25), and T_f (Eq. 5.9.44) in Eq. (5.9.30), the instantaneous-gain thermal-energy efficiency ($\eta_{g2,th}$) of system B can be expressed as follows:

$$\eta_{g2,th} = \left(\frac{A_b}{H} \right) \left\{ \frac{\left[h_{ef,E}(E_1 + E_2)A_{gE} + h_{ef,W}(E'_1 + E'_2)A_{gW} \right] \left[\frac{\overline{f_2(t)}}{a_2} (1 - e^{-a_2 \Delta t}) + T_{f0} e^{-a_2 \Delta t} \right] - \left[(K'_{1E} I_{SE}(t) + K'_{1W} I_{SW}(t)) + T_a(H_1 + H_2 + H_3 + H_4) \right]}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} \right\} \quad (5.9.45)$$

On substituting the expressions of $f_2(t)$ and a_2 in Eq. (5.9.45), one can obtain the following:

$$\begin{aligned} \eta_{g2,th} &= \left(\frac{A_b}{H} \right) \left(\frac{e^{-a_2 \Delta t}}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} \right) \left\{ \left\{ \left[\frac{h_{ef,E}(E_1 + E_2)A_{gE} + h_{ef,W}(E'_1 + E'_2)A_{gW}}{H'_{11} + H''_{33}} \right] \{ [(\alpha_f + 2\alpha_b h_1)H + K_1 E'] I_{SE}(t) \right. \right. \right. \\ &\quad \left. \left. + [(\alpha_f + 2\alpha_b h_1)H + K_1 W'] I_{SW}(t) + D_2 I_c(t) \} (e^{a_2 \Delta t} - 1) \right\} [K_1 E' I_{SE}(t) + K_1 W' I_{SW}(t)] e^{a_2 \Delta t} \right\} + H'_{11} (T_{f0} - T_a) \} \\ &= \left(\frac{A_b}{H} \right) e^{-a_2 \Delta t} \left\{ \frac{\left\{ \left\{ Z_{22} [(\alpha_f + 2\alpha_b h_1)H + K_1 E'] I_{SE}(t) + [(\alpha_f + 2\alpha_b h_1)H + K_1 W'] I_{SW}(t) + D_2 I_c(t)] (e^{a_2 \Delta t} - 1) \right\} \right. \right. \\ &\quad \left. \left. - [K_1 E' I_{SE}(t) + K_1 W' I_{SW}(t)] e^{a_2 \Delta t} \right\}}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} \right. \\ &\quad \left. + \left[\frac{(T_{f0} - T_a)}{[A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)]} \right] H'_{11} \right\} \\ \eta_{g2,th} &= F'_{g2} \left[(\alpha \tau)_{g2,eff} + \frac{(T_{f0} - T_a)}{I(t)} (U_{g2,eff}) \right] \end{aligned} \quad (5.9.46)$$

where

$$\begin{aligned} Z_{22} &= \frac{h_{ef,E}(E_1 + E_2)A_{gE} + h_{ef,W}(E'_1 + E'_2)A_{gW}}{H'_{11} + H''_{33}}; IF'_{g2} = \left(\frac{A_b}{H} \right) e^{-a_2 \Delta t}; U_{g2,eff} = H'_{11} \\ &\quad \left\{ \left\{ Z_{22} [(\alpha_f + 2\alpha_b h_1)H + K'_{1E}] I_{SE}(t) + [(\alpha_f + 2\alpha_b h_1)H + K'_{1W}] I_{SW}(t) + D_2 I_c(t) \right\} (e^{a_2 \Delta t} - 1) \right\} \\ &\quad - [K'_{1E} I_{SE}(t) + K'_{1W} I_{SW}(t)] e^{a_2 \Delta t} \} \\ (\alpha \tau)_{g2,eff} &= \frac{\quad}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} \end{aligned}$$

Equation (5.9.46) represents the instantaneous-gain thermal-energy efficiency (characteristic equation) of an active double-slope solar still coupled with a heli-coiled heat exchanger (system B). Furthermore, an expression of

instantaneous-loss thermal-energy efficiency (characteristic equation) of system B can be obtained on substituting Eq. (5.9.43) in Eq. (5.9.34) as follows:

$$\begin{aligned}\eta_{L2,th} &= \left(\frac{M_f C_f}{A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t)} \right) \left(\frac{1}{H'_{11} + H''_{33}} \right) \left\{ \left[(\alpha_f + 2\alpha_b h_1) H + K'_{1E} \right] I_{SE}(t) \right. \\ &\quad \left. + \left[(\alpha_f + 2\alpha_b h_1) H + K'_{1W} \right] I_{SW}(t) + D_2 I_c(t) \right\} (1 - e^{-a_2 \Delta t}) + (H'_{11} + H''_{33}) (T_{fo} - T_a) (e^{-a_2 \Delta t} - 1) \} \\ \eta_{L2,th} &= F'_{L2} \left[(\alpha \tau)_{L2,eff} - U'_{L2,eff} \frac{(T_{fo} - T_a)}{I(t)} \right]\end{aligned}\quad (5.9.47)$$

where

$$\begin{aligned}F'_{L2} &= \frac{M_f C_f}{(H'_{11} + H''_{33})}; \\ (\alpha \tau)_{L2,eff} &= \frac{\left\{ \left[(\alpha_f + 2\alpha_b h_1) H + K'_{1E} \right] I_{SE}(t) + \left[(\alpha_f + 2\alpha_b h_1) H + K'_{1W} \right] I_{SW}(t) + D_2 I_c(t) \right\} (1 - e^{-a_2 \Delta t})}{I(t)} \\ U'_{L2,eff} &= (H'_{11} + H''_{33}) (1 - e^{-a_2 \Delta t}); H''_{33} = U_b A_b - D_1\end{aligned}$$

Equation (5.9.47) represents the instantaneous-loss thermal-energy efficiency (characteristic equation) of an active double-slope solar still coupled with a helically coiled heat exchanger (system B).

The characteristic equation of a solar still is found to be similar to the characteristic equation of a conventional flat-plate collector (FPC) except for the heat-removal factor. The instantaneous-loss efficiency of the solar still should be nominal to make instantaneous the gain efficiency greater. The efficiency of an ideal solar still cannot be >60%. Therefore, the sum of instantaneous-gain and -loss efficiencies is always less than the efficiency of an ideal solar still [23]. The instantaneous-loss efficiency is minimal (for zero depth of water mass) as analyzed by Cooper [27]. For typical climatic and design parameters of the still, the variation of η_i with decreased temperature $\left(\frac{T_W - T_a}{I(t)} \right)$ will show a positive slope unlike the slope of a flat-plate collector (FPC). This is due to the fact that η_i is greater for the maximum top-loss coefficient, which includes the evaporative heat-transfer coefficient, and—in the case of FPC—it should be minimum for greater η_i .

Similarly, the characteristic equation for other active systems, i.e., solar stills integrated with PVT-CPC, and ETC operating with and without a heat exchanger can be developed to study their performance.

Problems and descriptive questions

- 5.1 Derive an expression of the basin-fluid temperature of an active solar double-slope still integrated with an N-photovoltaic thermal compound-parabolic concentrators (N-PVT-CPC).
- 5.2 Develop the characteristic equation (instantaneous thermal gain and loss efficiency) of an active single-slope solar still integrated with N-PVT-CPC by operating a helically coiled heat exchanger.

- 5.3 Derive an expression of the basin-fluid temperature and develop the characteristic equation of an active double-slope solar still integrated with N-PVT-CPC by operating a helically coiled heat exchanger.
- 5.4 Develop the characteristic equation of an active double-slope solar still integrated with N-PVT-CPC.
- 5.5 Derive an expression of the basin-fluid temperature of an active double-slope solar still integrated with N-evacuated tubular collectors (N-ETC).
- 5.6 Develop the characteristic equation of an active double-slope solar still integrated with N-ETC.
- 5.7 Derive an expression of the basin-fluid temperature and develop the characteristic equation of an active double-slope solar still integrated with N-ETC by operating a helically coiled heat exchanger.
- 5.8 Derive an expression of the basin-fluid temperature and develop the characteristic equation of an active single-slope solar still integrated with N-ETC by operating a helically coiled heat exchanger.
- 5.9 Discuss the following active solar-distillation systems in detail:
 - (a) a multi-effect active solar still (i.e., the effect of a number of stages),
 - (b) a fin-type solar still integrated with a fin-type mini solar pond
- 5.10 Discuss the multi-effect diffusion solar still integrated with a vacuum tubular collector and heat pipe.
- 5.11 Derive an expression for the characteristic equation of an active double-slope solar still integrated with N-PVT-FPC and a helically coiled heat exchanger. Calculate the thermal energy, exergy, instantaneous thermal gain/loss energy efficiency, and productivity of the system given the following:
 $I_c = 700 \text{ W/m}^2$, $I_{gE} = 600 \text{ W/m}^2$, $I_{gW} = 550 \text{ W/m}^2$, $T_a = 22^\circ\text{C}$, $N = 4$.

Other specifications of different parts of the active system are given below:

Parameter	Numerical value	Parameter	Numerical value
α_g	0.05	A_m	0.605 m^2
α_b	0.8	A_c	1.395 m^2
α_{BF}	0.6	L_p	0.002 m
α_c	0.9	K_p	64 w/m K
α_p	0.80	K_i	0.166 w/m K
β	0.89	L_i	0.1 m
ϵ_g	0.95	h_i	$5.7 \text{ w/m}^2 \text{ K}$
ϵ_{bf}	0.95	h_0	$9.5 \text{ w/m}^2 \text{ K}$
σ	$5.67 \times 10^{-8} \text{ (W/m}^2 \text{ K}^4)$	$U_{tc,p}$	$5.58 \text{ w/m}^2 \text{ K}$
K_g	$0.780 \text{ (W/m } ^\circ\text{C)}$	$U_{tc,a}$	$9.20 \text{ w/m}^2 \text{ K}$
K_B	$0.035 \text{ (W/m } ^\circ\text{C)}$	$U_{tp,a}$	$4.74 \text{ w/m}^2 \text{ K}$
L_g	0.004	$U_{L,m}$	$7.58 \text{ w/m}^2 \text{ K}$
L_b	0.005 m	$U_{L,c}$	$4.52 \text{ w/m}^2 \text{ K}$

(continued)

(continued)

Parameter	Numerical value	Parameter	Numerical value
β_0	0.0045/K	PF_1	0.378
X	0.33 m	PF_2	0.934
τ_g	0.95	PF_c	0.955
F'	0.968	η_0	0.15
<i>Double slope solar still</i>			
Area of the glass cover (A_{gE} and A_{gE})			1.025 m $\times$ 1.025 m
Basin area (A_B)			2 m $\times$ 1 m
Inclination of the cover (θ)			30°
<i>Flat Plate Collectors (tube in plate type)</i>			
Area of each collector	2.00 m ²	Thickness of the insulation	0.1 m
Tube material	Copper tubes	Weight of the collector	48 kg
Tube diameter	0.0125 m	Collector-efficiency factor	0.968
Plate thickness	0.002 m	Angle of collectors	45°
Riser, outer diameter	0.0127 m	Thickness of the top glass	0.004 m (Toughened)
Riser thickness	0.56×10^{-3}	Motor used for water pump	Dc shunt motor 18 V, 40 W and 2800 rpm
Spacing between the two risers	0.112 m	Effective area of the collector under the glass	1.34 m ²
Effective area of the collector under the PV module	0.66 m ²		
<i>PV module (under standard test conditions)</i>			
Area of a single solar cell	0.007 m ²	Fill factor	0.8
Size of the PV module	1.25 m $\times$ 0.55 m	Efficiency of the module	12%
No. of solar cells	36	Maximum power rating (P_{max})	40 W
<i>Helical heat exchanger (copper)</i>			
Length of the heat exchanger	0.937 m	Diameter of the coil	0.045 m
Diameter of the coil tube	0.0125 m	No. of turns	12

- 5.12 Derive an expression for the characteristic equation of an active double-slope solar still integrated with N-PVT-FPC (without a heat exchanger). Calculate the thermal-energy, exergy, instantaneous thermal gain/loss energy efficiency, and productivity of the system for the same specifications and parameters given in Problem 5.11.

Objective questions

- 5.1 A PVT system can be used in a water-heating system due to which of the following reasons?
- It produces both electrical and thermal energy.
 - It produces thermal energy only.
 - It produces electrical energy only.
- 5.2 Which of the following is the most essential factor to determine the performance of flat-plate collector (FPC)?
- Heat gain
 - Heat loss
 - None of these
- 5.3 What is the purpose of the aperture in a PVT compound-parabolic concentrator (PVT-CPC)?
- Reflect the beam radiation on the water-collector part
 - Reflect the total radiation on the water-collector part
 - Reflect the diffused radiation on the water-collector part
- 5.4 Which of the following is the correct solution of the first-order differential equation, $\frac{dT_w}{dt} + aT_w = f(t)$, of a solar still?
- $T_w = \frac{\overline{f(t)}}{a} [1 + e^{-a\Delta t}] + T_{w0} e^{-a\Delta t}$
 - $T_w = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] - T_{w0} e^{-a\Delta t}$
 - $T_w = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] + T_{w0} e^{-a\Delta t}$
 - $T_w = \frac{\overline{f(t)}}{a} [1 - e^{a\Delta t}] + T_{w0} e^{a\Delta t}$
- 5.5 The purpose of the reflector placed under the bottom of an inverted-absorber solar still integrated with a refrigeration cycle is:
- To heat the basin
 - For thermal-energy storage
 - None of these

- 5.6 In the system of an inverted-absorber solar still integrated with a refrigeration cycle, a uniform flow of cold water is used on the condensing cover of the still:
- (a) For maintaining the low temperature of the cover
 - (b) To minimize heat loss
 - (c) To decrease the temperature difference between the glass cover and the basin water
- 5.7 The refrigeration cycle part of the inverted-absorber solar still integrated with refrigeration-cycle system has which of the following significant effects?
- (a) Adds extra thermal energy only
 - (b) Increases the rate of condensation
 - (c) Saturates the rate of condensation
 - (d) Both (a) and (b)
- 5.8 What is the functioning of a heat-recovery exchanger in a multi-effect diffusion solar still integrated with a vacuum-tube collector and heat pipe?
- (a) Preheat the salt water
 - (b) Extract contamination from the saline water
 - (c) None of these
- 5.9 What is the purpose of bending a wick plate in the multi-effect diffusion unit (MDU)?
- (a) To avoid the contamination of distilled water only
 - (b) To avoid blockage of the heat-conduction path only
 - (c) To increase blockage of the heat-conduction path only
 - (d) Both (a) and (b)
- 5.10 Due to Which of the following reasons should a shallow solar pond be fully packed with water?
- (a) To decrease the evaporation process
 - (b) To increase evaporation process
 - (c) None of these
- 5.11 Due to which of the following reasons are fins installed on the basin surface of a fin-type solar still integrated with a fin-type solar pond?
- (a) Increase the surface area of the base
 - (b) Decrease the surface area of the base
 - (c) Lower the temperature of the saline water

- 5.12 The heat-storing capacity of a fin-type solar pond depends on what?
- The shape of the solar pond
 - The material to construct the solar pond
 - The surface area of the solar pond
 - None of these
- 5.13 The efficiency of an ideal solar still cannot be:
- >50%
 - >80%
 - >30%
 - >60%
- 5.14 For greater instantaneous gain efficiency, the instantaneous-loss efficiency of the solar still should be:
- Minimum
 - Maximum
 - Constant
- 5.15 From the variation of η_i with $\frac{(T_W - T_a)}{I(t)}$, the slope of a solar still is positive due to which of the following reasons?
- Minimum bottom-loss coefficient
 - Minimum top-loss coefficient
 - Maximum top-loss coefficient
 - Minimum side losses

Answers

- 5.1 (a) 5.2 (b) 5.3 (a) 5.4 (c) 5.5 (a) 5.6 (a) 5.7 (d) 5.8 (a) 5.9 (d) 5.10 (a) 5.11 (a) 5.12 (c) 5.13 (d) 5.14 (a) 5.15 (c)

References

- H.S. Soliman, *Solar still coupled with a solar water heater*. (Mosul University, Iraq, 1976)
- B.J. Huang, T.L. Chong, P.H. Wo, H.Y. Dai, Y.C. Kao, Spiral multiple-effect diffusion solar still coupled with vacuum-tube collector and heat pipe. *Desalination* **362**, 74–83 (2015)
- H. Ling, C. Chen, Y. Guan, S. Wei, Z. Chen, N. Li, Active heat storage characteristics of active–passive triple wall with phase change material. *Sol. Energy* **110**, 276–285 (2014)
- A.A. Sebaii, M.R.I. Ramadan, S. Enein, M. Naggar, Effect of fin configuration parameters on single basin solar still performance. *Desalination* **365**, 15–24 (2015)
- M. Feilizadeh, M.R.K. Estahbanati, A.S. Ardekani, S.M.E. Zakeri, K. Jafarpur, Effects of amount and mode of input energy on the performance of a multi-stage solar still: an experimental study. *Desalination* **375**, 108–115 (2015)
- N. Rahbar, J.A. Esfahani, E. Bafghi, Estimation of convective heat transfer coefficient and water-productivity in a tubular solar still—CFD simulation and theoretical analysis. *Sol. Energy* **113**, 313–323 (2015)

7. M.M. Morad, A.M. Maghawry, K.I. Wasfy, Improving the double slope solar still performance by using flat-plate solar collector and cooling glass cover. *Desalination* **373**, 1–9 (2015)
8. M.A. Nimr, M.E. Dahdolan, Modeling of a novel concentrated solar still enhanced with a porous evaporator and an internal condenser. *Sol. Energy* **114**, 8–16 (2015)
9. A.A. Dehghan, A. Afshari, N. Rahbar, Thermal modeling and exergetic analysis of a thermoelectric assisted solar still. *Sol. Energy* **115**, 277–288 (2015)
10. F.B. Ziabari, A.Z. Sharak, H. Moghadam, F.F. Tabrizi, Theoretical and experimental study of cascade solar stills. *Sol. Energy* **90**, 205–211 (2013)
11. O.A. Hamadou, K. Abdellatif, Modeling an active solar still for sea water desalination process optimization. *Desalination* **354**, 1–8 (2014)
12. H. Taghvaei, H. Taghvaei, K. Jafarpur, M. Feilizadeh, M.R.K. Estahbanati, Experimental investigation of the effect of solar collecting area on the performance of active solar stills with different brine depths. *Desalination* **358**, 76–83 (2015)
13. Shyam, G.N. Tiwari, I.M. Helal, Analytical expression of temperature dependent electrical efficiency of N-PVT water collectors connected in series. *Sol. Energy* **114**, 61–76 (2015)
14. D.B. Singh, J.K. Yadav, V.K. Dwivedi, S. Kumar, G.N. Tiwari, I.M. Al-Helal, Experimental studies of active solar still integrated with two hybrid PVT collectors. *Sol. Energy* **130**, 207–223 (2016)
15. S. Kumar, A. Dubey, G.N. Tiwari, A solar still augmented with an evacuated tubular collector in forced mode. *Desalination* **347**, 15–24 (2014)
16. G.N. Tiwari, *Solar Energy: Fundamentals, Designs, Modeling and Applications* (Narso Publishing House, New Delhi, 2002)
17. D.B. Singh, G.N. Tiwari, Effect of energy matrices on life cycle cost analysis of partially covered photovoltaic compound parabolic concentrator collector active solar distillation system. *Desalination* **397**, 75–91 (2016)
18. S.A.A. Wahab, Y.Y. Hatmi, Study of the performance of the inverted solar still integrated with a refrigeration cycle. *Procedia Eng.* **33**, 424–434 (2012)
19. B.J. Huang, T.L. Chong, P.H. Wo, Y.C. Kao, Multiple-effect diffusion solar still coupled with a vacuum-tube collector and heat pipe. *Desalination* **347**, 66–76 (2014)
20. M.R.K. Estahbanati, M. Feilizadeh, K. Jafarpur, M. Feilizadeh, M.R. Rahimpour, Experimental investigation of a multi-effect active solar still: the effect of the number of stages. *Appl. Energy* **137**, 46–55 (2015)
21. A.A. Sebaii, M.R.I. Ramadan, S.A. Enein, N. Salem, Thermal performance of a single-basin solar still integrated with a shallow solar pond. *Energy Convers. Manag.* **49**, 2839–2848 (2008)
22. M. Appadurai, V. Velmurugan, Performance analysis of fin type solar still integrated with fin type mini solar pond. *Sustain. Energy Technol. Assess.* **9**, 30–36 (2015)
23. R. Dev, G.N. Tiwari, Characteristic equation of a hybrid (PV-T) active solar still. *Desalination* **254**, 126–137 (2010)
24. A. Tamini, Performance of a solar still with reflectors and black dyes. *Solar Wind Technol.* **4**, 443–446 (1987)
25. M. Boukar, A. Harmim, Performance evaluation of a one-sided vertical solar still tested in the desert of Algeria. *Desalination* **183**, 113–126 (2005)
26. Shyam, G.N. Tiwari, O. Fischer, R.K. Mishra, I.M. Al-Helal, Performance evaluation of N-photovoltaic thermal (PVT) water collectors partially covered by photovoltaic module connected in series: an experimental study. *Sol. Energy* **130**, 302–313 (2016)
27. P.I. Cooper, Maximum efficiency of a single effect solar still. *Sol. Energy* **15**, 205–214 (1973)

Chapter 6

Parametric Study of Solar Distillation and Its Application

6.1 Introduction

The daily/annual productivity (yield) from any solar-distillation system (solar still) mainly depends on climatic parameters such as solar intensity, wind velocity, and ambient air temperature. In addition, it also depends on the design parameters of the solar still viz. absorptivity, water depth, impurity in water mass, inclination of condensing cover, and bottom insulation thickness, etc. These parameters affect the temperature difference between the basin-water surface (evaporative surface) and the inner surface of transparent-glass cover. Basically, this temperature difference acts as a driving force for the solar-distillation process, as explained previously in Chap. 3, such that a greater temperature difference between these two surfaces in the solar still cavity gives to a greater daily/annual productivity. The meteorological parameters significantly affect the performance of solar stills. It has been reported in the literature that the output from solar stills is high for low ambient temperature and greater solar radiation intensity. The effect of different parameters is discussed in detail. The distilled water obtained from a solar still has the following applications:

- (i) **Charging of batteries:** distilled water (specification Table 6.5) can be used for charging batteries to boost their life. This enables the economic viability of batteries in remote areas of underdeveloped countries. Generally, they use tap water due to (a) the non-availability of distilled water and (ii) the high cost.
- (ii) **Cleaning of medical tools:** Generally, the dispensary equipment in remote areas is cleaned with tap water, which is not hygienic due to the non-availability of proper distilled water. Distilled water obtained from a solar still will solve this problem.

- (iii) **Industrial application:** There is much use of distilled water in chemical and textile industries where purity of water plays very important role, i.e., double distillation or dyeing of cloth, etc.

Moreover, in this chapter, various other applications of solar-distillation systems are explored in detail.

6.2 Effect of Basin Absorptivity

The basin surface plays a vital role to improve solar still productivity (yield). The basin liner or blackened surface of the solar still is responsible to absorb the maximum solar radiation incident on the solar still. Therefore, the inner surface of the solar still basin is painted matte black. The absorbed thermal energy in the basin is further transferred to the saline or filthy water in the solar still by way of the mechanism of natural convection and thus increases the basin-water temperature. Consequently, it improves heat-transfer rates from the basin-water surface to the inner surface of the transparent-glass cover and hence in turn increases the system productivity. The absorptivity can be enhanced by the following methods.

6.2.1 Influence of Using Dye

As discussed in previous chapters, most of the solar energy that penetrates through the transparent-glass cover is absorbed by the basin liner in a conventional solar still. Therefore, it becomes hotter, and the absorbed thermal energy is transferred to the basin water. Generally, the basin liner transfers most of the stored thermal energy to the basin water, but a significant amount is lost from the bottom and sides to the ambient air by way of the conduction mechanism for a solar still fabricated without insulation. This difficulty can be solved by incorporating the black dye to the saline water in the solar still. As a consequence, most of the solar energy is absorbed by the basin water itself on adding a dye such that the basin of the solar still does not become heated and hence minimizes losses from the solar still (sides and bottom) to the ambient. The significant enhancement of basin-water (saline) temperature on the addition of dye increases the temperature difference between the water surface and the inner surface of the transparent-glass cover, which in turn remarkably improves the solar still productivity.

Experimentally, it has been observed that dye improves the total output of the solar still by 16% (average) at greater depth. Among three different colors (red, blue, and black) of the dyes, black color gives a better output at greater basin-water depth (≥ 10 m).

Rajvanshi and Hsieh [1] systematically studied the effect of a dye on the performance of a solar still by assuming a blackened surface and a thermally stratified

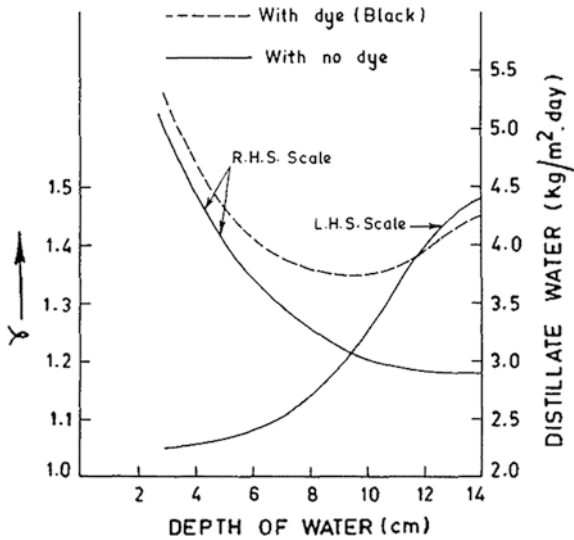
Table 6.1 Effect of dye on the daily productivity [1]

Color of dye	Daily productivity/m ² , (liter, l), Depth = 0.1 m		$R = \frac{\text{Output with dye}}{\text{Output without dye}}$	Total insolation (kJ/m ² day)
	With dye	Without dye		
Black	3.862	3.066	1.26	2.477×10^4
Red	3.3037	3.066	1.08	2.477×10^4
Violet	3.799	3.09	1.23	2.871×10^4

water-column system. They developed a computer program to investigate the energy-exchange process between the fluid layers and the blackened surface. They observed good agreement between the theoretical and experimental results. Table 6.1 lists the daily productivity of the solar still using different dyes. It has been found that black and violet dyes give better results in terms of productivity (solar still). This is understandable in terms of the spectral distribution of solar radiation. The variation of daily productivity of a solar still with and without dye as a function of basin-water depth is shown in Fig. 6.1.

It has been observed that the incorporation of black dye into a 0.10 m depth of saline water enhances the solar still productivity by approximately 26%. The productivity of a solar still with and without dye was found to be independent of water depth for a basin-water depth >0.10 m as presented in Fig. 6.1. In addition, Bloemer et al. [2] and Cooper [3] achieved the same result for the case of a solar still without dye. Cooper [4] reported an improvement in productivity of approximately 60% for 0.02 m water depth. The effect of dye on solar-still performance has been found to improve marginally for low basin-water depths.

Fig. 6.1 Variation of daily distillate output of the still obtained using dye (*black*) and without dye with the basin water depth [5]



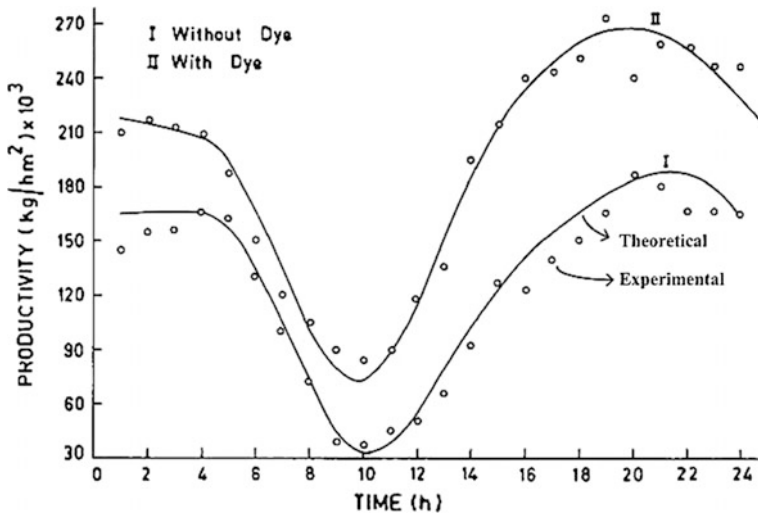


Fig. 6.2 Hourly variation of productivity per meter square basin area of the still [5]

On the basis of theoretical and experimental observations, the hourly variation of productivity per unit basin area of the solar still with and without dye is shown in Fig. 6.2. It has been perceived that the computed values are in close agreement with the experimental results.

6.2.2 Influence of Scaling in the Basin

Scaling is an important parameter, and its effect depends on the salinity of the available basin water for distillation. Frequent cleaning of the solar still basin is required for highly saline water. The salinity of the seawater is 5×10^4 ppm, which requires frequent basin cleaning compared with underground water having a salinity of approximately 5×10^3 ppm. Therefore, solar-still maintenance for seawater as feed water for distillation may not be practicable due to a rapid decrease in the absorptivity of the basin line, which occurs due to the fast scaling of salt.

The presence of impurities—such as arsenic, fluoride, and iron content—in basin water does not affect solar-still productivity very much. In contrast, the daily/annual productivity per square meter of the solar still (experimentally) decreases linearly on increasing the salt concentration of the basin water up to the saturation point. Moreover, it is essential to use highly non-corrosive or non-oxidized materials in the solar still to avoid corrosion damage of the components due to high salt concentration. Therefore, high salt concentration or highly saline water in a solar still decreases its productivity and life and increases the maintenance (cleaning) costs.

6.2.3 Influence of Algae Formation

The presence of any kind of deposit materials on the basin-water surface and basin liner can significantly decrease solar-still productivity. The basin liner has absorbing properties (except at normal incidence); therefore, the basin liner reflection appears to be more favorable than the basin water–surface reflection. Consequently, the formation of algae prevents radiation to reach the basin surface, which decreases the solar-still productivity and increases the maintenance (periodic cleaning) costs.

6.2.4 Effect of Charcoal

Akinsete and Duru [6] investigated the effect of charcoal and concluded that its effect is most prominent on cloudy days as well as in the early morning (low direct solar radiation). The presence of charcoal pieces enables diffuse radiation much better than the conventional unlined solar still. Furthermore, it has been found that the charcoal-lined solar still is relatively insensitive to basin-water depth as long as a good amount of the charcoal remains uncovered. The solar-still basin and charcoal surface requires regular cleaning, which makes the solar still very expensive from a maintenance point of view. A similar problem occurred in the case of a solar still with black dye. The effect of black dye is significant at greater basin-water depth (≥ 0.10 m) as discussed previously. Because a solar still with charcoal gives a better performance (daily/annual productivity) at lower basin-water depth, charcoal is recommended for this case.

The following are facts about the use of charcoal significantly to enhance the productivity of solar still:

- (i) Charcoal is wettable.
- (ii) Charcoal has a large absorption coefficient to receive solar radiation.
- (iii) Charcoal has the property of scattering rather than reflecting solar radiation.

Wibulswas and Tadtium [7] also studied solar-still performance by incorporating a black butyl rubber sheet and charcoal chips. It was found that both show the same effect on solar-still performance; therefore, charcoal is recommended from an economic point of view.

Experimentally, for greater basin-water depths, a significant enhancement approximately 24–28% in the overall efficiency of the solar still has been observed with floating charcoal pieces. The combined effect of black dye and floating charcoal over the basin-water mass does not improve the solar-still performance. This is credited to the fact that charcoal has two desirable properties viz. a large black surface area for the absorption of solar radiation and a large surface area for evaporation (Table 6.2).

Table 6.2 Solar still productivity containing floating charcoal with and without dye for 0.06 m basin water depth [21]

Set	With floating coal (l/m ² day)	Without floating coal (l/m ² day)	Enhancement (%)
(a) <i>Effect of floating charcoal (without any dye)</i>			
I	1.44	1.08	33
	0.68	0.55	23
	1.15	0.90	27
	1.25	0.90	30
	1.31	1.01	30
	Average increase = 28.6%		
II	3.28	2.56	28
	3.43	2.76	24
	2.84	2.56	11
	3.43	2.58	32
		Average increase = 24%	
(b) <i>Effect of floating charcoal in presence of dye 500 ppm</i>			
III	1.50	1.42	5
	1.71	1.40	22
	0.78	0.68	14
	1.69	1.25	35
		Average increase = 23.6%	

6.3 Effect of Climatic Conditions

Climatic parameters strongly influence solar-still productivity. Some important climatic parameters are discussed as follows.

6.3.1 Wind Velocity

Wind can flow over the top transparent-glass cover as well as below the bottom of the solar still (e.g., solar still placed on a stand). However, the wind below the solar still bottom has an insignificant effect on the annual/daily productivity (yield) if the basin is constructed with an insulating material. Greater wind velocity over the glass cover increases the convective-heat loss, which in turn lowers the temperature of the glass cover. Eventually, the temperature difference between the evaporative or basin-water surface and inner surface of the glass cover increases; hence, this significantly increases the solar-still productivity. It has been found that this effect dominates at lower basin-water depth, and approximately 1–10% variation in the overall daily/annual productivity [8] has been reported. Löf et al. [9], Cooper [10], and Morse and Read [11] studied the effect of wind velocity on solar-still performance and reported different results. Löf et al. [9] observed that solar-still

productivity decreases on increasing the wind velocity. These results beg to find the exact effect of the wind velocity on solar-still performance. Farid and Hamad [12] also reported the same results as given by Löf et al. [9]. They concluded that the solar still can be placed in an area of lower wind velocity for better productivity.

Elsherbiny and Fath [33] observed a decrement in total productivity by <10% on increasing the wind velocity from 0 to 8 m/s. In contrast; Toure and Meukam [13] predicted an enhancement in total productivity by <10% on increasing the wind speed from 0 to 9 m/s. This result is in agreement with the analysis carried by Cooper [4], who concluded that for greater basin-water temperature, the temperature difference between basin-water surface and the inner surface of the glass cover can be increased further by lowering the glass cover temperature at a faster rate by increasing the wind velocity. This eventually increases the evaporative heat-transfer rate and hence increases the solar-still productivity. For passive solar stills, the effect of wind velocity is in agreement with the results of Cooper. Solar-still productivity decreases only at lower wind velocity (<1 m/s), and it remains constant at greater wind velocity. Agrawal [14] found that the productivity of a conventional solar still enhances by 11% on increasing the wind velocity from 1 to 7 m/s.

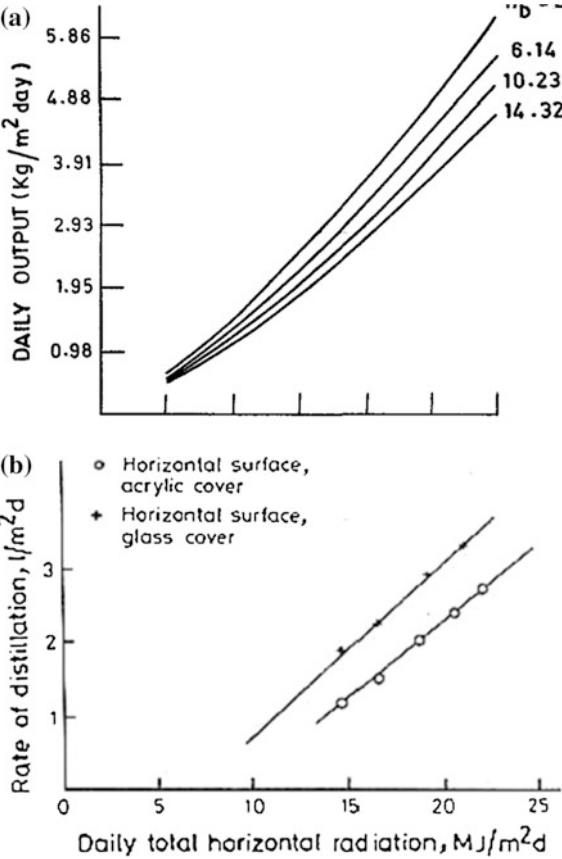
In the case of an active solar still, there is a considerable increase in productivity with an increase in wind velocity. This is credited to the fact that the mutual effect of the preheated basin water and the wind velocity (which cools the glass surface) increases the temperature difference, between two surfaces (water surface and inner surface of the cover) within the solar still cavity; which in turn increases the evaporative heat transfer and hence the solar-still productivity. Precisely, the solar-still productivity improves by 45% on increasing the wind velocity from 1 to 8 m/s in the case of active solar still. The results for an active solar still are in accordance with those of Soliman [15].

6.3.2 *Solar Radiation*

Solar radiation falling on the solar still acts as an input energy to heat the basin-water mass, and thus it plays a direct role on the daily productivity of a solar still. Ahmadzadeh [16] and Cooper [17] observed that solar-still productivity increases continuously with an increase in total solar radiation. This occurs due to an increase in basin-water temperature, which enhances the rate of evaporation. Hourly variation of daily distillate output depends upon the way in which the solar radiation is distributed throughout the day. In case of both an active and a passive solar still, the net increase in daily productivity decreases significantly at high insolation due to greater glass-cover temperature. This is due to the fact that the rate of release of latent heat of water vapor (vaporization) is not much greater than the rate of release of heat from the glass to the ambient air.

Solar radiation (insolation) is the single most significant factor to determine the solar-still productivity as shown in Fig. 6.3a, b [7, 18]. To some extent, it depends on the distribution of solar radiation throughout the day, however, it is a

Fig. 6.3 a Effect of solar radiation and loss coefficient on predicted output, from the still at ambient temperature $T_a = 27^\circ\text{C}$, heat capacity $= 327\text{ kJ/m}^2\text{ }^\circ\text{C}$, wind velocity $v = 2.23\text{ m/s}$ [18] and **b** comparison of rates of distillation of solar stills with horizontal absorbing surfaces [7]



second-order effect, and it is usually sufficient to consider only the total radiation received each day.

Greater values of both daily insolation [19] and mean ambient temperature are the best conditions for a solar still (Fig. 6.3a, b). Figure 6.4 clearly shows that the bottom-loss coefficient has same influence on all ambient temperatures. The solar-still productivity increases approximately 45% for decrease in loss coefficient by a factor of 5, which is in close agreement with the work of Morse and Read [11].

6.3.3 Sky and Ambient Temperature

6.3.3.1 Effect of Sky Temperature

On the basis of external (radiative and convective) heat-transfer coefficients from the glass to the ambient, the effect of sky temperature on daily solar-still

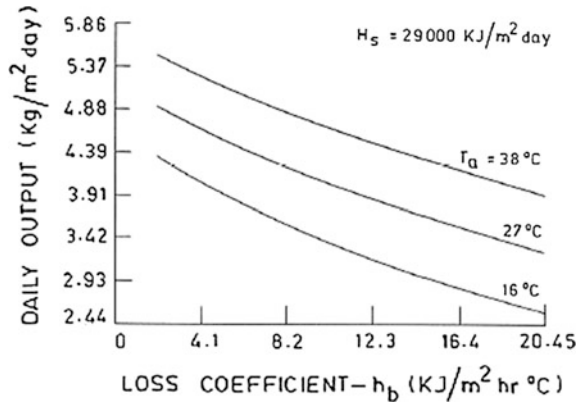


Fig. 6.4 Effect of ambient temperature and loss coefficient on predicted still productivity at solar intensity 29,000 $\text{kJ/m}^2 \text{ day}$ [18]

productivity can be observed. The total productivity increases by only 40 ml with every 2°C increase in ambient temperature. The improvement is very small compared with the total productivity.

6.3.3.2 Effect of Ambient Temperature

The ambient temperature decreases smoothly and gradually, especially in winter seasons or cooler locations, which significantly lowers the transparent glass-cover temperature. Consequently, the temperature difference between two surfaces (the evaporative surface and the inner surface of the glass cover) within the still cavity increases, which ultimately increases the solar-still productivity despite the general decrease in the overall system temperature. If the ambient temperature is low during the night, the solar still performs better at greater basin-water depths. A solar still gives maximum daily/annual productivity in locations where lower values of ambient air and high solar radiation are observed.

Morse and Read [11] observed an approximately 11% enhancement in solar-still productivity for a change in ambient temperature from 26.7 to 37.8°C , whereas a 14% decrease has been found for a change in ambient temperature from 26.7 to 15.6°C . Furthermore, Cooper [3] reported that solar-still productivity decreases on decreasing the average ambient temperature. In this case, it is not sufficient to compensate for the general decrease in the overall temperature of the system even though both the water and glass temperatures decrease (difference increases). This effect becomes an evident at relatively lower temperatures, which is in agreement with the previous work of Lof et al. [9]. This phenomenon to a good extent clarifies the increase in internal convective and evaporative heat-transfer coefficients with an increase in basin-water temperature.

6.3.4 *Inclination of Glass Cover and Bottom Insulation*

The effects of the glass-cover inclination and the bottom insulation on solar-still productivity are as follows.

6.3.4.1 **Effect of Inclination**

Various researchers have studied the effect of glass-cover inclination on solar-still performance. For better productivity, the proper inclination angle of the top glass cover varies from season to season (i.e., retrieved solar radiation). It can be optimized on the basis of annual productivity per m^2 of the solar still. Singh and Tiwari [20] suggested that the optimized inclination of the glass cover is equal to the latitude of the place for the northern part of India and also depends on the climatic parameters of that particular place. For both single-slope and non-symmetrical double-slope solar stills, it mainly depends on the location, season, and cover material. On an experimental basis, various researchers have suggested that the minimum inclination angle of the glass cover should be at least 10° to avoid the drop-back of condensate. Moreover, it can be avoided by proper cleaning of inner surface of the glass cover before the final assembly; however, this may generally not possible in the case of large installations. It is essential to optimize the inclination angle for summer conditions due to the large demand of potable water during this season. For an acrylic plastic cover, the optimized inclination angle is different compared with the case of transparent-glass cover due to a greater surface tension between the evaporative surface and the plastic cover.

Figure 6.5 shows the variation of rate of distillate output per m^2 -day with different slopes of the acrylic cover. It has been perceived that solar-still productivity is lower by approximately 30% with an acrylic cover for an annual average daily radiation of 17 MJ/m^2 (Wibulswas and Tadtium [7]). The optimum inclinations of the glass cover for some locations obtained on the basis of experiment observations are listed in Table 6.3.

Aberibigbc [22] reported the optimized inclination angle of the glazing (transparent-glass cover) for maximum annual productivity by considering the heat and mass transfer as a function of latitude (Table 6.4). The glazing surface area increases by 5 and 14% on increasing the inclination angle from 10° to 20° , and 10° to 30° , respectively. Moreover, it increases the cavity volume within the solar still, which delays the start of the distillation process by the time that vapors fill it.

6.3.4.2 **Effect of Bottom Insulation**

Optimization of the bottom-insulation thickness of the basin depends on the basin-water depth. It plays a vital role at greater depth due to the nocturnal

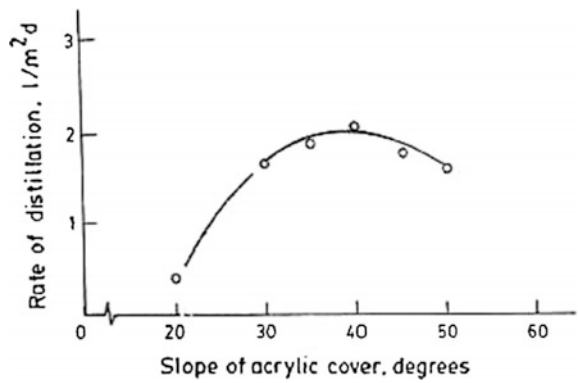


Fig. 6.5 Variation of the rate of distillation with the slope of the acrylic cover using a horizontal absorbing surface [7]

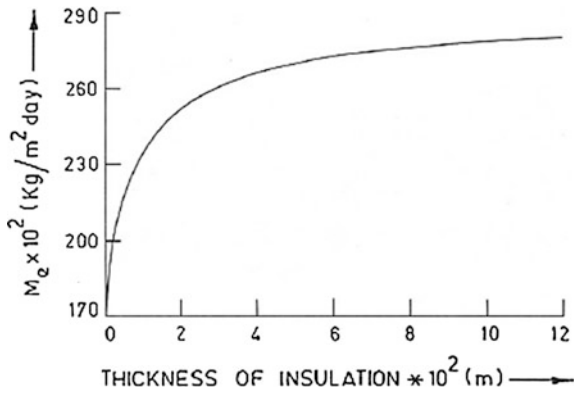
Table 6.3 Optimum tilt of condensing cover for different locations

Location (Country)	Latitude	References	Season	Optimum tilt angle (°)
Bagdad (Iraq)	32°N	Ahmed [34]	Spring	30
Bangkok (Thailand)	13° 42'N	Wibulsawas et al. [35]	Summer	14
Cairo (Egypt)	30° 2'N	Abdel-Salem et al. [36]	Summer Winter	5
Delhi (India)	28° 38'N	Garg and Mann [37] and Malik et al. [38] Tiwari and Tiwari [39]	Summer Summer Winter Annual	10–20 15 45
Irbid (Jordon)	32°N	Tamini [27]	Winter	45
Japan	40°N	Watanabe et al. [40]	Over the year	30
Jeddah (Saudi Arabia)	21° 32'N	Madani and Zaki [43]	Over the year	20
Nasar (Egypt)	25°N	El-Rafaie et al. [41]	–	30
Nigeria	10°N	Akinsete [42]	–	12
Tripoli (Libya)	32° 50'N	Zaki et al. [44]	Winter	10
Qatar	25° 30'N	Kamal [45]	Summer	10

Table 6.4 Optimum tilts of condensing cover [22]

Inclination (°)	Latitude (°)
$\beta = 14^\circ$	$\varphi \leq 14^\circ\text{N}$ or 14°S
$6^\circ < \beta < 26^\circ$	$14^\circ\text{N} < \varphi < 53^\circ\text{N}$
$7.5^\circ < \beta < 20^\circ$	$15^\circ\text{S} < \varphi < 55^\circ\text{S}$

Fig. 6.6 Variation of average production per unit basin area of mounted still with thickness of insulation [23]



production of potable water. The thickness also depends on the type of insulation and its compactness. For example, the basin of fibre-reinforced plastic (FRP) may be on the order of 0.003 m thick.

The variation of productivity of the solar still according to insulation thickness is depicted in Fig. 6.6. It can be observed that the productivity increases rapidly on increasing the insulation thickness ≤ 4 cm, and then it increases rather slowly (i.e., becomes almost completely saturated).

The variation of solar-still productivity with insolation for both the bottom-insulated and non-insulated solar still is shown in Fig. 6.7. The daily productivity varies from 0.3 to 2.722 kg for insolation of 4100 and 130,000 kJ/m^2 , respectively. It has been found that for constant feed water flow, the productivity increases with increasing insolation and ambient temperature. It lowers the

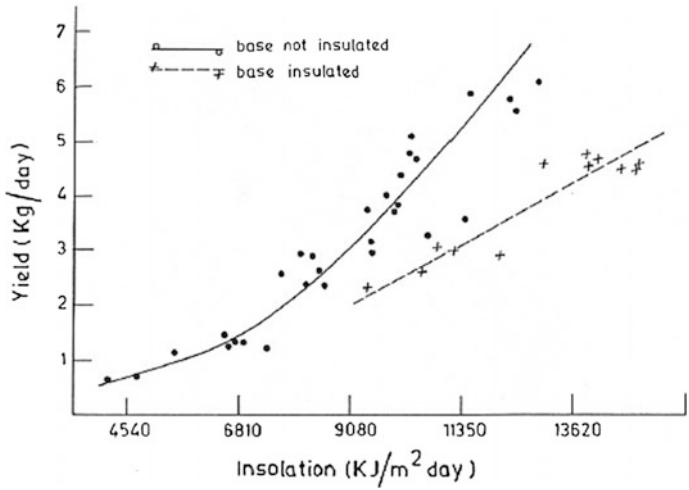


Fig. 6.7 Total productivity (yield) per day [24]

discharge brine flow and hence the sensible heat loss. It is expected that the productivity enhancement with increasing insolation will tend to flatten due to greater thermal losses at greater insolation and temperature. Scattering of the experimental results is credited to the inability to keep the flow rate and ratio of flows constant over long periods of time. In general, the points above the curve are for flows less than those chosen below the curve.

6.4 Effect of Water Depth

So far, it is clear and understood that greater basin-water depth means (basin water) greater heat-storing capacity of the solar still. The effect of this storing capacity plays a different role in passive versus active solar still as discussed here.

6.4.1 *Passive Solar Still*

Solar-still performance is better at low basin-water depths. This is credited to the a fast increase in basin-water temperature with a minimum storage effect, which increases the evaporation rate and hence improves the solar-still productivity. For greater basin-water depth, solar-still productivity can be improved by flowing water over the top transparent-glass cover. This heat removal increases the temperature difference between the basin-water surface and the inner surface of the glass cover, which drives the greater rate of evaporation and hence productivity. It has been observed that there is no significant enhancement in productivity on increasing the water-low rate over the glass cover.

Daily/annual productivity of the solar still decreases rapidly up to water depth of 0.10 m, and then it deteriorates for a passive solar still. It is a crucial parameter that affects the daily/annual productivity for a passive solar still. El-Sebaï [25] reported that the operating basin-water depth is approximately 0.05 m. The overall thermal efficiency of a passive versus active solar still is different because it depends on an operating temperature for given climatic parameters.

The operating-temperature range for an active solar still is much greater than that for a passive solar still. It depends on (a) the type of the collectors used for active heating, (b) the number of collectors used for heating, and (c) the connection of the collectors (series vs. parallel).

Morse and Read [11] investigated the effect of thermal water capacity on solar-still productivity. According to CSIRO (Commonwealth Scientific and Industrial Research Organization), a ground-based, bottom-insulated solar still (Australia), the most suitable water depth is 7.6 cm corresponding to 1.41 kJ/m^2 thermal capacity. For the solar stills resting on the ground without insulation, the most suitable water depth has been found to be 2.54 cm. The solar-still productivity enhances by 9% on decreasing the thermal capacity from $1.41 \text{ kJ/m}^2/\text{h}$ to zero for

225 kJ/m² daily insolation. In contrast, 0.3 m water depth decreases solar-still productivity by 7%. Thus, basin-water depth is not a critical parameter for the maintenance, and it should be as low as possible.

The effect of water depth on solar-still productivity was investigated by Cooper [3], and the results are presented in Fig. 6.8. It is clear that there is marginal enhancement in the gain on lowering the water depth for the solar still without insulation. However, a drastic change has been observed in case of the case of solar still with insulation especially in shallow water depths. For the water depths 1.27–30.48 cm, an approximately 30% enhancement in the productivity has been found, which is in good agreement with the results of Bloemer et al. [2]. A characteristic of the deep-basin solar still shows that the ground temperature varies more smoothly compared with a shallow-basin solar still.

The author conducted experiments at the university of Papua New Guinea during a period of 6 months (May 1989–Oct 1989) to compare the performance of a double-slope solar still with and without G.I. sheet, FRP, and concrete. The observations were taken for different water depths, i.e., 0.04, 0.06, 0.08, 0.10, 0.12 and 0.14 m, respectively. The climatic conditions were not the same due to the presence of patches of cloud, dust, breeze, winds and rains, etc., during this period; therefore, the results were compared in terms of liters per kWh of incident radiation. The comparative performance of the double-slope solar still with and without FRP coating in concrete and G.I. sheet is depicted in Fig. 6.9. The following is inferred from these figures:

1. The performance of the FRP solar still shown in Fig. 6.9a, b is the same throughout the experiments.
2. The performance of the solar still made of G.I. sheet and the concrete without FRP lining is poorer compared with the FRP solar still without these materials due to large heat loss from the sides and bottom.
3. The performance of the concrete solar still is poorer than that of the G.I.-sheet solar still (Fig. 6.9b) due to energy storage of the basin water in the concrete structure.

Fig. 6.8 Variation of still productivity with basin water depth for an insulated and non-insulated bottom [3]

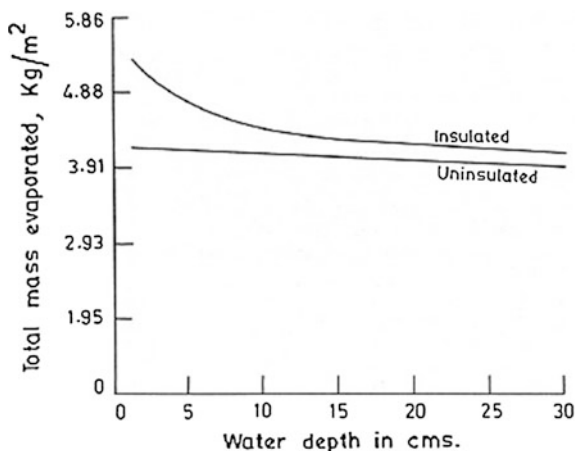
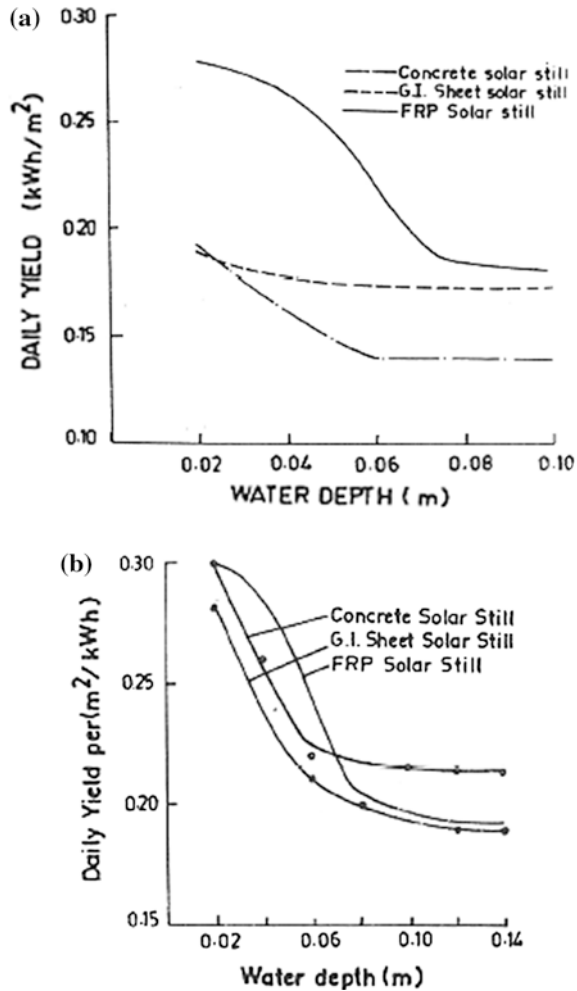


Fig. 6.9 a Effect of water depth on the performance of solar still without lining/coating [26] and **b** effect of water depth on the performance of solar still with lining/coating [26]

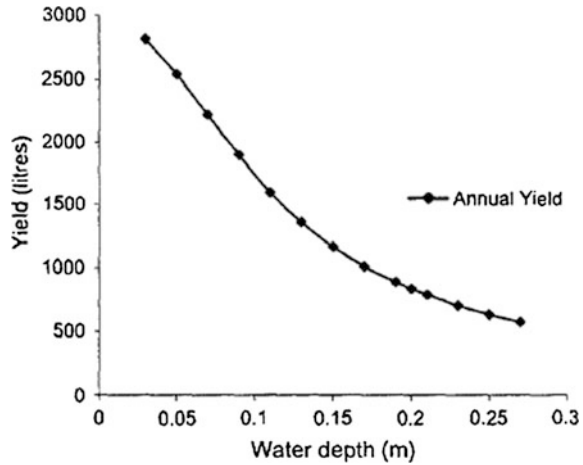


- The FRP lining inside the surface of the concrete and G.I. sheet solar still decreases the heat losses from the sides and the bottom appreciably. Consequently, the performance of these stills improved to a good level and approaches the performance of the FRP solar still as shown in Fig. 6.9b.

6.4.2 Active Solar Still

Figure 6.10 shows the effect of water depth on the annual yield of an active solar still ($A_s = 1 \text{ m}^2$, $A_c = 2 \text{ m}^2$) having a top transparent glass-cover inclination of the

Fig. 6.10 Annual yield of an active solar still with different water depths ($A_s = 1 \text{ m}^2$, $A_c = 2 \text{ m}^2$)



solar still at 13.58° and flat-plate collector (FPC) inclination at 18.5° . A similar effect on the productivity of active solar still was found as observed in case of passive solar stills.

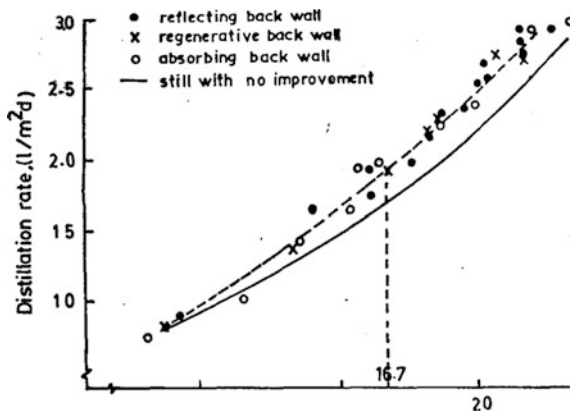
6.5 Other Methods to Improve Solar-Still Productivity

As explained previously, the temperature difference between the evaporative surface and the inner surface of the transparent-glass cover acts as a driving force for potable-water production in the solar still. Therefore, it is essential to increase the water temperature for maximum evaporation to improve the productivity, which can be attained with various techniques. The following techniques are used in a distillation unit to enhance productivity and efficiency:

- (a) Back wall as reflector [7, 28];
- (b) Back wall with cotton cloth [7];
- (c) Regenerative effect in back wall [7]; and
- (d) Solar still with internal condenser [16].

In the first technique, a highly reflecting material is used to polish the inner surface of the back vertical wall, or the back wall is replaced by polished stainless steel or mirror. The back-wall surface reflects the incident solar radiation toward the basin water. Furthermore, the incident solar radiation can be used for evaporation from the back vertical wall using black cotton cloth, which sucks water from the basin due to capillary action. In regenerative effect, the raw water is allowed to flow on the outer side of the back wall to heat it. The heated water is fed into the basin for further evaporation.

Fig. 6.11 Comparison of distillation rate obtained from three methods of improvement [7]



On the basis of observations from using the above-mentioned methods, the following improvements in solar-still performance have been reported:

1. Enhancement in the rate of daily distillation has been found to be 13–15% using the above-mentioned first three methods as shown in Fig. 6.11. The results are in good agreement with the results found by Tamini [27] for the case of a reflector.
2. The daily efficiency of a single basin solar still is improved by approximately 10% due to an internal condenser. This improvement can be achieved with greater slope of the top transparent-glass cover ($>45^\circ$) so that the height of the back wall should be large enough for a significant effect.

6.6 Applications of Solar Distillation

The chemical analysis of distilled water obtained from fibre reinforced plastic (FRP)–made solar still, a galvanized iron multi-wick (G.I.D. water) solar still, L-539 (D. water), and tap water was performed at Central Soil and Material Station (C and S division), New Delhi in the year 1984, Tiwari [28]. The test was performed according to IS 1070-1977, and the results are listed in Table 6.5. It was perceived that the distilled water obtained from a multi-wick solar still is better than one made from conventional fibre-reinforced plastic (FRP). This is credited to the direct contact of water with the fibre material; whereas, in the case of multi-wick solar still, the water is in contact of jute cloth. However, the quality of distilled water is much improved compared with tap water as listed in Table 6.5. Various applications of solar stills are discussed in detail as follows.

Table 6.5 Test results of distilled and tape water (Central Soil and Material Station (C and S division)), [28]

Characteristic	Result			Requirements as per remarks (IS 1070-1977)
	L—539 (D. water)	L—540 (GID. water)	L—541 (tap water)	
Ammonia (as N), mg/l	Little more intense color than control solution	More intense color than control solution	More intense color than control solution	0.1 Max
Calcium and magnesium (as Cal mg/l)	3.2 ppm	2.00 ppm	166 ppm	1.00 Max
Chloride (as Cl), mg/l	Denser—not as clear as control solution	Clear	Denser—not as clear as control solution	0.50 Max
Heavy metal (mg/l)	Passes the test	Passes the test	Passes the test	To pass test
Oxidizing matter	Color completely discharged	Color completely discharged	Color of potassium permanganate exists	100 ml of the material shall not discharged completely by the color of 1 ml of 0.01 N-potassium permanganate solution
pH	6.90	6.99	7.78	5.0–7.5
Residue on evaporation at 110 °C mg/l	18.00	10.00	1095	5.00 Max
Residue on ignition at 750 °C mg/l	12.00	8.00	995.00	2.00 Max
Specific conductivity at 20 °C ms/m	2.60	1.40	210.00	0.50 Max
Sulphate (as 509), mg/l	Clear	Clear	Opalescence	1.00 Max

6.6.1 Production of Potable Drinking Water

The distillate output of solar stills is demineralized water, which cannot be used as such for drinking purposes. To make it potable, the distilled water must be mixed with brackish/saline water. Consequently, the mixing should be in a precise ratio so that the salinity should not reach beyond the permissible limit (1500 ppm) as per Indian standards. However, according to the World Health Organization (WHO), this standard is approximately 500 ppm. The demineralized water produced by solar stills was found to have a total dissolved solid (TDS) <25 mg/L (8 ppm) as listed in Table 6.5.

Therefore, for the purpose of drinking, it is essential to mix the distilled water with some saline water so that the total dissolved solids (TDS) meets the mineral requirements of the human body, due to which the amount of potable water prepared will be more.

If government provides subsidy, one can expect a further decrease in the cost of distilled water; its cost can also be decreased by adding some amount of rainwater. The following equations are used to determine the quantity of saline water to be mixed with the demineralized water to obtain the required total dissolved solid (TDS) (1500 ppm) in potable water on the basis of the mass balance of salt in water:

$$V_b + V_d = V_w \quad (6.7.1)$$

$$S_b V_b + S_d V_d = S_w V_w \quad (6.7.2)$$

where V_b , V_d and V_w are volumes of brackish, distilled, and drinking water, respectively, and S_b , S_d and S_w are their respective salinities. Table 6.6 clearly lists the amount of saline water required to be mixed with the demineralized water to obtain total dissolved solid (TDS) of 1500 ppm. It has been observed that the quantity of saline water to be mixed decreases with an increase in total dissolved solid (TDS). This implies that more drinking water can be prepared with a decrease in the salinity of saline water, which thus decreases the cost of potable water per liter. Therefore, a solar still becomes more economical at lower salinity.

Here, it is important to mention that a solar-distillation system should not be used to distillate seawater having salinity >40,000 ppm. As discussed previously, this is due to the fact that high salinity causes fast scaling at the basin liner, which may then require frequent cleaning. It will not make the system cost-effective (distilled water per liter) due to high maintenance costs.

Table 6.6 Requirement of distilled water with varying salinity of brackish water

Brackish water		Distilled water of salinity 20 ppm, V_d (l)	Drinking water of salinity 1500 ppm, V_w (l)
Salinity (ppm)	Volume, V_b (l)		
Very high	0	40.0	40
2000	29.95	10.05	
2500	23.94	16.06	
3000	19.93	20.07	
3500	17.08	22.92	
4000	14.94	25.06	
4500	13.27	26.73	
5000	11.94	28.06	
5500	10.86	29.14	
6000	9.95	30.05	
6500	9.18	30.82	
7000	8.53	31.47	

6.6.2 Production of Rose Water

Rose water, a very dilute aqueous solution of rose essence, is important to people in many countries. It is used for cosmetics, mixing in foods, religious ceremonies, festivals, and medicine in few countries. It attracts the attention of the researcher to find methods to produce rose water in these countries. Recently, solar-distillation method has been used to produce rose water at the Indian Institute of Technology Delhi, India. A tilted wick-type solar still is used for this purpose, in which the wick comprises several overlapping layers of blackened jute cloth. The upper edges of the jute cloths are immersed in the water tank along with upper edge of sloping surface. Capillary forces distribute water from the exposed surfaces to the jute layers.

Initially, the rose flowers and buds are wetted with water for approximately 15–20 min and then spread inside the solar still. The water present in the jute clothes becomes heated with incident solar radiation, and the evaporation mechanism takes place. The water vapors carry some of the oily essence with them from the rose petals. Condensation of the mixture of water vapor and rose essence takes place at the inner surface of the top transparent-glass cover and is collected in clean bottles at the lower end of the solar still through a separate channel. The rose buds are placed in two different solar stills viz. wick-type solar still (mentioned previously) and a conventional basin-type solar still for the comparative study (6 Nov, 1980). The productivity of both systems was studied for an equal amount of roses for a few weeks. It was perceived that the wick-type and conventional basin-type solar still, respectively, produces 2.2 and 1.8 l/m² rose water. Furthermore, it was observed that the product from the wick-type still was free from bacteria compared with the basin-type solar still. This occurs due to greater temperature in the wick-type solar still, (70 °C) compared with the conventional basin-type solar still (50 °C). Moreover, the quality of rose water produced decreases with time and requires a new charge of rose petals every 3 days to maintain quality.

A simplified economic analysis of rose-water production is listed in Table 6.7. The wick-type solar still is found to be more economic than the basin type solar

Table 6.7 Cost analyses of multi-wick and basin solar still (\$1 = Rs. 8, (1980))

Comparison of rose water production from two solar stills	Simple multiple wick solar still	Single basin solar still
Cost of still/m ² (Rs.)	365	550
Life of still (years)	10	10
Recurring expenditure/days (Rs.)	2.50	3.10
Production: annual daily avg. yield	3.0	2.5
Income @ Rs. 1.5 l	4.5	3.75
Net profit/day (Rs.)	2.0	0.65
Annual profit from single unit (Rs.) of 1 m ² area	730	240

still. The wick-type solar still brings an annual revenue of Rs. 730 m⁻² compared with a basin-type still (Rs. 240 m⁻²). This economic study was carried only for several months; therefore, further analysis should be made to determine the long-term performance.

6.6.3 Greenhouse-cum-Solar Distillation System

Greenhouse technology and water-conservation techniques in agriculture have been developed in recent times [29]. It makes it possible/easier to have small-scale agricultural activity in remote places where only saline or brackish water is available. Solar distillation may be able to fulfill the rather modest demand of fresh water in most cases. It is in consistent with the clever choice of crops and suitable thermal environment provided by the greenhouse as well as efficient water-conservation technology. Consequently, the integrated design of greenhouse-cum-solar distillation system presents an exciting possibility for the support of small-scale agriculture in remote places. The part of solar radiation that essential for the growth of plants may be provided by having part of a barrier of transparent-glass or transparent-plastic material or the base of the solar still forming the roof of a greenhouse made of transparent material.

Several greenhouses with inbuilt solar stills have been constructed and tested. A few of them are discussed in the following sections. The theoretical aspects are discussed in detail as follows.

(a) Solar still-greenhouse combination

Qasim [30] constructed two small test greenhouses-cum-solar stills in Texas, USA. A systematic view of the system is presented in Fig. 6.12a (Unit I).

The first unit is a double-story structure with a solar still in the upper and lower part being the greenhouse. The greenhouse floor is also used as a basin to hold the water. The lower portion acts as a solar still. On the floor, plants are kept in pots and crates. The wooden frame is covered with 0.25 mm clear polythene sheet. To avoid ventilation and portholes (for probes), some of the walls are made of Plexiglas sheets, which also provides rigidity to the structure. The roof is wedge-shaped so that condensed water can trickle down along the roof and be collected through the channels at lower ends. The basin (trough) area of the upper solar still measures 0.68 m × 0.15 m, and the trough is 0.08 m deep. The base of the greenhouse is covered with a black plastic sheet. The brackish water, approximately 1.5 l, is maintained in the lower basin. The second unit is also constructed along the same lines as the first one with only one alteration, i.e., the sealing -off the top part (solar still) from the greenhouse below (Fig. 6.12b, Unit II). The entire house is covered with a 0.1 mm-thick plastic sheet instead of the 0.25 mm sheet as used in upper part. The solar still dimensions are 0.58 m × 1.45 m × 0.10 m. The temperature inside the greenhouse can be minimized by painting the south- and west-facing

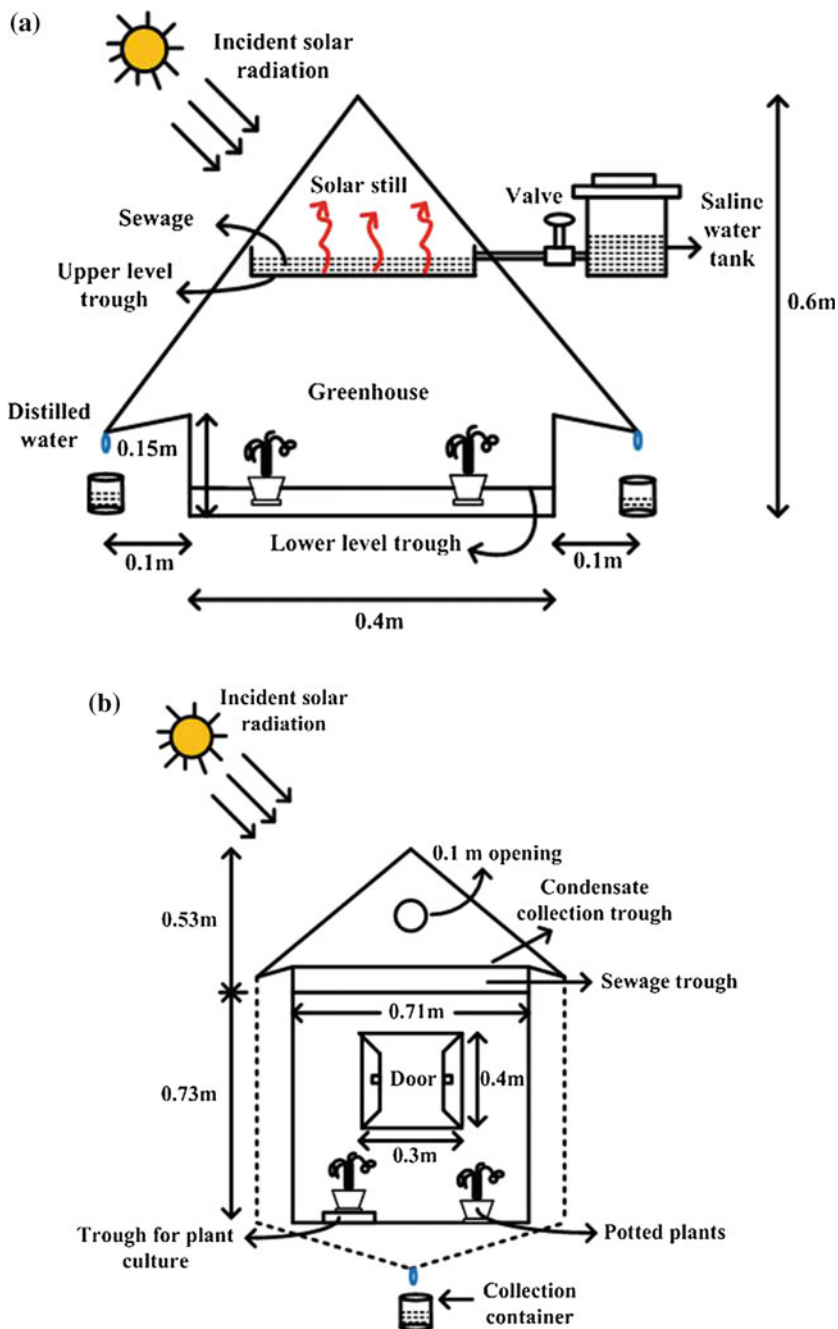


Fig. 6.12 **a** Schematic view of Unit I [30] and **b** schematic view of Unit II [30]

Table 6.8 Comparison in performance of both units

Feature	Unit No. 1 February 10–May 8, 75	Unit No. 2 July 8–September 1, 75
Condensate produced	0.33 kg/day	0.23 kg/day
Condensate quality	None of plants survived	All plants survived in the greenhouse
Daytime average temperature inside solar still (°C)	50.6	51.1 (slightly lower than)
Daytime average temperature inside solar still (°C)	50.6	51.1 (slightly lower than)
Highest temperature inside solar still (°C)	61	63
Relative humidity in greenhouse	0.90 (doors were closed) 0.38 (doors were opened)	
Sewage temperature in evaporating pan (°C)	31.1	51.1
Temperature in the greenhouse (°C)	43.9	42.8 (door was closed)

walls white if required. The performance of both of these units is listed in Table 6.8.

(b) Materials for greenhouse–cum–solar still system

It is very interesting to construct the solar still above the greenhouse using inexpensive and durable materials. Among all, the most vital material is the transparent-glass cover for the house. Penetrated solar radiation inside the greenhouse is essential for the growth of plants; therefore, it is necessary to use transparent material for the base of the solar still. The water and base use the solar radiation to produce the distilled water. The photosynthesis (plants growth) in the plants and their productivity should be studied separately for different transparent materials for the solar still base or greenhouse roof.

A systematic view of the greenhouse constructed by Tinaut et al. [31] is shown in Fig. 6.13. These investigators studied the viability of different types of polythene sheets. A semi-transparent plastic sheet is used as a base of the solar still to allow the incident solar radiation into the greenhouse. It is lodged in the upper part of the house and helps plant growth due to improved photosynthetic activity.

The absorption spectrum of chlorophylls (maximum between 0.640–0.667 μm and 0.41–0.44 μm) and carotenoids (maximum between 0.40 and 0.45 μm) is modified only slightly when these pigments are combined with other molecules. The fact that there is no plastic material with an absorption spectrum in this range allows free choice. Tinaut et al. [31] selected the following:

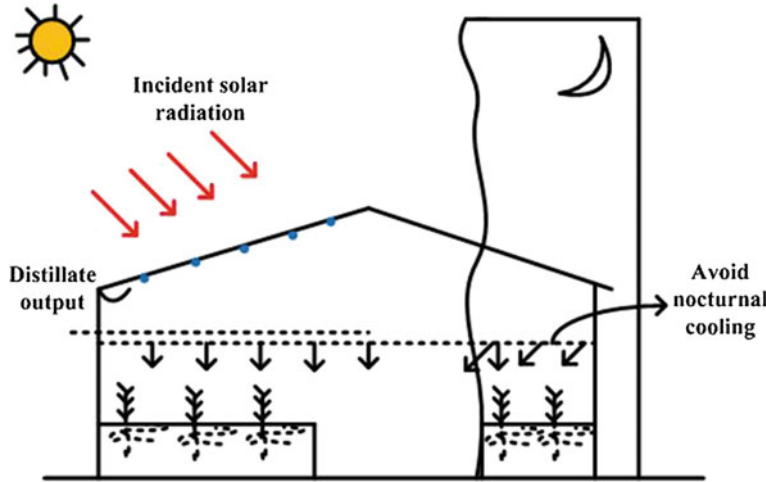


Fig. 6.13 Systematic view of greenhouse [31]

Blue methacrylate	Rigid
Blue polythene I	Flexible
Blue polythene II	Flexible (more opaque than the other)
Red methacrylate	Rigid
Red polythene	Flexible

(c) **Measurement of photosynthetic activity**

Photosynthetic activity is expressed in fixed micromoles of carbon dioxide per square centimeter of leaf area per hour of exposure. Experiments were performed on freshly germinated barley plants to determine the rate of photosynthesis due to radiation passing through the transparent material under test. A sample of barely leaf, 14 mm in diameter, was prepared and kept in the test chamber. It was then irradiated with light passing through the test material, and a controlled amount of air, containing CO₂ gas labeled with a radioactive isotope of carbon C¹⁴, was pumped into the chamber. The extent of photosynthetic activity was determined by monitoring the amount of radioactivity in the barely leaf.

Five barley plants were used for testing each material. It was concluded that all of the selected plastic materials were acceptable. Furthermore, maximum photosynthetic activity was obtained with the red methacrylate, and minimum photosynthetic activity corresponded to the blue polyethylene.

(d) **Estimation of solar-still yield**

Tinaut et al. [31] also considered the spectral distribution of solar radiation and the absorption curves of these plastics to calculate the absorbed radiation for each

Table 6.9 Relative photosynthetic activity, percentage (%) and annual water production with different transparent materials

Material	Relative photosynthetic activity (%)	Annual water production (kg/100 m ²)
Blue methacrylate	52.7	23.81
Blue polythene I	44.3	14.35
Blue polythene II	55.7	25.02
Red methacrylate	102.6	35.05
Red polythene	69.5	21.06

material and consequently predicted the system productivity. The results are listed in Table 6.9.

6.6.4 Seawater Greenhouse Distillation

Seawater trickles down onto the front-wall evaporator, through which air is drawn into the greenhouse (Fig. 6.14). Dust, salt spray, pollen, and insects are filtered out leaving the air humidified and cooled; sunlight is filtered to remove radiation that does not contribute to photosynthesis. Air passes through the second evaporator and is further humidified to a saturation point; saturated air passes through the condenser, which is cooled using seawater. The condensed distilled water is collected through a channel and stored in a separate collector.

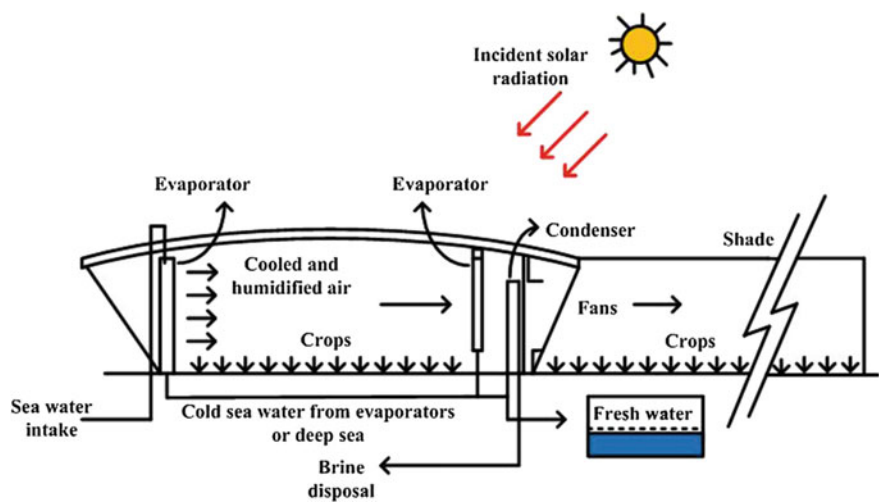


Fig. 6.14 Systematic view of seawater greenhouse

6.6.5 Desert Greenhouse

This system is suitable for tropical desert conditions. It uses the coupling of condensed and transpired water. Fresh water is also collected at the southern side wall of the greenhouse. The integrated solar still on the southern side consists of an evaporative surface facing toward the Sun, a saltwater–distribution pipe, and a basin. The contaminated saltwater flows continuously over the hot evaporative surface by way of a distribution pipe, which leads to evaporation and vapors being condensed under the enclosure at three points. A conceptual diagram of the system is depicted in Fig. 6.15.

A greenhouse-based integrated solar still was developed by Chaibi and Jilar [32] at the National Research Institute of Rural Engineering, Water and Forestry. In their system, solar radiation is absorbed by a layer of flowing water on the internal glass, which is covered with another transparent top glass (transparent) cover (this decreases the transmission). Eventually, the evaporation mechanism takes place, and the vapors condenses on the inner surface of the transparent-glass cover and collects at the roof eaves as shown in Fig. 6.16.

Problems and descriptive questions

- 6.1 Discuss the following parameters in detail regarding solar-still productivity:
 - (a) the Influence of using dye,
 - (b) the influence of algae formation, and
 - (c) the influence of charcoal.
- 6.2 Discuss the effect of (a) wind velocity and (b) inclination of condensing cover and bottom insulation on solar-still productivity.
- 6.3 What is the effect of water depth in the case of passive solar stills? Explain in detail.

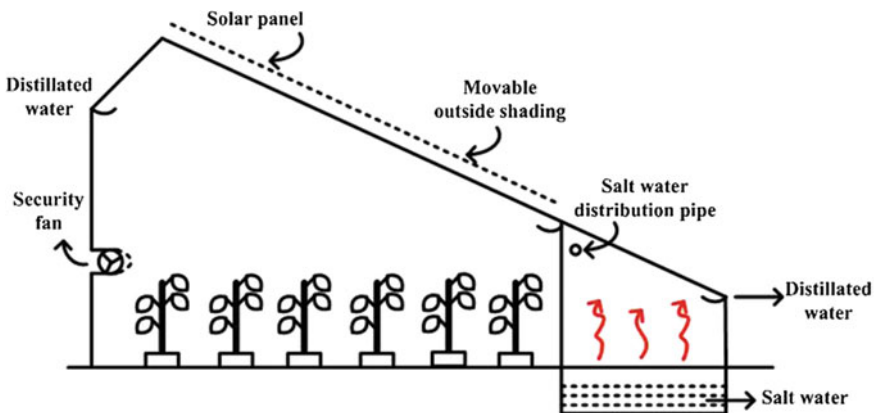


Fig. 6.15 Cross-section of desert greenhouse designed by ITG in 1987 at Adana University Turkey

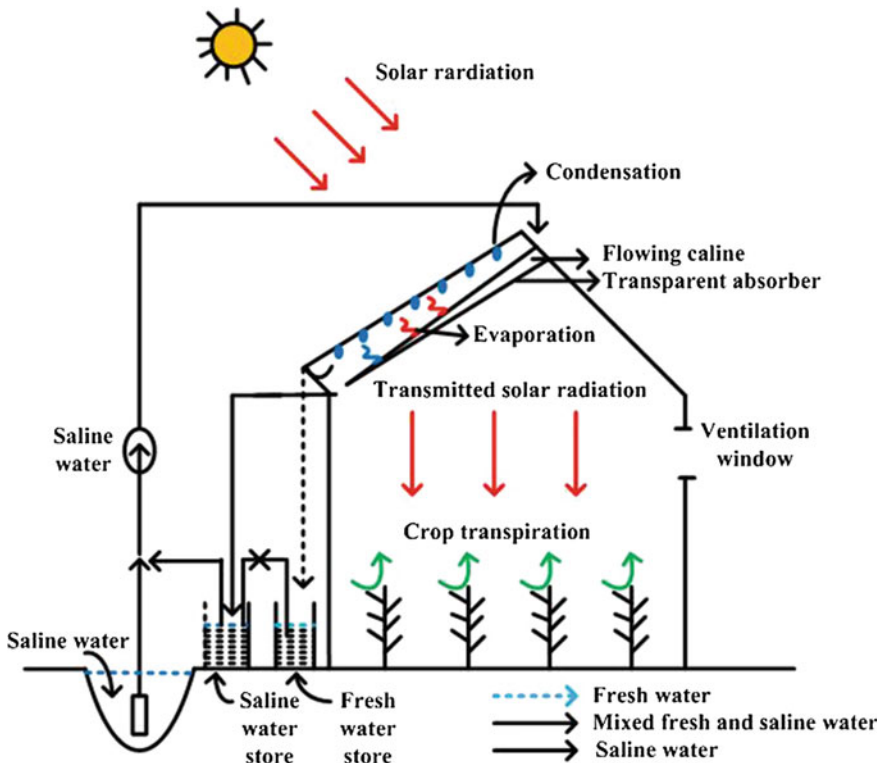


Fig. 6.16 System principle for water desalination integrated on greenhouse roof

- 6.4 Discuss the greenhouse-cum-solar distillation system with a suitable diagram.
 6.5 Explain the mechanism of potable-water production using a solar-distillation system.

Objective questions

- 6.1 Which of the following effects/methods can be used to improve solar-still productivity?
- Addition of dye
 - Algae formation
 - Addition of charcoal
 - All of these.
- 6.2 A conventional solar still can purify saline water up to maximum concentration of:
- 10,000 ppm
 - 50,000 ppm

- (c) 5000 ppm
 - (d) Independent of concentration.
- 6.3 High salt concentration of feed water in the solar-still basin causes:
- (a) A decrease in absorptivity
 - (b) Increases maintenance cost
 - (c) A reduction of productivity
 - (d) All of these.
- 6.4 What is the effect of dye on solar-still productivity?
- (a) Increases productivity
 - (b) Decreases productivity
 - (c) No effect.
- 6.5 Which of the following dye colors has a more dominating effect on solar-still performance?
- (a) Green
 - (b) Black
 - (c) Red
 - (d) Independent of color.
- 6.6 Which of the following is the true effect of using dye in the basin water?
- (a) It decreases the rate of heat transfer from the basin to the ambient
 - (b) It increase the rate of heat transfer from the basin to the ambient
 - (c) The basin water itself absorbs the maximum solar radiation
 - (d) (a) and (c).
- 6.7 The effect of black dye is significant at:
- (a) Greater basin-water depth
 - (b) Lower basin-water depth
 - (c) Independent on depth.
- 6.8 The effect of black dye is significant at:
- (a) Greater basin-water depth
 - (b) Lower basin-water depth
 - (c) Independent of depth.
- 6.9 Which of the following facts about charcoal are responsible for enhancing solar-still productivity?
- (a) Wettability
 - (b) Large absorption coefficient to decrease solar radiation
 - (c) Property to scatter rather than reflect solar radiation
 - (d) All of these.

- 6.10 What is the effect of greater wind velocity over the top glass cover on solar-still productivity?
- (a) It decreases the temperature difference between the water surface and the inner surface of the glass cover
 - (b) It increases the temperature difference between the water surface and the inner surface of the glass cover
 - (c) It has no effect.
- 6.11 Which of the following is true for the enhancement of solar-still productivity at low ambient temperature at midnight?
- (a) Low basin-water depth
 - (b) Greater basin-water depth
 - (c) Neither of these.
- 6.12 The optimized inclination angle of a glass cover is equal to:
- (a) Latitude of the place (Northern India)
 - (b) Altitude of the place (Northern India)
 - (c) Climatic conditions
 - (d) Both (a) and (c).
- 6.13 Both active and passive solar-still performance is better at:
- (a) Low water depth
 - (b) Greater water depth
 - (c) Independent on water depth.
- 6.14 Which of the following technique is not suitable to improve solar-still productivity?
- (a) Back wall as a reflector
 - (b) Back wall with cotton cloth
 - (c) Regenerative effect in back wall
 - (d) None of these.
- 6.15 Which of the following is not an application of a solar still?
- (a) Production of pure drinking water
 - (b) Production of rose water
 - (c) Greenhouse–cum–distillation
 - (d) Seawater greenhouse distillation
 - (e) None of these.

Answers

- 6.1 (d) 6.2 (a) 6.3 (d) 6.4 (a) 6.5 (b) 6.6 (d) 6.7 (a) 6.8 (a) 6.9 (d) 6.10 (b) 6.11 (b) 6.12 (d) 6.13 (a) 6.14 (d) 6.15 (e).

References

1. A.K. Rajvanshi, C.K. Hsieh, *Effect of Dye on Solar Distillation: Analysis and Experimental Evaluation*. Proceedings of Int. Congress of ISES, Georgia 20, p. 327 (1979)
2. J.W. Bloemer, J.R. Irwin, J.A. Eibling, G.O.G. Lof, A practical basin type solar still. *J. Solar Energy* **9**, 197 (1965)
3. P.I. Cooper, Digital simulation of transient solar still processes. *Sol. Energy* **12**, 313 (1969)
4. P.I. Cooper, Maximum efficiency of single effect solar still data. *Sol. Energy* **15**, 205 (1973)
5. M.S. Sodha, A. Kumar, G.N. Tiwari, G.C. Pandey, Effect of dye on thermal performance of solar still. *J. Appl. Energy* **7**, 147 (1980)
6. V.A. Akinsete, D.A. Aderibigbe, *Performance of the Charcoal-bed Roof Type Solar Still*, Solar World Congress at Perth, April 14–19 (1983)
7. P. Wibuswas, S. Tadtium, *Improvement of a Basin Type Solar Still by Means of a Vertical Back Wall*, Int. Symposium Workshop on Renewable Energy Sources (Lahore, Elvier, Amsterdam, 1984)
8. P.I. Cooper, The absorption of solar energy radiation in solar stills. *Sol. Energy* **12**, 333 (1969)
9. G.O.G. Lof, J.A. Eibling, J.W. Bloemer, Energy balances in solar distillation. *J. Am. Inst. Chem. Eng.* **7**, 641 (1961)
10. P.I. Cooper, *The Transient Analysis of Glass Covered Solar Still*, Ph.D. Thesis, University of Western Australia, Australia, 1970
11. R.N. Morse, W.R.W. Read, A rational basis of engineering development of solar still. *Sol. Energy* **12**, 5 (1968)
12. M. Farid, F. Hamad, Performance of a single basin solar still. *Renew Energy* **3**, 75 (1993)
13. S. Toure, P. Meukam, A numerical model and experimental investigation for a solar still in climatic conditions in Abidjan. *J. Renew. Energy* **11**, 319 (1997)
14. S. Aggarwal, *Computer Based Thermal Modeling of Advanced Solar Water Distillation System: An Experimental Validation.*, Ph.D. Thesis, IIT Delhi, India, 1998
15. H.S. Soliman, Effect of wind on solar distillation. *J. Solar Energy* **13**, 403 (1972)
16. J. Ahmadzadeh, Solar earth water still. *Sol. Energy* **20**, 387 (1978)
17. P.I. Cooper, *Solar Distillation: State of Art and Future Prospects*. Solar Energy and Arab World, Proc. of 1st Arab Int. Solar Energy Conf., Kuwait, p. 311 (1983)
18. United Nations, *Solar Distillation* (Department of Economics and Social Affairs, New York, 1970)
19. V.A. Akinsete, C.U. Duru, A Cheap Method of Improving the Performance of Roof Type Solar Still. *Sol. Energy* **23**, 271 (1979)
20. H.N. Singh, G.N. Tiwari, Monthly performance of passive and active solar stills for different Indian climatic conditions. *Desalination* **168**, 145 (2004)
21. G.C. Pandey, Liquid collector efficiency solar still. *Int. J. Energy Res.* **6**, 21 (1982)
22. D.A. Aberibigce, *Optimal Cover Inclination for Maximum Yearly Average Productivity in Roof Type Solar Still*. Private Communication to A.I. Kudish (1985)
23. J.K. Nayak, G.N. Tiwari, M.S. Sodha, Periodic theory of Solar still. *Int. J. Energy Res.* **4**, 41 (1980)
24. P.I. Cooper, Appleyard, *The Construction and Performance of a Three Effect Wick Type Tilted Solar Still*. Sun at Work, 12, p. 4 (1967)
25. A. El-Sebaei, The effect of wind speed on active and passive solar stills. *Energy Convers. Manag.* **45**, 1187 (2003)
26. G.N. Tiwari, S.A. Lawrence, Experimental evaluation of solar distiller units with FRP lining under PNG climatic conditions. *Int. J. Solar Energy* **9**, 241 (1991)
27. A. Tamini, *Performance of a Solar Still with Reflectors and Black Dye*. *Int. J. Solar Wind Tech.* **4**, 443 (1987)
28. G.N. Tiwari, Demonstration plant of multi-wick solar still. *J. Energy Convers. Manage.* **24**, 313 (1984)

29. G.N. Tiwari, *Solar Energy: Fundamentals, Design, Modelling and Applications* (CRC Press, New York and Narosa Publishing House, New Delhi, India, 2002)
30. S.R. Qasim, Treatment of domestic sewage by using solar distillation and plant culture. *J. Environ. Sci. Health* **13**, 615 (1978)
31. D. Tinaut, G. Echaniz, F. Ramos, Materials for a solar still greenhouse. *Optical Pura Y. Aplicada* **11**, 59 (1978)
32. M.T. Chaibi, T. Jilar, System design, operation and performance of roof integrated desalination in greenhouses. *Sol. Energy* **76**, 545 (2004)
33. Elsherbiny, Fath, *Desalination and Water Resources—Renewable Energy Systems and Desalination*, vol 3 (EOLSS, UK, 1995)
34. S.T. Ahmed, Study of single effect solar still with an internal condenser. *Int. J. Solar and Wind Tech.* **5**, 637 (1988)
35. P. Wibulswas, S. Suntrirat, B. Direkstoporn, T. Kiatsiriroat, Developments of solar still having acrylic plastic covers in Thailand. *Alternative Energy Sources, IC*, Ann Arbor Sciences, Michigan 385 (1982)
36. M.S. Abdel-Salam, Effect of cover slope and inside air volume on the performance of a solar still. *Solar Energy Prospects in the Arab World*, 293 (1986)
37. H.P. Garg, H.S. Mann, Effect of climatic, operational and design parameters on the year round performance of single-sloped and double-sloped solar still under Indian arid zone conditions. *Solar Energy* **18**, 159 (1976)
38. M.A.S. Malik, G.N. Tiwari, A. Kumar, M.S. Sodha, *Solar Distillation* (Pergamon Press, Oxford, UK, 1982)
39. A.K. Tiwari, G.N. Tiwari, Effect of water depth on heat and mass transfer in a passive solar still: in summer. *Desalination* **195**, 78 (2006)
40. K. Watanabe, Fundamental study of the Solar Distillation System. *Research of Natural Energy* **8**, 125 (1984)
41. M.E. El-Rafaie, Effect of step width and depth on the productivity of cascaded solar still. *Proc. 4th Int. Conf. for Mechanical Power Engineering*, Cairo, Egypt 8 (1982)
42. V.A. Akinsete, D.A. Aderibigbe, *Performance of the Charcoal-bed Roof Type Solar Still*, Solar World Congress at Perth, April 14–19 (1983)
43. A.A. Madani, G.M. Zaki, Performance of solar still with intermittent flow of waste hot water in the basin. *Desalination* **73**, 167 (1989)
44. G.M. Zaki, T.E. Dali, H.E. Shafieng, Improved performance of solar still. *Proc. 1st Arab Int. Solar Energy*, Kuwait, 331 (1983)
45. W.A. Kamal, A theoretical and experimental study of basin type solar still under the Gulf climatic conditions. *Solar and Wind Technology* **5**, 147 (1988)

Chapter 7

Energy and Exergy Analysis of Solar-Distillation Systems

7.1 Introduction

The availability of useful energy and exergy of a solar thermal system determines its performance. To optimize the design and operating parameters of such systems, energy and exergy analyses have been performed by various researchers [1–8]. Fossil fuels are essentially required for the generation of electrical energy; however, the availability of these fuels is decreasing daily due to their extensive use for power production. This is credited to the fact of rapid growth in population along with that of industrial development. Moreover, the consumption or burning of fossil fuels causes environmental degradation (air pollution) by way of CO₂ emissions. Fossil fuels are also becoming scare with time; hence, it is necessary to find alternative energy to conserve fossil fuels. From this perspective, knowledge and awareness about the use of renewable-energy sources, i.e., solar energy, which is an ample source of energy, has gained momentum worldwide.

The theory of exergy analysis is equally important to understand as that of available-energy analysis. In recent years, numerous investigators [9–11] have discussed and shown the use of exergy analysis in thermal designs (optimization). An execution of exergy analysis for the performance of a thermal system is based on the second law of thermodynamics, which overcomes the limitations of an energy-based analysis. Exergy destruction is the measure of irreversibility (source of performance loss). Therefore, an exergetic analysis has been performed to assess the magnitude of exergy destruction by identifying the location, magnitude, and source of thermodynamic inefficiencies in a thermal system [12, 13]. The advanced exergy analysis splits total exergy destruction into parts such as avoidable and unavoidable exergy destruction. Moreover, it can be divided into categories of endogenous and exogenous exergy destruction.

Exergetic analysis basically predicts the thermodynamic performance of an energy system as well as the efficiency of the system components by precisely quantifying the entropy generation of the components. Dincer [14] reported

important associations between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy-making and exergy. In this chapter, the energy and exergy analysis of different passive and active solar-distillation systems is discussed in detail.

7.2 Energy and Exergy Analysis of Conventional Solar Still

Energy analysis is based on the first law of thermodynamics that is used to evaluate the energy efficiency and distillate output of any solar-distillation system. Energy analysis deliberates only the quantitative aspect of the energy transfer. In contrast, the quality of energy, i.e., availability of energy or exergy, which is defined by the second law of thermodynamics, is usually ignored. The analysis is the most effective thermodynamic tool for achieving the goal of more efficient use of the resources because it enables the locations, the types and true magnitudes of energy waste, and the losses to be determined [15].

The analysis has been effectively applied in the optimization of either an entire system or of specific variables in a single component of a thermal system [16, 17]. Moreover, this awareness can be used for solar-still design in order to decrease sources of inefficiency and irreversibility in the existing processes and components of the system. This technique or approach may be very useful to achieve greater cost-effective efficiency and productivity [18–21].

7.2.1 Conventional Single Slope Solar Still

Following assumptions as given in Chap. 5, the energy balances of different components of a passive single-slope solar still (SSSS) (Fig. 3.1a) are given as follows [22]:

(i) Glass Cover

$$\alpha_g I_S + h_{1f} (T_f - T_{gi}) = h_{1g} (T_{go} - T_a) \quad (7.2.1)$$

where α_g —absorptivity of the glass; $I_S(t)$ —solar intensity on the still (W/m^2); $h_{1f}(=h_{ew} + h_{cw} + h_{rw})$ —total internal heat-transfer coefficient from the fluid (water) to the glass; h_{ew} , h_{cw} , h_{rw} , respectively, are the evaporative, convective, and radiative heat-transfer coefficients from the water surface; $h_{1g}(=h_{rg} + h_{cg})$ —total external heat-transfer coefficient from the glass to the ambient; h_{rg} and h_{cg} are the radiative and convective heat-transfer coefficients, respectively, from the glass surface to the ambient; T_f —basin-water temperature ($^{\circ}\text{C}$), T_{gi} —temperature of the inner surface of the glass cover ($^{\circ}\text{C}$); T_{go} —temperature of the outer surface of the glass cover ($^{\circ}\text{C}$); and T_a the ambient temperature ($^{\circ}\text{C}$).

(ii) **Basin liner**

$$\alpha_b I_S = h_{b,f} (T_b - T_f) + h_{ba} (T_b - T_a) \left(1 + \frac{A_{ss}}{A_S} \right) \quad (7.2.2)$$

where α_b —absorptivity of the basin liner; $h_{b,f}$ —convective heat-transfer coefficient from the basin liner to the fluid (water); h_{ba} —heat-transfer coefficient from the basin to the ambient ($W/m^2\text{ }^\circ\text{C}$); T_b —temperature of the basin liner ($^\circ\text{C}$); and A_{ss} —area of the sides of the solar still (m^2).

The side area, A_{ss} , is very small compared with the still basin area of the solar still (A_S); therefore, the term $\frac{A_{ss}}{A_S}$ can be neglected for a lower depth of basin water. Therefore, Eq. (7.2.2) can be expressed as follows:

$$\alpha_b I_S = h_{b,f} (T_b - T_f) + h_{ba} (T_b - T_a) \quad (7.2.3)$$

(iii) **Base-fluid (water) mass**

$$M_f C_f \frac{dT_f}{dt} = \alpha_f I_S + h_{b,f} (T_b - T_f) - h_{1f} (T_f - T_{gi}) \quad (7.2.4)$$

where M_f —basin-fluid (water) mass (kg); C_f —specific heat of the fluid ($\text{J/kg}\cdot\text{K}$); α_f absorptivity of the basin water; and α_b absorptivity of the basin.

The empirical relation for the top-loss coefficient (h_{1g}) is discussed in detail in Sect. 2.4.4. of Chap. 2. Moreover, the relation to evaluate the internal (i.e., radiative, convective, evaporative, and natural convective) and external (i.e., radiative and convective) heat-transfer coefficients are given in detail in Chap. 2.

The value of h_{1f} can be determined by considering known values of the water and glass temperatures at $t = 0$ i.e. $T_f(t = 0) = T_{f0}$ and $T_g(t = 0) = T_{g0}$, respectively.

Assuming $T_{gi} \approx T_{go}$, by substituting the values of T_{gi} and T_{gi} from Eqs. (7.2.1) and (7.2.2), respectively, in Eq. (7.2.4), one can obtain (according to same procedure discussed in Chap. 5 for active solar still) this equation:

$$\frac{dT_f}{dt} + aT_f = f(t) \quad (7.2.5)$$

where

$$a = \frac{U_L}{(MC)_f}; f(t) = \frac{(\alpha\tau)_{\text{eff}} I(t) + U_L T_a}{(MC)_f}; (\alpha\tau)_{\text{eff}} = a_b \left(\frac{h_f}{h_f + h_b} \right) + a_w + a_g \left(\frac{h_{1f}}{h_{1f} + h_{1g}} \right)$$

$$U_L = U_b + U_t; U_b = \frac{h_{bf} h_b}{h_{bf} + h_b}; \text{ and } U_t = \frac{h_{1f} h_{1g}}{h_{1f} + h_{1g}}$$

$$\dot{q}_{\text{ef}} = h_{\text{ef}} (T_f - T_g).$$

As discussed in Sect. 5.2, the solution of (first-order differential equation) Eq. (7.2.5) for basin-water temperature can be expressed as follows:

$$T_w = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] + T_{w0} e^{-a\Delta t} \quad (7.2.6)$$

where T_{w0} is the basin-water temperature at $t = 0$; and $\overline{f(t)}$ is the average value of $f(t)$ for the time interval between 0 and t .

From Eq. (5.2.12d), the yield of the system can be expressed as follows:

$$\dot{m}_{ef} = \frac{\dot{q}_{ef}}{L} \times 3600 = \frac{h_{ef}(T_f - T_g)}{L} \times 3600 \text{ kg/m}^2\text{h} \quad (7.2.7)$$

where L is the latent heat of vaporization, which can be obtained from Eqs. (5.2.12e) and (5.2.12f), respectively; and $\dot{q}_{ef}$ is the rate of evaporative heat transfer, which can be expressed as follows:

$$\dot{q}_{ef} = h_{ef}(T_f - T_g) \quad (7.2.8)$$

After obtaining the hourly yield ($\dot{m}_{ef}$) from Eq. (7.2.7), becomes $(M_f C_f - m_{ef} C)$.

The thermal energy and exergy of passive single-slope solar still (SSSS) can be expressed as follows:

$$E_{\text{hourly, en}} = h_{ef}(T_f - T_{gi}) \quad (7.2.9)$$

$$E_{\text{hourly, ex}} = h_{ef} \left[(T_f - T_{gi}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{gi} + 273} \right) \right] \quad (7.2.10)$$

A detailed derivation of the exergy formulae is given in Appendix J.

Input exergy can be calculated using the expression given by Petela [23] as follows:

$$\dot{E}_{\text{ex, in}} = A_g I(t) \left[1 - \frac{4}{3} \left(\frac{T_a}{T_s} \right) + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right] \quad (7.2.11)$$

where T_s is the Sun temperature ($^{\circ}\text{C}$).

Furthermore, the instantaneous-gain thermal-energy efficiency of distillation unit can be determined as follows:

$$\eta_i = \frac{\dot{q}_{ef}}{I(t)} = \frac{h_{ef}(T_f - T_g)}{I(t)} \quad (7.2.12)$$

The previous equation can be re-expressed by substituting the value of T_f from Eq. (7.2.6) as follows:

$$\eta_i = \left(\frac{h_{ef} h_{lg}}{h_{1f} + h_{1g}} \right) \left(\frac{1}{U_L} \right) \left[(\alpha\tau)_{\text{eff}} (1 - e^{-a\Delta t}) + U_L \frac{(T_{f0} - T_a)}{I(t)} e^{-a\Delta t} \right] \quad (7.2.13)$$

The plot of η_i versus $\frac{(T_{f0} - T_a)}{I(t)}$ will represent a straight line as discussed previously in Sect. 2.8 in Chap. 2.

Example 7.1 Calculate the time taken for the water temperature to increase to 40 °C from an initial value of 20 °C. Given: $(\alpha\tau)_{\text{eff}} = 0.65$, $I(t) = 900 \text{ W/m}^2$, $T_a = 8.5 \text{ °C}$, $(MC)_f = 41,900 \text{ J/°C}$, $U_L = 9.48 \text{ W/m}^2 \text{ °C}$.

Solution

From Eq. (7.2.5),

$$\Delta t = -\frac{1}{a} \ln \left[\frac{T_f - \frac{\bar{f}(t)}{a}}{T_{f0} - \frac{\bar{f}(t)}{a}} \right]$$

where

$$a = \frac{U_L}{(MC)_f} = \frac{9.44}{41,900} = 2.26 \times 10^{-4} \text{ and } f(t) = \frac{(0.65 \times 900) + (9.48 \times 8.5)}{41,900} = 0.0159.$$

Hence

$$\Delta t = -\frac{1}{(2.26 \times 10^{-4})} \ln \left[\frac{40 - \frac{0.0159}{2.26 \times 10^{-4}}}{20 - \frac{0.0159}{2.26 \times 10^{-4}}} \right] = 2239 \text{ s} = 37 \text{ min.}$$

Example 7.2 Estimate the basin-fluid (water) temperature, daily yield, energy, and exergy of a passive single-slope solar still with an area of $1 \times 1 \text{ m}^2$. Given: $L = 2.5 \times 10^6 \text{ J/kg}$, $T_{gi} = 37 \text{ °C}$, $h_{e,f} = 45 \text{ W/m}^2 \text{ °C}$, $I(t) = 700 \text{ W/m}^2$, $T_a = 15 \text{ °C}$, $(MC)_f = 41,900 \text{ J/°C}$, $U_L = 9.44 \text{ W/m}^2 \text{ °C}$, $\Delta t = 3600 \text{ s}$, $(\alpha\tau)_{\text{eff}} = 0.65$

Solution From Eq. (7.2.5),

$$a = \frac{U_L}{(MC)_f} = \frac{9.44}{41,900} = 2.26 \times 10^{-4} \text{ and}$$

$$f(t) = \frac{(\alpha\tau)_{\text{eff}} I(t) + U_L T_a}{(MC)_f} = \frac{(0.65 \times 700) + (9.44 \times 15)}{41,900} = 0.0142$$

$$T_f = \left(\frac{0.0142}{2.26 \times 10^{-4}} \right) \left[1 - e^{-(2.26 \times 10^{-4}) \times 3600} \right] + 15 \times e^{-(2.26 \times 10^{-4}) \times 3600} = 41.63 \text{ °C}$$

From Eq. (7.2.9),

$$E_{\text{hourly,en}} = h_{\text{ef}}(T_f - T_{\text{gi}})A_b = 45 \times (41.63 - 37) = 210.15 \text{ W}$$

From Eq. (7.2.10),

$$\begin{aligned} E_{\text{hourly,ex}} &= h_{\text{ef}} \left[(T_f - T_{\text{gi}}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{gi}} + 273} \right) \right] \\ &= 45 \times \left(4.67 - (288) \ln \left(\frac{314.63}{310} \right) \right) = 18.017 \text{ W} \end{aligned}$$

From Eq. (7.2.7),

$$\dot{m}_{\text{ef}} = \frac{h_{\text{ef}}(T_f - T_g)}{L} \times 3600 = \left(\frac{45 \times (4.67)}{2.5 \times 10^6} \right) \times 3600 = 0.3026 \text{ kg/h}$$

7.2.2 Conventional Double-Slope Solar Still (DSSS)

Energy balances of different components of a conventional double-slope solar still (DSSS) (Fig. 3.1b) are given as follows [24]:

(i) **East side of DSSS**

$$\begin{aligned} \alpha_g I_{\text{SE}} A_{\text{gE}} + h_{\text{lf,E}} (T_f - T_{\text{giE}}) \left(\frac{A_b}{2} \right) - h_{\text{EW}} (T_{\text{giE}} - T_{\text{giW}}) A_{\text{gE}} \\ = \left(\frac{K_g}{L_g} \right) (T_{\text{giE}} - T_{\text{goE}}) A_{\text{gE}} \end{aligned} \quad (7.2.14)$$

where α_g —solar energy absorbed by the transparent-glass cover; I_{SE} —solar intensity on the east side of the glass cover (W/m^2); A_{gE} —surface area of the east-side glass cover (m^2); $h_{\text{lf,E}} (= h_{\text{ef,E}} + h_{\text{rf,E}} + h_{\text{cf,E}})$ —total internal heat-transfer coefficient on the east side ($\text{W/m}^2 \text{ } ^\circ\text{C}$); $h_{\text{ef,E}}$, $h_{\text{rf,E}}$, $h_{\text{cf,E}}$ —internal evaporative, radiative, and convective heat-transfer coefficient, respectively, on the east side ($\text{W/m}^2 \text{ } ^\circ\text{C}$); $h_{\text{ef,W}}$, $h_{\text{rf,W}}$, and $h_{\text{cf,W}}$ —internal evaporative, radiative, and convective heat-transfer coefficient on the west side ($\text{W/m}^2 \text{ } ^\circ\text{C}$); $h_{\text{lf,W}} (= h_{\text{ef,W}} + h_{\text{rf,W}} + h_{\text{cf,W}})$ —total internal heat-transfer coefficient on the west side ($\text{W/m}^2 \text{ } ^\circ\text{C}$); h_{EW} —internal radiative heat-transfer coefficient between the east and west glass covers ($\text{W/m}^2 \text{ } ^\circ\text{C}$); K_g —thermal conductivity of the glass cover ($\text{W/m } ^\circ\text{C}$); L_g —thickness of the glass cover (m); T_{goE} —temperature of the outer surface of the east-side glass cover ($^\circ\text{C}$); A_b —area of the rectangular basin (m^2); T_{giE} —temperature of the inner surface of the east-side glass cover ($^\circ\text{C}$); and T_{giW} —temperature of the inner surface of the west-side glass cover ($^\circ\text{C}$).

$$\left(\frac{K_g}{L_g}\right)(T_{giE} - T_{goE})A_{gE} = h_{lgE}(T_{goE} - T_a)A_{gE} \quad (7.2.15)$$

where $h_{lgE}(=h_{cg,E} + h_{rg,E})$ —total external heat-transfer coefficient from the east-side glass cover to the ambient ($\text{W/m}^2\text{ }^\circ\text{C}$); $h_{cg,E}$ —external convective heat-transfer coefficient from the east-side glass cover to the ambient ($\text{W/m}^2\text{ }^\circ\text{C}$); $h_{rg,E}$ —external radiative heat-transfer coefficient from the east-side glass cover to the ambient ($\text{W/m}^2\text{ }^\circ\text{C}$); and T_a —the ambient temperature ($^\circ\text{C}$).

(ii) **West side of DSSS**

$$\begin{aligned} \alpha_g I_{SW} A_{gW} + h_{lf,W}(T_f - T_{giW})\left(\frac{A_b}{2}\right) - h_{EW}(T_{giE} - T_{giW})A_{gW} \\ = \left(\frac{K_g}{L_g}\right)(T_{giW} - T_{goW})A_{gW} \end{aligned} \quad (7.2.16)$$

where I_{SW} —solar intensity on the west side of the glass cover (W/m^2); A_{gW} —surface area of the east-side glass cover (m^2); T_f —basin-fluid (water) temperature ($^\circ\text{C}$); and T_{goW} —temperature of outer surface of the west-side glass cover ($^\circ\text{C}$).

$$\left(\frac{K_g}{L_g}\right)(T_{giW} - T_{goW})A_{gW} = h_{lgW}(T_{goW} - T_a)A_{gW} \quad (7.2.17)$$

where $h_{lf,W} = h_{ef} + h_{cf} + h_{rf}$; and $h_{lgW} = h_{cW} + h_{rW}$.

(iii) **Basin liner**

$$\alpha_b(I_{SE} + I_{SW}) = 2h_{b,f}(T_b - T_f) + 2h_{ba}(T_b - T_a) \quad (7.2.18)$$

where $h_{b,f}$ —heat-transfer coefficient from the basin liner to the fluid (water) ($\text{W/m}^2\text{ }^\circ\text{C}$); α_b —absorptivity of the basin liner; T_b —the basin temperature ($^\circ\text{C}$); T_a —the ambient temperature ($^\circ\text{C}$); T_f (fluid) water temperature ($^\circ\text{C}$); and h_{ba} —heat-transfer coefficient from the basin liner to the ambient air ($\text{W/m}^2\text{ }^\circ\text{C}$).

(iv) **Base-fluid (water) mass**

$$\begin{aligned} M_f C_f \frac{dT_f}{dt} = \alpha_f(I_{SE} + I_{SW})\left(\frac{A_b}{2}\right) + 2h_{b,f}(T_b - T_f)\left(\frac{A_b}{2}\right) \\ - h_{lf,E}(T_f - T_{giE})\left(\frac{A_b}{2}\right) - h_{lf,W}(T_f - T_{giW})\left(\frac{A_b}{2}\right) \end{aligned} \quad (7.2.19)$$

where α_f —solar energy absorbed by the basin fluid (water); C_f —specific heat of water (J/kg K), M_f —mass of the basin fluid (water) (kg).

On solving Eqs. (7.2.14)–(7.2.18), one can obtain the following:

$$T_{\text{giE}} = \frac{[A + T_{\text{f}}B]}{H} \quad (7.2.20)$$

and

$$T_{\text{giW}} = \frac{[A' + T_{\text{f}}B']}{H} \quad (7.2.21)$$

On solving Eq. (7.2.19) using Eqs. (7.2.20) and (7.2.21), one can obtain the following:

$$\frac{dT_{\text{f}}}{dt} + aT_{\text{f}} = f(t) \quad (7.2.22)$$

Again, the solution of the previous differential equation can be expressed as follows:

$$T_{\text{f}} = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] + T_{\text{f0}}e^{-a\Delta t} \quad (7.2.23)$$

where $a = \left(\frac{A_{\text{b}}}{2H}\right) [h_{1\text{f,E}}(E_1 + E_2) + h_{1\text{f,W}}(E'_1 + E'_2)]$

$$f(t) = \left(\frac{A_{\text{b}}}{2H}\right) \{[(K_{1\text{E}} + \alpha_{\text{wb}})I_{\text{SE}}(t) + (K_{1\text{W}} + \alpha_{\text{wb}})I_{\text{SW}}(t)] + T_{\text{a}}(H_1 + H_2 + H_3 + H_4)\}$$

where

$$\begin{aligned} K_{1\text{E}} &= \left[h_{1\text{bf,W}} \left(\frac{A_{\text{b}}}{2A_{\text{gW}}} \right) + h_{\text{EW}} \left(1 + \frac{1}{h_{1\text{bf,E}}} \right) + U_{\text{gaW}} \right] A_{\text{gE}} A_{\text{gW}} \alpha_{\text{g}} h_{1\text{bf,E}} \\ K_{1\text{W}} &= \left[h_{1\text{bf,E}} \left(\frac{A_{\text{b}}}{2A_{\text{gE}}} \right) + h_{\text{EW}} \left(1 + \frac{1}{h_{1\text{bf,W}}} \right) + U_{\text{gaE}} \right] A_{\text{gE}} A_{\text{gW}} \alpha_{\text{g}} h_{1\text{bf,W}} \\ H_1 &= \left(\frac{A_{\text{b}}}{2} \right) (U_{\text{gaE}} A_{\text{gE}} + U_{\text{gaW}} A_{\text{gW}}) h_{1\text{bf,E}} h_{1\text{bf,W}} \\ H_2 &= A_{\text{gE}} A_{\text{gW}} h_{\text{EW}} (U_{\text{gaE}} h_{1\text{bf,E}} + U_{\text{gaW}} h_{1\text{bf,W}}) \\ H_3 &= A_{\text{gE}} A_{\text{gW}} U_{\text{gaE}} U_{\text{gaW}} (h_{1\text{bf,E}} + h_{1\text{bf,W}}) \\ H_4 &= A_{\text{gE}} A_{\text{gW}} h_{\text{EW}} (U_{\text{gaE}} h_{1\text{bf,W}} + U_{\text{gaW}} h_{1\text{bf,E}}); \\ E_1 &= U_{\text{gaE}} \left[h_{\text{EW}} + h_{1\text{bf,W}} \left(\frac{A_{\text{b}}}{2A_{\text{gW}}} \right) \right]; E_2 = U_{\text{gaW}} (h_{\text{EW}} + U_{\text{gaE}}) A_{\text{gE}} A_{\text{gW}} \\ E'_1 &= U_{\text{gaW}} \left[h_{\text{EW}} + h_{1\text{bf,E}} \left(\frac{A_{\text{b}}}{2A_{\text{gE}}} \right) \right]; E'_2 = U_{\text{gaE}} (h_{\text{EW}} + U_{\text{gaW}}) A_{\text{gE}} A_{\text{gW}} \end{aligned}$$

The thermal energy and exergy of a passive DSSS are given as follows:

$$E_{\text{hourly,en}} = [h_{\text{ef,E}}(T_f - T_{\text{giE}}) + h_{\text{ef,W}}(T_f - T_{\text{giW}})] \left(\frac{A_b}{2} \right) \quad (7.2.24)$$

$$E_{\text{hourly,ex}} = \left\{ h_{\text{ef,E}} \left[(T_f - T_{\text{giE}}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{giE}} + 273} \right) \right] + h_{\text{ef,W}} \left[(T_f - T_{\text{giW}}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{giW}} + 273} \right) \right] \right\} \left(\frac{A_b}{2} \right) \quad (7.2.25)$$

The instantaneous-gain thermal-energy efficiency (η_{th}) of the DSSS can be written as follows:

$$\eta_{\text{th}} = \frac{[h_{\text{ef,E}}(T_f - T_{\text{giE}}) + h_{\text{ef,W}}(T_f - T_{\text{giW}})] \left(\frac{A_b}{2} \right)}{A_{\text{gE}}I_{\text{SE}}(t) + A_{\text{gW}}I_{\text{SW}}(t)} \quad (7.2.26)$$

On substituting Eqs. (7.2.20) and (7.2.21) in the previous equation, one can obtain the following:

$$\eta_{\text{th}} = \left(\frac{A_b}{H} \right) \left\{ \frac{[h_{\text{ef,E}}(H - B) + h_{\text{ef,W}}(H - B')]T_f - [h_{\text{ef,E}}(A) + h_{\text{ef,W}}(A')]}{A_{\text{gE}}I_{\text{SE}}(t) + A_{\text{gW}}I_{\text{SW}}(t)} \right\}$$

On substituting the values of A, A', B , and B' , one can obtain the following:

$$\eta_{\text{th}} = \left(\frac{A_b}{H} \right) \left\{ \frac{[h_{\text{ef,E}}(E_1 + E_2) + h_{\text{ef,W}}(E'_1 + E'_2)]T_f - [(K'_{\text{IE}}I_{\text{SE}}(t) + K'_{\text{IW}}I_{\text{SW}}(t)) + T_a(H_1 + H_2 + H_3 + H_4)]}{A_{\text{gE}}I_{\text{SE}}(t) + A_{\text{gW}}I_{\text{SW}}(t)} \right\} \quad (7.2.27)$$

On substituting, $H - B = E_1 + E_2$; $H - B' = E'_1 + E'_2$ in Eq. (7.2.27) with expressions a and $f(t)$, one can obtain the following:

$$\begin{aligned}
\eta_{\text{th}} &= \left[\frac{(A_b/H)}{A_{\text{gE}}I_{\text{SE}}(t) + A_{\text{gW}}I_{\text{SW}}(t)} \right] \\
&\quad \left\{ \left\{ [(K_{\text{IE}} - K'_{\text{IE}} + \alpha_{\text{wb}})I_{\text{SE}}(t) + (K_{\text{IW}} - K'_{\text{IW}} + \alpha_{\text{wb}})I_{\text{SW}}(t)]e^{a\Delta t} \right\} + (T_{\text{f0}} - T_a) \right\} \\
&\quad (H_1 + H_2 + H_3 + H_4)e^{-a\Delta t} \\
&= \left[\frac{A_b}{H} \right] \left\{ \frac{\left\{ [(K_{\text{IE}} - K'_{\text{IE}} + \alpha_{\text{wb}})I_{\text{SE}}(t) + (K_{\text{IW}} - K'_{\text{IW}} + \alpha_{\text{wb}})I_{\text{SW}}(t)]e^{a\Delta t} \right\} - [(K_{\text{IE}} + \alpha_{\text{wb}})I_{\text{SE}}(t) + (K_{\text{IW}} + \alpha_{\text{wb}})I_{\text{SW}}(t)]e^{-a\Delta t}}{A_{\text{gE}}I_{\text{SE}}(t) + A_{\text{gW}}I_{\text{SW}}(t)} \right\} \\
&\quad + \left[\frac{(T_{\text{f0}} - T_a)}{A_{\text{gE}}I_{\text{SE}}(t) + A_{\text{gW}}I_{\text{SW}}(t)} \right] (H_1 + H_2 + H_3 + H_4)e^{-a\Delta t} \Big\} \\
&= \left[\left(\frac{A_b}{H} \right) \right] \left\{ \frac{\left\{ [(K_{\text{IE}} + \alpha_{\text{wb}})I_{\text{SE}}(t) + (K_{\text{IW}} + \alpha_{\text{wb}})I_{\text{SW}}(t)](1 - e^{-a\Delta t}) \right\} - [K'_{\text{IE}}I_{\text{SE}}(t) + K'_{\text{IW}}I_{\text{SW}}(t)]}{A_{\text{gE}}I_{\text{SE}}(t) + A_{\text{gW}}I_{\text{SW}}(t)} \right\} \\
&\quad + \left[\frac{(T_{\text{f0}} - T_a)}{A_{\text{gE}}I_{\text{SE}}(t) + A_{\text{gW}}I_{\text{SW}}(t)} \right] (H')e^{-a\Delta t} \Big\} \\
&\text{Or} \\
\eta_{\text{th}} &= F' \left[(\alpha\tau)_{\text{eff}} + \frac{(T_{\text{bf0}} - T_a)}{I(t)} U_{\text{eff}} \right]
\end{aligned} \tag{7.2.28}$$

Equation (7.2.28) is the characteristic equation of a passive DSSS system. The unknowns in the previous equations are given as follows:

$$\begin{aligned}
(\alpha\tau)_{\text{eff}} &= \frac{\left\{ [(K_{\text{IE}} + \alpha_{\text{wb}})I_{\text{SE}}(t) + (K_{\text{IW}} + \alpha_{\text{wb}})I_{\text{SW}}(t)](1 - e^{-a\Delta t}) \right\} - [K'_{\text{IE}}I_{\text{SE}}(t) + K'_{\text{IW}}I_{\text{SW}}(t)]}{A_{\text{gE}}I_{\text{SE}}(t) + A_{\text{gW}}I_{\text{SW}}(t)} \\
F' &= \left(\frac{A_b}{H} \right); U_{\text{eff}} = (H')e^{-a\Delta t} = (H_1 + H_2 + H_3 + H_4)e^{-a\Delta t} \\
I(t) &= A_{\text{gE}}I_{\text{SE}}(t) + A_{\text{gW}}I_{\text{SW}}(t) \\
\alpha_{\text{wb}} &= \left(\frac{A_b}{2} \right) (\alpha_{\text{w}} + 2\alpha_{\text{b}}U_{\text{ga}}) \\
K'_{\text{IE}} &= \left[h_{\text{lf,w}} \left(\frac{A_b}{2} \right) + h_{\text{EW}} \left(1 + \frac{h_{\text{lf,w}}}{h_{\text{lf,E}}} \right) A_{\text{gW}} + U_{\text{gaW}} A_{\text{gW}} \right] A_{\text{gE}} \alpha_{\text{g}} h_{\text{lf,E}} \\
K'_{\text{IW}} &= \left[h_{\text{lf,E}} \left(\frac{A_b}{2} \right) + h_{\text{EW}} \left(1 + \frac{h_{\text{lf,E}}}{h_{\text{lf,w}}} \right) A_{\text{gE}} + U_{\text{gaE}} A_{\text{gE}} \right] A_{\text{gW}} \alpha_{\text{g}} h_{\text{lf,w}}
\end{aligned}$$

The convective $[h_{cf,E}(T_{bf} - T_{giE}) + h_{cf,W}(T_{bf} - T_{giW})] \left(\frac{A_b}{2}\right)$ and radiative $[h_{rf,E}(T_f - T_{giE}) + h_{rf,W}(T_f - T_{giW})] \left(\frac{A_b}{2}\right)$ thermal losses from the evaporative surface to the inner surface of the top transparent-glass cover (east and west side) are negligible compared with the heat lost in increasing the temperature of the water (sensible heat). Therefore, the lost thermal-energy efficiency of a passive DSSS can be obtained as follows:

$$\eta_{L,th} = \frac{M_f C_f (T_f - T_{bf0})}{(A_{gE} I_{SE} + A_{gW} I_{SW})} \quad (7.2.29)$$

On substituting T_f from Eq. (7.2.23) with the expressions a and $f(t)$, one can obtain the following:

$$\eta_{L,th} = \left(\frac{M_f C_f}{H'} \right) \left[\frac{[(K_{1E} + \alpha_{wb}) I_{SE}(t) + (K_{1W} + \alpha_{wb}) I_{SW}(t)]}{(A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t))} - \frac{H' (e^{-a\Delta t} - 1) (T_{f0} - T_a)}{(A_{gE} I_{SE}(t) + A_{gW} I_{SW}(t))} \right]$$

$$\eta_{L,th} = F'_L \left[(\alpha\tau)_{eff} - U'_{eff} \frac{(T_{f0} - T_a)}{I(t)} \right] \quad (7.2.30)$$

where $F'_L = \frac{M_f C_f}{H'}$; $(\alpha\tau)_{eff} = \frac{[(K_{1E} + \alpha_{wb}) I_{SE}(t) + (K_{1W} + \alpha_{wb}) I_{SW}(t)]}{I(t)}$; $U'_{eff} = H' (e^{-a\Delta t} - 1)$.

For the given parameters of the system, the variation η_{th} and $\eta_{L,th}$ with decreased temperature $((T_{f0} - T_a)/I(t))$ gives the instantaneous thermal-gain energy efficiency and thermal loss-energy efficiency, respectively.

The hourly thermal exergy efficiency of a passive DSSS can be obtained from the following modified equation:

$$\eta_{hourly,ex} = \left(\frac{1}{0.933 \times A_S \times I_S(t)} \right) \left\{ h_{ef,E} \left[(T_f - T_{giE}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{giE} + 273} \right) \right] \right. \\ \left. + h_{ef,W} \left[(T_f - T_{giW}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{giW} + 273} \right) \right] \right\} \left(\frac{A_b}{2} \right) \quad (7.2.31)$$

The factor 0.933 has been used to convert Sun radiation to exergy.

Singh et al. [25] experimentally studied the energy and exergy analysis of both a conventional single-slope (area $1 \times 1 \text{ m}^2$ and inclination 15°) and a double-slope (area $2 \times 1 \text{ m}^2$ and inclination 15°) solar-distillation system for the climatic conditions of New Delhi (India). The hourly variation of thermal energy and exergy of both the systems for typical days in the months of May and January is shown in Fig. 7.1.

The hourly thermal energy and exergy for the passive single-slope solar still was found to be greater than compared with those of the passive double-slope solar still for both the months. This is credited to the fact that a single-slope solar still absorbs greater solar radiation for both months due to its orientation, which results in a higher temperature. Furthermore, the thermal exergy for May was greater for both

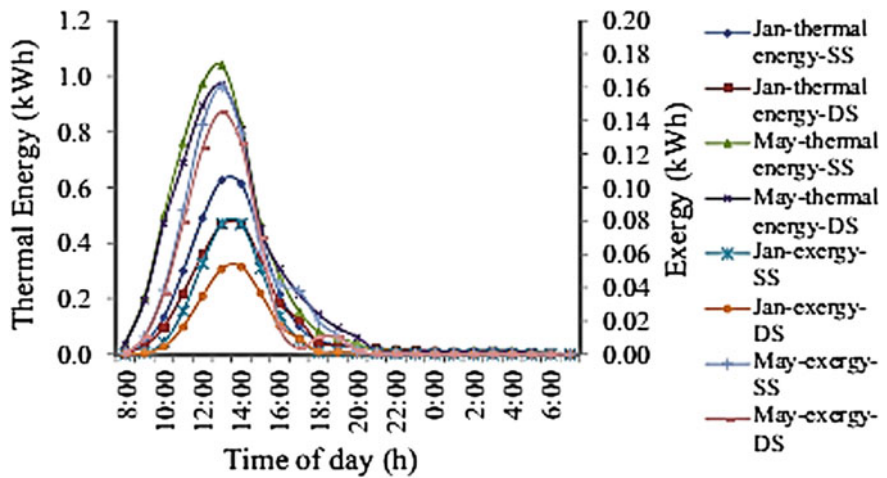


Fig. 7.1 Hourly variation of thermal energy and exergy of passive single slope and double slope solar still for the months of January and May

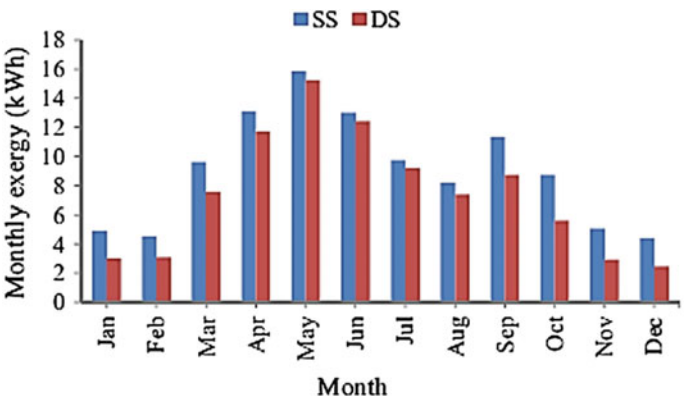


Fig. 7.2 Variation of monthly exergy of passive single slope and double slope solar stills

systems due to the greater solar radiation in that month, which enhances the temperature difference between the evaporative (fluid) surface and the inner surface of the glass cover. The monthly exergy gain (kWh) for both systems is presented in Fig. 7.2. The maximum value of exergy was found for May for both the systems due to the availability of maximum solar radiation during this month. The minimum exergy was found for December for both systems. The variation of monthly yield obtained from a passive single- and a double-slope solar still for a basin-water mass of 50 kg is depicted in Fig. 7.3. The yield was found to be greater for May for both systems.

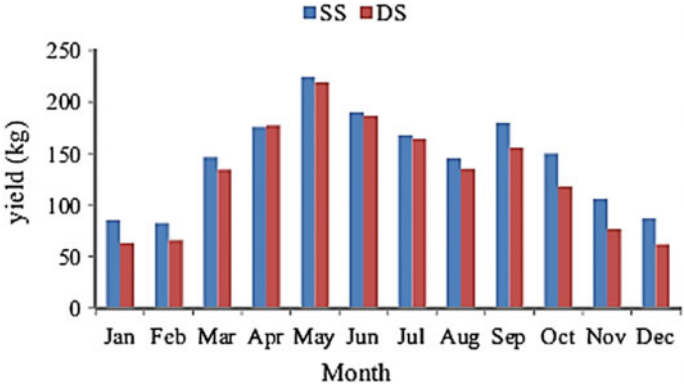


Fig. 7.3 Variation of monthly yield of passive single slope and double slope solar stills

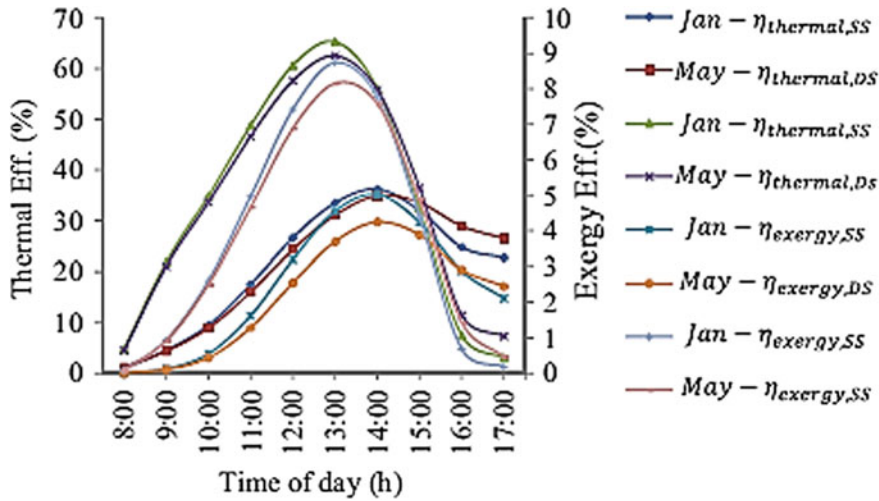


Fig. 7.4 Hourly variation of thermal energy and exergy efficiency of passive single slope and double slope solar stills for the months of May and January

Furthermore, the hourly variation of thermal-energy efficiency and exergy efficiency of both systems for the months of January and May is shown in Fig. 7.4. It was observed that both the thermal-energy and -exergy efficiency were greater for the passive single-slope solar still than the passive double-slope solar still until 2:00 pm. This is due to the fact that the orientation of the single-slope solar still receives the maximum solar radiation compared with that of the double-slope solar still. Even after 2:00 2 pm, the passive double-slope solar still yielded greater thermal-energy and -exergy efficiency due to its orientation.

The daily thermal-exergy efficiency of the passive SSSS and DSSS for May was found to be 4.49 and 4.35%, respectively. In contrast, the daily thermal-exergy efficiency of the passive SSSS and DSSS for January was found to be 2.91 and 2.50%, respectively. A daily thermal-energy efficiency of 45.03 and 42.67% was found for the SSSS and DSSS, respectively, for May. In contrast, a daily thermal-energy efficiency of 25.12 and 25.01%, respectively, was found for the SSSS and DSSS during January. Consequently, it was concluded that the passive SSSS gives a better performance than the passive DSSS on the basis of daily thermal-exergy and -energy efficiency. This is credited to the occurrence of greater hourly thermal-exergy and -energy efficiency of the single-slope compared with the double-slope still for a longer period of time.

Example 7.3 Estimate the basin-fluid (water) temperature, daily yield, energy, and exergy of a passive double-slope solar still with an area of $2 \times 1 \text{ m}^2$. Given, $a = 3.16 \times 10^{-4}$; $f(t) = 2.01 \times 10^{-2}$; $h_{\text{ef,E}} = 48 \text{ W/m}^2 \text{ }^\circ\text{C}$, $h_{\text{ef,W}} = 54 \text{ W/m}^2 \text{ }^\circ\text{C}$, $T_{\text{giE}} = 47 \text{ }^\circ\text{C}$, $T_{\text{giW}} = 48 \text{ }^\circ\text{C}$; $I_{\text{SE}}(t) = 750 \text{ W/m}^2$, $I_{\text{SW}}(t) = 650 \text{ W/m}^2$, $T_{\text{a}} = 22 \text{ }^\circ\text{C}$ (MC)_f = 41,900 J/ $^\circ\text{C}$, $\Delta t = 3600 \text{ s}$, $L = 3.1 \times 10^6 \text{ J/kg}$.

Solution

From Eq. (7.2.22), basin fluid temperature is

$$T_{\text{f}} = \left(\frac{2.01 \times 10^{-2}}{3.16 \times 10^{-4}} \right) \left[1 - e^{-(3.16 \times 10^{-4}) \times 3600} \right] + 22 \times e^{-(3.16 \times 10^{-4}) \times 3600} \\ = 50.26 \text{ }^\circ\text{C}$$

From Eq. (7.2.24), hourly thermal energy is

$$E_{\text{hourly,en}} = h_{\text{ef,E}}(T_{\text{f}} - T_{\text{giE}}) + h_{\text{ef,W}}(T_{\text{f}} - T_{\text{giW}}) \left(\frac{A_{\text{b}}}{2} \right) \\ = [48 \times (3.26) + 54 \times (2.26)] \times 1 = 0.279 \text{ kW}$$

From Eq. (7.2.25), hourly thermal exergy is

$$E_{\text{hourly,ex}} = h_{\text{ef,E}} \left[(T_{\text{f}} - T_{\text{giE}}) - (T_{\text{a}} + 273) \ln \left(\frac{T_{\text{f}} + 273}{T_{\text{giE}} + 273} \right) \right] \left(\frac{A_{\text{b}}}{2} \right) + h_{\text{ef,W}} [(T_{\text{f}} - T_{\text{giW}}) \\ - (T_{\text{a}} + 273) \ln \left(\frac{T_{\text{f}} + 273}{T_{\text{giW}} + 273} \right)] \left(\frac{A_{\text{b}}}{2} \right) = 48 \times \left(3.26 - (295) \ln \left(\frac{323.26}{320} \right) \right) \\ + 54 \times \left(2.26 - (295) \ln \left(\frac{323.26}{321} \right) \right) = 0.0233 \text{ kW}$$

From Eq. (7.2.7), productivity (yield) of the system is

$$\dot{m}_{\text{ef}} = \frac{h_{\text{ef,E}}(T_{\text{f}} - T_{\text{giE}}) + h_{\text{ef,W}}(T_{\text{f}} - T_{\text{giW}}) \left(\frac{A_{\text{b}}}{2} \right)}{L} \times 3600 \\ = \left(\frac{0.279 \times 10^3}{3.1 \times 10^6} \right) \times 3600 = 0.324 \text{ kg/h}$$

7.3 Energy and Exergy Analysis of an Active Solar Still

As explained in Chaps. 4 and 5, in the case of an active solar still the additional or external thermal energy fed into the integrated still basin enhances the temperature difference between the evaporative and inner surfaces of the transparent-glass cover. The water in the basin is circulated through the external system under either a natural or forced mode of operation per the requirement. The basin water can be heated either by direct feeding of external thermal energy or indirectly by way of heat exchanger. The insulated connecting pipes are used to minimize the thermal losses during circulation.

The energy and exergy analysis of different active solar-distillation systems is discussed in detail as follows.

7.3.1 Coupling with N-Photovoltaic Thermal Partially Covered Flat-Plate Collectors (N-PVT-FPC)

N-photovoltaic thermal partially covered flat-plate collectors (N-PVT-FPC) are discussed in detail in Chap. 4. Furthermore, an analytical expression of basin-water temperature of an active solar still integrated with N-PVT-FPC is presented in Chap. 5 (Sect. 5.2) as given below:

$$T_f = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] + T_{f0} e^{-a\Delta t} \quad (7.3.32)$$

The unknown terms in the previous equation can be retrieved from Sect. 5.2.

Thermal energy and exergy of an active single-slope solar-distillation system can be obtained from Eqs. (7.2.9) and (7.2.10), respectively.

The thermal energy and exergy efficiency of the active system can be expressed as follows:

The thermal-energy efficiency is expressed as follows:

$$\eta_{\text{the,en}} = \frac{\dot{m}_{\text{ef}} \times L}{[A_b I(t) + N A_c I_c(t)]} \times 100 \quad (7.3.33)$$

The thermal-exergy efficiency is expressed as follows:

$$\eta_{\text{the,ex}} = \frac{h_{\text{ef}} \left[(T_f - T_{\text{gi}}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{gi}} + 273} \right) \right] A_b}{(0.933)[A_b I(t) + N A_c I_c(t)]} \times 100 \quad (7.3.34)$$

where $I_c(t)$ and $I(t)$ are the total solar radiation falling on the flat-plate collector (FPC) and the transparent-glass cover of the still, respectively; and A_c —area of the solar collector (m^2).

On the basis of annual experimental observations, Dev and Tiwari [26, 27] studied the performance of a hybrid (PVT) active solar still by developing the characteristic equation for the climatic conditions of New Delhi (India). According to Dev and Tiwari [26], the instantaneous thermal (gain) energy–efficiency of their system is expressed as follows:

$$\eta_i = \frac{\dot{q}_{ew}}{(A.I(t))_{\text{eff}}} = \frac{h_{\text{ef}}(T_f - T_{\text{gi}})A_b}{I(t) + \eta_{\text{sc}}A_c I_c(t)} = \left(\frac{h_{\text{ef}}h_{1g}}{h_{1f} + h_{1g}} \right) \left(\frac{(T_f - T_a)}{I(t) + \eta_{\text{sc}}A_c I_c(t)} \right) \quad (7.3.35)$$

where η_{sc} —efficiency of the solar collector.

Case 1: For the same inclination angle of the transparent-glass cover of the still and a flat-plate collector ($I(t) = I_c(t)$), one can obtain the following:

$$\eta_i = F' \left[(\alpha\tau)_{\text{eff1}} (1 - e^{-a\Delta t}) + (U)_{\text{eff1}} e^{-a\Delta t} \left(\frac{T_f - T_a}{I(t)} \right) \right] \quad (7.3.36)$$

Case 2: For a different inclination angle of the transparent-glass cover of the still and a flat-plate collector ($I(t) \neq I_c(t)$), one can obtain the following:

$$\eta_i = F'' \left[(\alpha\tau)_{\text{eff2}} (1 - e^{-a\Delta t}) + (U)_{\text{eff2}} e^{-a\Delta t} \left(\frac{T_f - T_a}{I(t)} \right) \right] \quad (7.3.37)$$

The previous equation can be expressed as follows:

$$\eta_i = m_1 \left(\frac{T_f - T_a}{I(t)} \right) + C_1 \quad (\text{linear characteristic equation}) \quad (7.3.38)$$

where $m_1 = F''(U)_{\text{eff2}} e^{-a\Delta t}$; and $C_1 = F''(\alpha\tau)_{\text{eff2}} (1 - e^{-a\Delta t})$ are the regression coefficients. Similarly, the instantaneous thermal-loss efficiency can be expressed as follows:

$$\eta_{\text{iL}} = \frac{M_f C_f (T_f - T_{f0})}{I(t) \times 3600} \quad (7.3.39)$$

$$\eta_{\text{iL}} = \left[(\alpha\tau)_{\text{EFF}} - U''_{\text{L}} \frac{(T_f - T_a)}{I(t)} \right]$$

$$\text{or } \eta_{\text{iL}} = m_2 \left(\frac{T_f - T_a}{I(t)} \right) + C_2 \quad (\text{linear characteristic equation}) \quad (7.3.40)$$

where $m_2 = -U''_{\text{L}}$; and $C_2 = (\alpha\tau)_{\text{EFF}}$

$$(\alpha\tau)_{\text{eff2}} = \frac{(\alpha\tau)_{\text{eff}} B \psi}{1 + A'_{\text{c}} \psi}.$$

$(\alpha\tau)_{\text{eff}}$ is the optical-efficiency factor for an FPC.

$(\alpha\tau)_{\text{EFF}}$ is the optical efficiency factor for a hybrid PVT active solar still.

U_L'' is the solar still heat-loss factor ($\text{W/m}^2 \text{K}$).

ψ is the ratio of solar intensities on the collector and the solar still.

Quantitatively, the constants m_1 and m_2 of the linear characteristic equations (method 1) represent the overall heat-transfer coefficients. It has been observed that the value of m_1 is greater in the months of April, September, and March due to higher heat input to the system for New Delhi climatic conditions [26]. In contrast, m_1 remains low for other months, i.e., June and July, irrespective of both greater solar radiation and ambient temperature. This is credited to the fact that the inclination angles of the transparent-glass cover of the still and the FPC are greater compared with their optimum tilt in summer. Furthermore, it has been observed that the maximum values of instantaneous-gain and -loss efficiencies are same for the linear characteristic equations, whereas these are different in the case of non-linear characteristic equations.

The daily yield can be expressed as follows:

$$\dot{M}_{\text{ef}} = \sum_{i=1}^{24} \dot{m}_{\text{ef}} \quad (7.3.41)$$

The previous equation was used to estimate the daily yield for an active solar still for different condensing materials, and the results are shown in Fig. 7.5. It can be observed that the daily yield for copper-condensing material is slightly greater than that of glass cover-condensing material. It should also be noted that the active solar still with opaque condensing-cover material (Copper) can be integrated into the building to provide distilled water as well as hot water for domestic application in order to make the system economical.

Singh et al. [28] experimentally studied an active solar-distillation system coupled with two hybrid photovoltaic thermal flat-plate collectors (PVT-FPC) for the climatic conditions of New Delhi (India).

The electrical-exergy efficiency can be expressed as follows:

$$\eta_{\text{hourly,ex}}^{\text{elc}} = \frac{(FF \times V_0 \times I_{\text{sc}}) - V_L I_L}{0.933 \times A_m \times I_c} \times 100 \quad (7.3.42)$$

The overall thermal-energy efficiency can be expressed as follows:

$$\eta_{\text{hourly,en}}^{\text{ovr}} = \left[\frac{\dot{m}_{\text{ef}} L}{(A_c I_c + A_s I_s) \times 3600} + \frac{(FF \times V_0 \times I_{\text{sc}})}{0.38 \times A_m I_c} \right] \times 100 \quad (7.3.43)$$

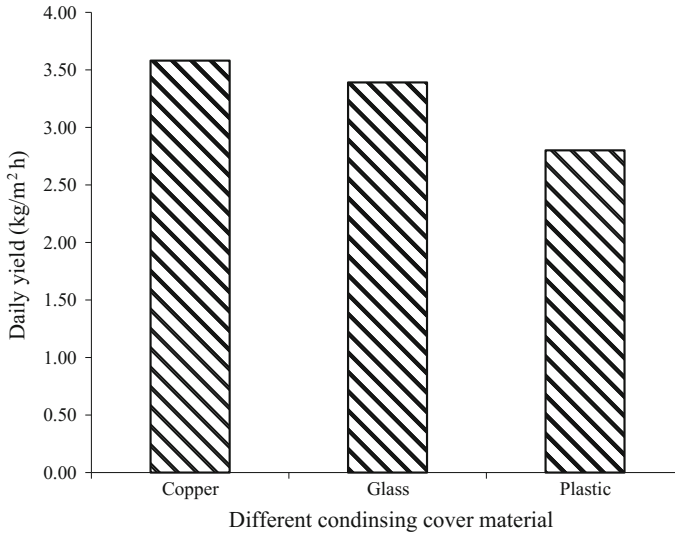


Fig. 7.5 Effect of condensing cover material on daily yield

The overall thermal-exergy efficiency can be expressed as follows:

$$\eta_{\text{hourly,ex}}^{\text{ovr}} = \frac{h_{\text{ef}} \left[(T_{\text{f}} - T_{\text{gi}}) - (T_{\text{a}} + 273) \ln \left(\frac{T_{\text{f}} + 273}{T_{\text{gi}} + 273} \right) \right] A_{\text{b}} + [(FF \times V_0 \times I_{\text{sc}}) - V_{\text{L}} I_{\text{L}}]}{0.933[(A_{\text{m}} + A_{\text{c}})I_{\text{c}} + A_{\text{s}}I_{\text{s}}]} \times 100 \quad (7.3.44)$$

The hourly variation of the thermal-energy efficiency of an active solar still for the months of November and February is shown in Fig. 7.6a, b, respectively. The variation was found to be in the range of 2–75%. The daily thermal efficiency was found to be 11.6 and 11.35% for the months of November and February, respectively. The low value of daily thermal efficiency is credited to the fact that a partially covered portion of the flat-plate collector results in lower heat gain, and hence lower heat is delivered to the basin-water mass. It causes a slow increase in basin-water temperature and therefore a low rate of evaporation.

The instantaneous efficiency or the characteristic curve of the active hybrid system for the months of November and February is presented in Fig. 7.7a, b, respectively. The curves give a fair agreement between the experimental and theoretical results.

The variation of hourly thermal-exergy efficiency for the months of November and February is shown in Fig. 7.8. The variation was found to be in the range of 0.06–20.74%, and the daily thermal-exergy efficiency was estimated at 3.92 and 3.93%, respectively, for the months of November and February.

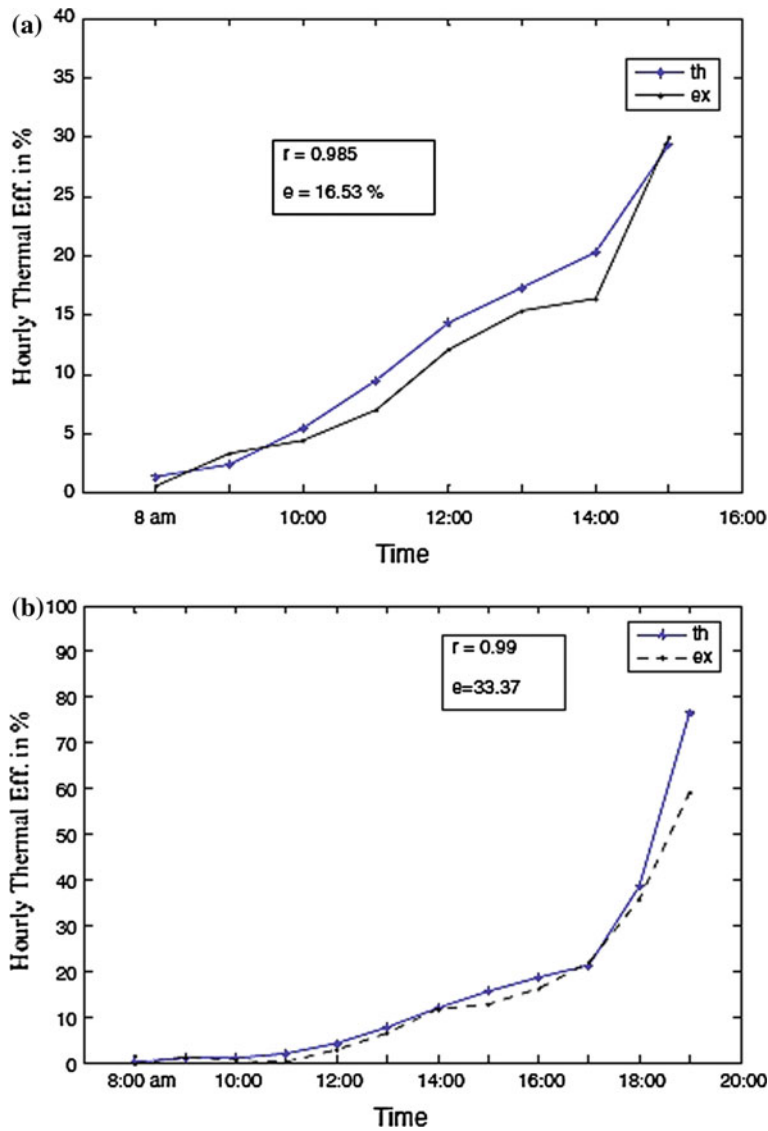


Fig. 7.6 The hourly variation of thermal energy efficiency of active solar still for the month of **a** November and **b** February

The variation of hourly electrical-exergy efficiency is shown in Fig. 7.9 and was found to be in the range of 2.21–28.53%. The daily electrical-exergy efficiency was estimated as 7.24 and 15.36%, respectively, for the months of November and February.

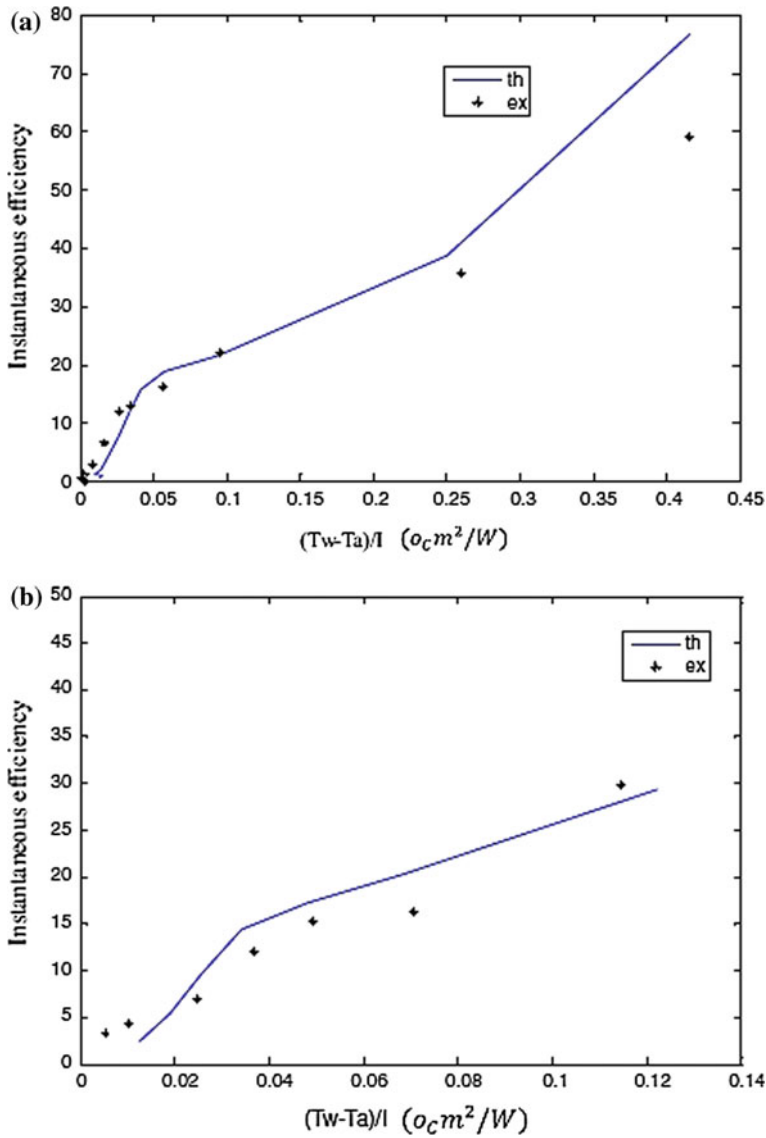


Fig. 7.7 Variation of instantaneous efficiency of the active hybrid system for the month of **a** November and **b** February

The variation of hourly overall thermal-exergy and energy efficiency is presented in Fig. 7.10a, b for the months of November and February, respectively. The overall thermal-exergy and -energy efficiency was found to be in the range of 0.03–25% and 1.02–69.06%, respectively. The daily overall exergy and energy

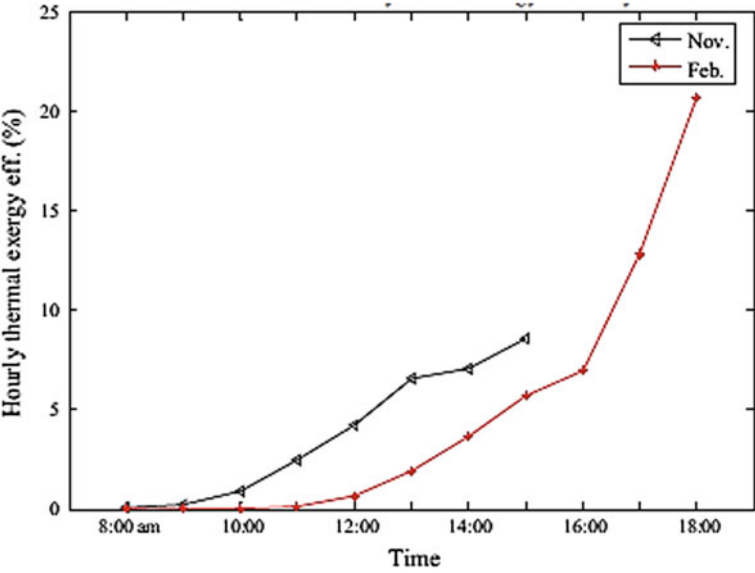


Fig. 7.8 Variation of hourly thermal exergy efficiency for the month of November and February

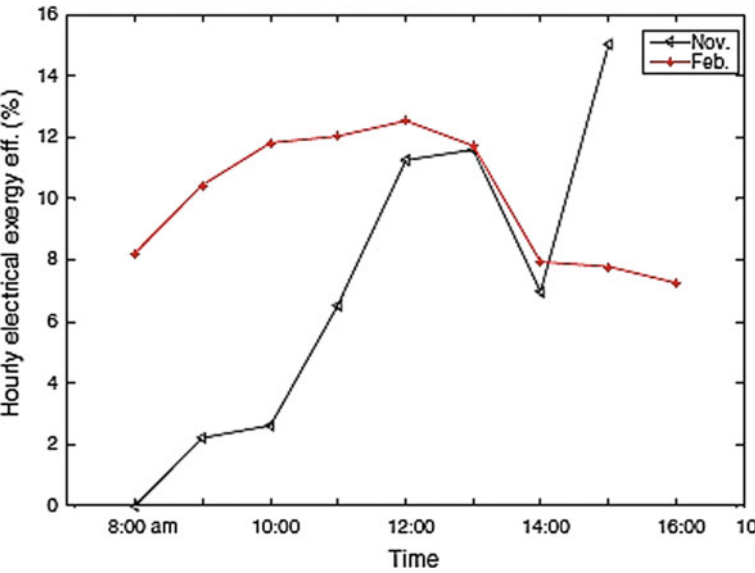


Fig. 7.9 Variation of hourly electrical exergy efficiency for the month of November and February

efficiency was found to be 5.71 and 10.09%, respectively, for November and 51.28 and 68.13%, respectively, for February.

A greater value of overall thermal efficiency is due to the conversion of electrical energy to the equivalent thermal energy obtained by dividing with factor 0.38 (efficiency of a conventional thermal power plant) as well as the electrical and thermal energy provided by the photovoltaic module. The variation of hourly

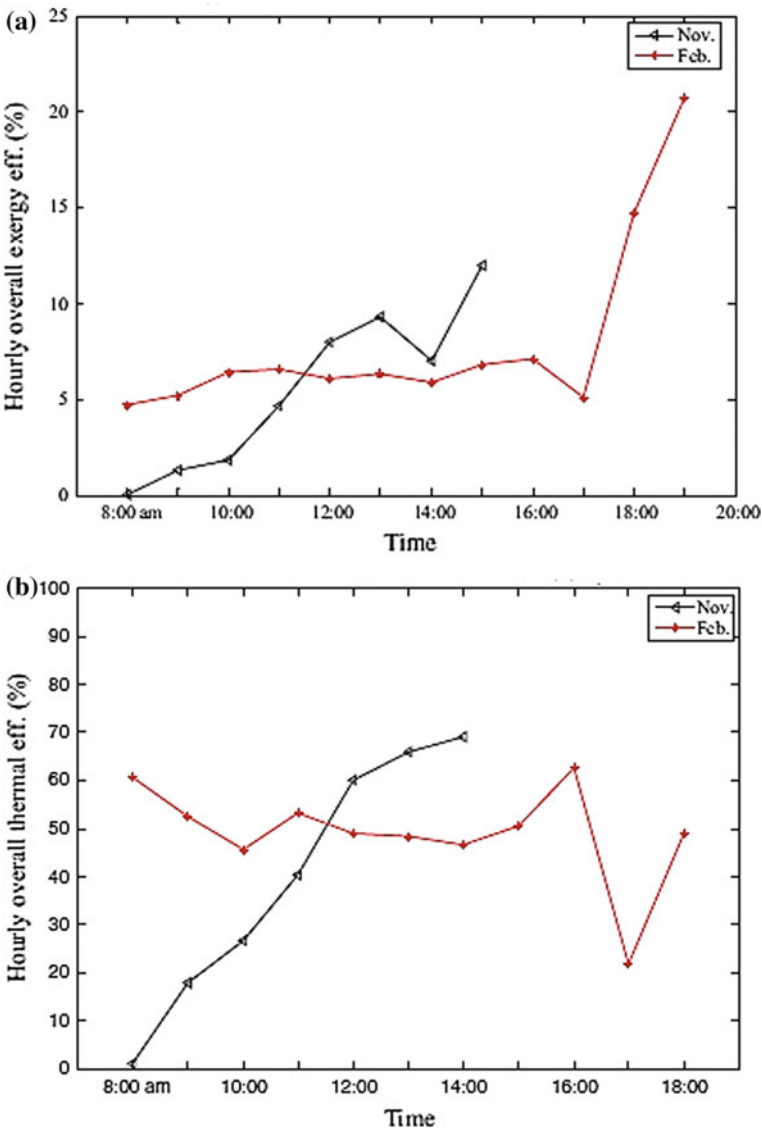


Fig. 7.10 Hourly variation of **a** overall thermal exergy and **b** overall thermal energy efficiency for the month of November and February

productivity (yield) obtained from the active hybrid system for the months of November and February is presented in Fig. 7.11a, b, respectively.

The maximum daily yield was found in May (7.74 kg), and the minimum daily yield occurred in December (1.67 kg). The maximum value of monthly yield was obtained for June (160.44 kg), and the minimum value of monthly yield was found to be 48.43 kg for December. This may be due to the intensity difference as well as the number of clear days in a particular month.

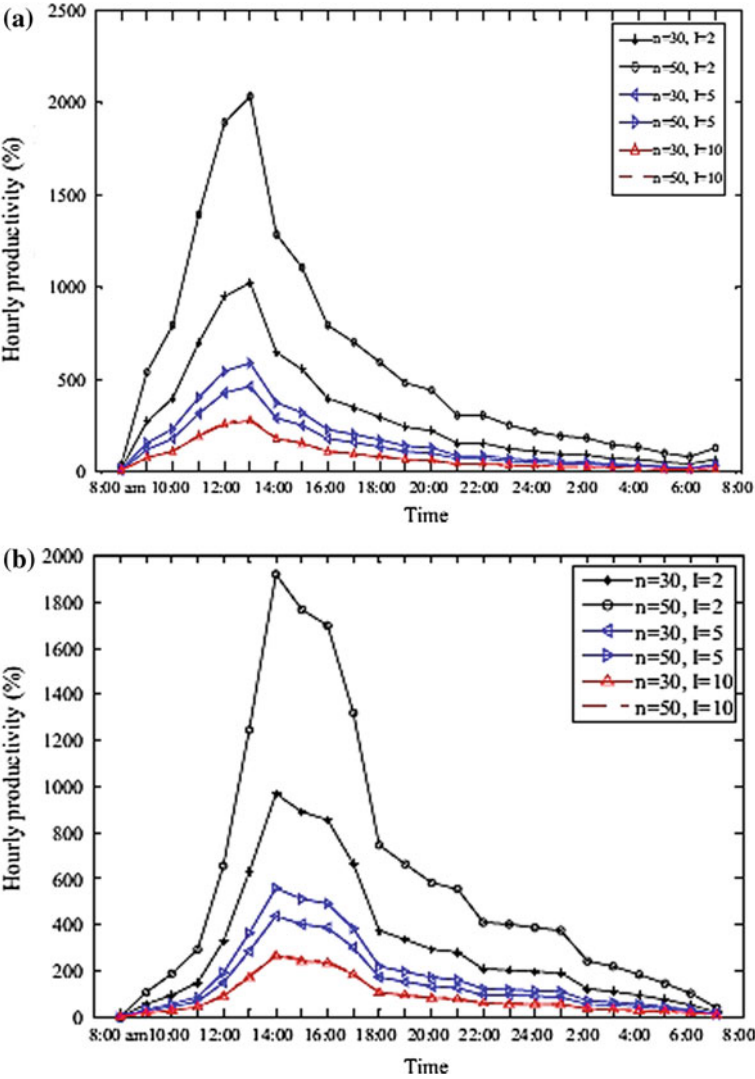


Fig. 7.11 Hourly variation of productivity for the month of a November and b February

Example 7.4 Calculate the thermal-energy and -exergy efficiency of an active double-slope solar still integrated with two photovoltaic thermal flat-plate collectors. Given, $N = 2$, $a = 2.96 \times 10^{-4}$; $f(t) = 2.28 \times 10^{-2}$; $h_{\text{ef,E}} = 51 \text{ W/m}^2 \text{ } ^\circ\text{C}$, $h_{\text{ef,W}} = 54 \text{ W/m}^2 \text{ } ^\circ\text{C}$, $T_{\text{giE}} = 56 \text{ } ^\circ\text{C}$, $T_{\text{giW}} = 58 \text{ } ^\circ\text{C}$, $I_{\text{SE}}(t) = 400 \text{ W/m}^2$, $I_{\text{SW}}(t) = 430 \text{ W/m}^2$, $T_a = 28 \text{ } ^\circ\text{C}$ $(\text{MC})_f = 41,900 \text{ J/} ^\circ\text{C}$, $\Delta t = 3600 \text{ s}$, $L = 2.80 \times 10^6 \text{ J/kg}$, $A_c = 1.395 \text{ m}^2$, $I_c(t) = 380 \text{ W/m}^2$.

Solution

From Eq. (7.3.32), basin water temperature is

$$T_f = \left(\frac{2.28 \times 10^{-2}}{2.96 \times 10^{-4}} \right) \left[1 - e^{-(2.96 \times 10^{-4}) \times 3600} \right] + 22 \times e^{-(2.96 \times 10^{-4}) \times 3600} \\ = 60.13 \text{ } ^\circ\text{C}$$

From Eq. (7.2.24), hourly thermal energy is

$$E_{\text{hourly,en}} = [h_{\text{ef,E}}(T_f - T_{\text{giE}}) + h_{\text{ef,W}}(T_f - T_{\text{giW}})] \left(\frac{A_b}{2} \right) \\ = [51 \times (4.13) + 54 \times (2.13)] \times 1 = 0.326 \text{ kW}$$

From Eq. (7.2.25), hourly thermal exergy is

$$E_{\text{hourly,ex}} = h_{\text{ef,E}} \left[(T_f - T_{\text{giE}}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{giE}} + 273} \right) \right] \left(\frac{A_b}{2} \right) + h_{\text{ef,W}} \left[(T_f - T_{\text{giW}}) \right. \\ \left. - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{giW}} + 273} \right) \right] \left(\frac{A_b}{2} \right) = 51 \times \left(4.13 - (295) \ln \left(\frac{333.13}{329} \right) \right) \\ + 54 \times (2.13 - (295) \ln \left(\frac{333.13}{331} \right)) = 0.029 \text{ kW}$$

From Eq. (7.2.7), productivity (yield) of the system is

$$\dot{m}_{\text{ef}} = \frac{[h_{\text{ef,E}}(T_f - T_{\text{giE}}) + h_{\text{ef,W}}(T_f - T_{\text{giW}})] \left(\frac{A_b}{2} \right)}{L} \times 3600 \\ = \left(\frac{0.279 \times 10^3}{2.80 \times 10^6} \right) \times 3600 = 0.419 \text{ kg/h}$$

From, Eq. (7.3.33), thermal energy efficiency is

$$\eta_{\text{the,en}} = \frac{\dot{m}_{\text{ef}} \times L}{[A_b I(t) + N A_c I_c(t)]} \times 100 = \frac{0.419 \times 2.80 \times 10^6}{[(2 \times 415) + 2 \times 1.395 \times 380]} = 17.2\%$$

From, Eq. (7.3.34), thermal exergy efficiency is

$$\eta_{\text{the,ex}} = \frac{\left\{ h_{\text{ef,E}} \left[(T_f - T_{\text{gi}}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{giE}} + 273} \right) \right] + h_{\text{ef,W}} \left[(T_f - T_{\text{giW}}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{giW}} + 273} \right) \right] \right\} \left(\frac{A_b}{2} \right)}{(0.933)[A_b I(t) + N A_c I_c(t)]} \times 100$$

$$= \frac{14.97}{0.933 \times [(2 \times 415) + 2 \times 1.395 \times 380]} \times 100 = 0.85\%$$

7.3.2 Coupling with N-Photovoltaic Thermal Partially Covered Compound-Parabolic Concentrator Collectors (N-PVT-CPC)

N-photovoltaic thermal partially covered compound-parabolic concentrator collectors (N-PVT-CPC) are discussed in detail in Chap. 4. Furthermore, an analytical expression of the basin-water temperature of an active single-slope solar still integrated with an N-PVT-FPC, as presented in Chap. 5 (Sect. 5.4), is given by Eq. (5.4.18).

Singh and Tiwari [29] analytically studied the performance of a single-slope versus a double-slope PVT-CPC solar-distillation system (Fig. 5.2a, b). Their system mainly comprised three components viz. N-identical partially (25%) covered PVT-CPC collectors and a single-slope solar still and a pump driven by a DC motor in the proposed system. In the configuration, the outlet of N-identical series-connected partially covered PVT-CPC water collectors is linked to the solar-still basin. The hybrid active solar-distillation system is explained in detail in Chap. 5 (Sect. 5.3).

The overall annual energy of the system is obtained from the sum of the annual thermal energy of the solar still and the equivalent annual thermal energy of the N-identical series-connected PVT-CPC water collectors. Hence, the overall thermal energy (E_{out}) of a PVT-CPC active solar-distillation system can be expressed as follows:

$$E_{\text{out}} = (M_{\text{ew}} \times L) + \frac{(P_m - P_u)}{0.38} \quad (7.3.45)$$

Here M_{ew} is the annual yield from the solar still; P_m is the annual power generated from the photovoltaic module; P_u is the annual power used by the pump; and L is the latent heat of vaporization. The difference $(P_m - P_u)$ signifies net electrical energy for the whole year. Electrical energy is high-grade energy;

therefore, the factor 0.38 was used for converting electrical energy into the equivalent thermal energy. This factor corresponds to the power-generation efficiency for a conventional power plant [30]. The expression for hourly electrical energy/electrical exergy ($\dot{E}x_e$) can be expressed as follows:

$$\dot{E}x_e = A_m I_b(t) \sum_1^N (\alpha \tau_g \eta_{cN}) \quad (7.3.46)$$

The hourly output of thermal energy for a single-slope versus a double-slope active solar-distillation system can be obtained from Eqs. (7.2.9) and (7.2.24), respectively. In addition, the hourly output thermal exergy for a single-slope versus a double-slope active solar-distillation system can be obtained from Eqs. (7.2.10) and (7.2.25), respectively.

The overall annual exergy gain ($G_{ex,annual}$) for a single-slope and double-slope PVT-CPC active solar-distillation system can be written as follows:

$$G_{ex,annual} = Ex_{out} + (P_m - P_u) \quad (7.3.47)$$

where Ex_{out} is the annual thermal exergy output obtained from an active solar still; P_m is the annual electrical exergy obtained from the N-identical series-connected PVT-CPC water collectors; and P_u is the power required to drive the pump.

The hourly variation of solar-cell temperature and electrical exergy for June is presented in Figs. 7.12 and 7.13, respectively. The hourly variation of electrical efficiency of the module is also shown, and it was observed that it decreases with an increase in average solar-cell temperature. This is credited to the fact that thermal-energy losses are greater at higher temperature and more collisions occur

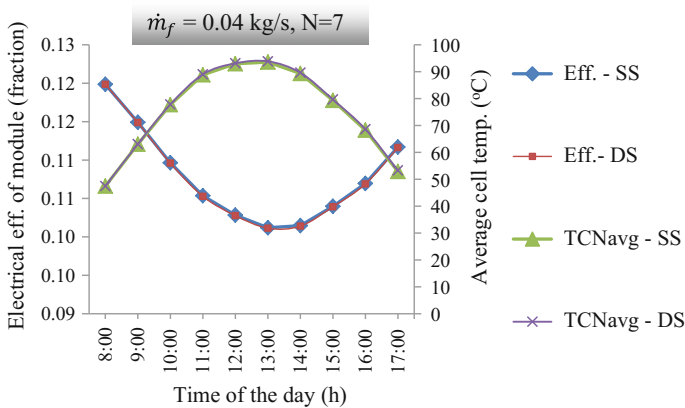


Fig. 7.12 Hourly variation of electrical efficiency of module and average solar cell temperature for a typical day in the month of June

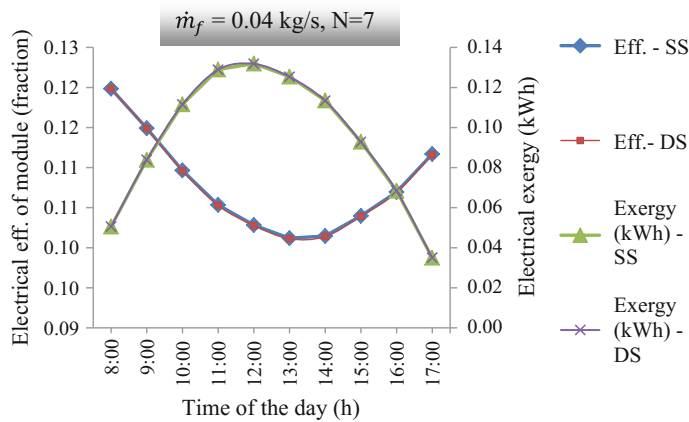


Fig. 7.13 Hourly variation of electrical efficiency and electrical exergy of module for a typical day in the month of June

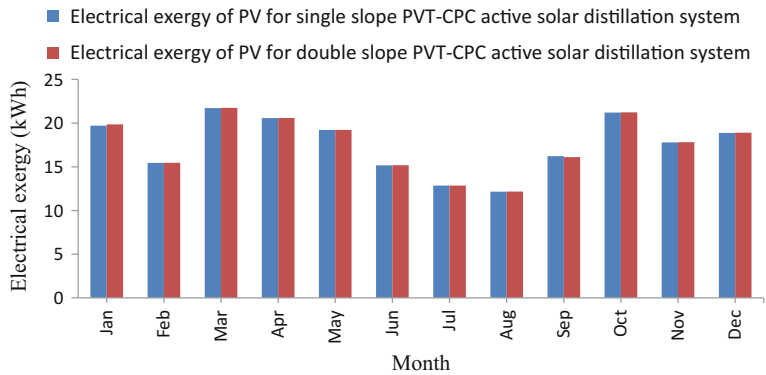


Fig. 7.14 Variation of monthly electrical exergy of PVT for single and double slope PVT-CPC active solar distillation system

between electrons in the depletion layer of the solar cell. Consequently, at low temperature, the electrical efficiency increases with a decrease in average solar-cell temperature.

The variation of monthly electrical exergy of PVT for a single- and double-slope PVT-CPC active solar-distillation system is shown in Fig. 7.14. As expected, the electrical exergy of PVT is approximately the same for both the single- and double-slope PVT-CPC active solar-distillation systems. This is due to the south-facing orientation of the series-connected N-PVT-CPC water collectors in both cases.

Fig. 7.15 Variation of daily yield of single and double slope PVT-CPC active solar distillation system for a typical day in the month of June and January

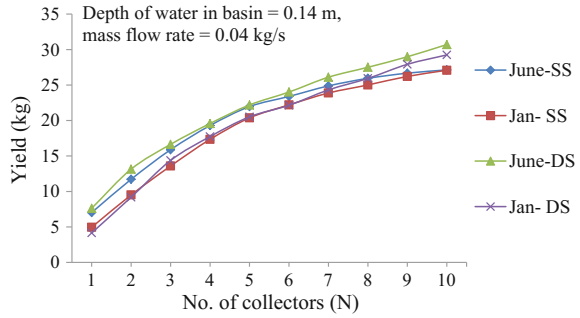


Figure 7.15 depicts the variation of daily yield obtained from a single- and a double-slope PVT-CPC solar-distillation system with the number of collectors for June and January. Daily yield increases progressively with an increase in the number of collectors.

7.3.3 Coupling with N-Evacuated Tubular Collectors (N-ETC)

Detailed insight about N-evacuated tubular collectors is given in Chap. 4. In Sect. 5.3 (Chap. 5), the temperature of the basin water is derived for a single-slope active solar still coupled with N-evacuated tubular collectors (N-ETC) given by Eq. (5.3.15).

As discussed in the previous section, the hourly output of thermal energy for a single-slope versus a double-slope active solar-distillation system can be obtained from Eqs. (7.2.9) and (7.2.24), respectively; and the hourly output of thermal exergy for both of the active systems can be obtained from Eqs. (7.2.10) and (7.2.25), respectively.

Sing et al. [31] analytically studied the performance of a single-slope solar still integrated with an evacuated tubular collector under natural circular mode for a typical summer day of New Delhi climactic conditions. The system comprises of mainly a single-slope solar still (with an area of $1 \times 1 \text{ m}^2$ and inclination of the glass cover at 30°) and an evacuated tubular collector (inclination 30°) having a number of borosilicate tubes (length 1.4 m and diameter 0.04 m). Instantaneous solar-energy input, fluid (water) temperature, and collector configuration drives the circulation flow (natural mode) inside the collector loop. Figure 7.16a, b show the variation of instantaneous overall thermal-energy and -exergy efficiency of the system, respectively, which was found to be in the range of 5.1–54.4% and 0.15–8.25%, respectively, at 0.03 m water depth during sunshine hours. Greater instantaneous thermal-energy and exergy efficiencies at 0.03 m depth are due to the higher productivity of the system, and this decreases with an increase in basin-water depth. Exergy efficiency decreases with an increase in irreversibility of the system.

Fig. 7.16 Hourly variation of instantaneous **a** energy efficiency and **b** exergy efficiency at three different basin water depths 0.03, 0.04 and 0.05 m

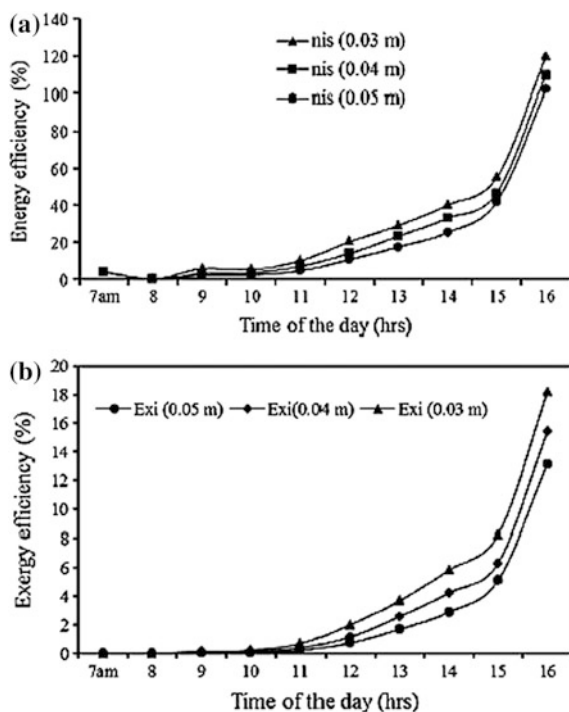


Figure 7.17 presents the hourly variation of energy and exergy output during sunshine hours at different basin-water depths. Total energy and exergy output was found to be 1.75 and 0.21 kWh, respectively, during this period (solar-energy input 7.8 kWh and exergy input 7.2 kWh).

It was observed that the evaporative fraction exergy dominates over the convective and radiative fraction energies as shown in Fig. 7.18a. It was found to be >50% for most of the time in 24 h. Figure 7.18b shows the variation of daily energy and exergy efficiency with different combinations of basin-water depth and number of borosilicate collector tubes. The best combination that makes the system more efficient is 10 numbers collector tubes and a 0.03 m basin-water depth, which yields 33 and 2.5% maximum daily energy and exergy efficiency respectively, and produces a daily yield of 3.8 kg/m².

Later, Kumar et al. [32] studied the energy and exergy analysis of a single-slope solar still coupled with an evacuated tubular collector under forced mode of operation for the same configuration as deliberated for natural mode. They optimized the mass-flow rate 0.06 kg/s and the basin-water depth 0.03 m for the best performance of the active system. The daily energy and exergy efficiency was found

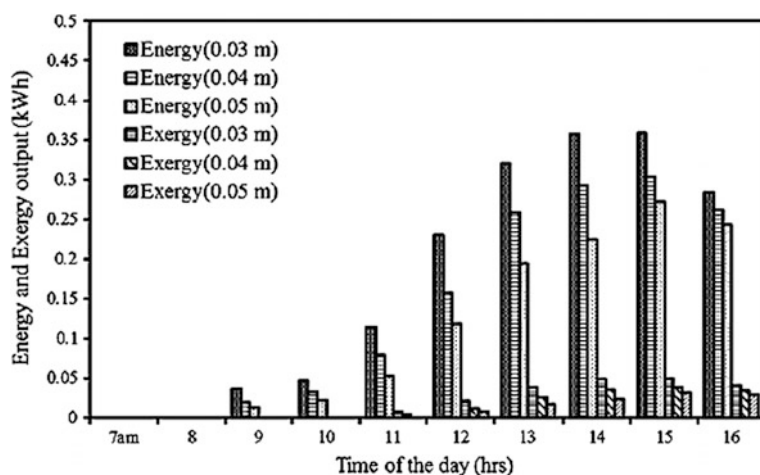


Fig. 7.17 Hourly variation of energy and exergy output at different basin water depths of the system

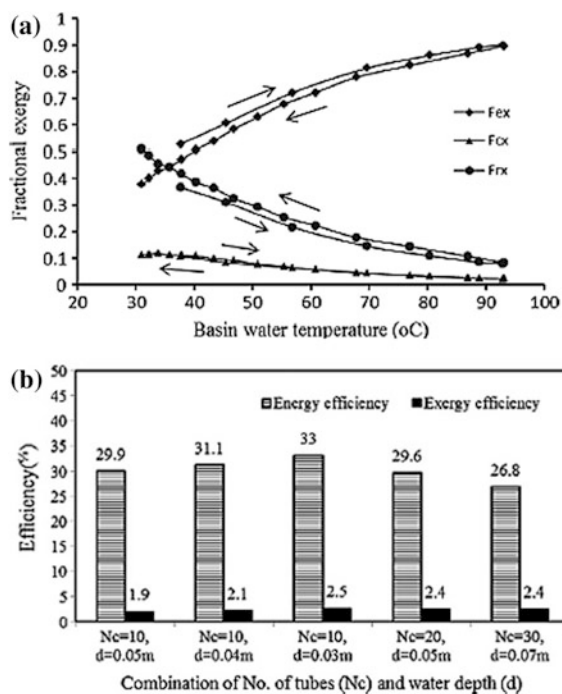


Fig. 7.18 **a** Variation of fraction exergy with basin water temperature and **b** variation of energy and exergy efficiencies with different combinations of number of tubes and basin water depth

to be 33.8 and 2.6%, respectively, with an optimum daily yield of 3.9 kg for a typical summer day of New Delhi climatic conditions.

Problems and descriptive questions

- 7.1 Derive an expression for the basin-fluid temperature for the following cases:
- Conventional single-slope solar still
 - Conventional double-slope solar still
 - Active single-slope solar still integrated with N-PVT-FPC
- 7.2 Develop the characteristic equation of (a) a conventional single-slope solar still and (b) an active single-slope solar still integrated with N-PVT-FPC.
- 7.3 Derive an expression for the lost thermal efficiency of a passive double-slope solar still.
- 7.4 Discuss the behaviors of thermal-energy and -exergy efficiency curve of an active single-slope solar still integrated with N-PVT-FPC.
- 7.5 Discuss the energy and exergy analysis of an active photovoltaic compound-parabolic concentrator active solar still.
- 7.6 Calculate the thermal energy, exergy, instantaneous thermal-gain/-loss efficiencies, and productivity of a passive double-slope solar still. Given $L = 2.5 \times 10^6 \text{ J/kg}$, $T_{gi} = 32^\circ\text{C}$, $h_{e,f} = 55 \text{ W/m}^2\text{ }^\circ\text{C}$, $(t) = 860 \text{ W/m}^2$, $T_a = 20^\circ\text{C}$, $(MC)_f = 41,900 \text{ J/}^\circ\text{C}$, $U_L = 9.22 \text{ W/m}^2\text{ }^\circ\text{C}$, $\Delta t = 3600 \text{ s}$, $(\alpha\tau)_{\text{eff}} = 0.69$. Other specifications of the system are given below:

Dimensions of passive DSSS		Constants	Numerical value
A_{gE}	$1.025 \text{ m} \times 1.025 \text{ m}$	σ	$5.67 \times 10^{-8} (\text{W/m}^2 \text{ K}^4)$
A_{gW}	$1.025 \text{ m} \times 1.025 \text{ m}$	C_{bf}	4188 (J/Kg $^\circ\text{C}$)
A_b	$2 \text{ m} \times 1 \text{ m}$	α_g	0.05
X	1.5 m	α_b	0.8
θ	30°	α_{bf}	0.6
K_g	$0.780 (\text{W/m } ^\circ\text{C})$	ϵ_g	0.95
K_B	$0.035 (\text{W/m } ^\circ\text{C})$	Where X is the characteristic length; and θ is the inclination angle of the glass cover.	
L_g	0.004 m		
L_b	0.005 m		

- 7.7 Calculate the basin-fluid temperature of an active single-slope solar still integrated with N-PVT-FPC. Use other parameters as given below:
 Basin area = $1 \times 1 \text{ m}^2$, $L = 2.8 \times 10^6 \text{ J/kg}$, $T_{gi} = 40^\circ\text{C}$, $h_{e,f} = 54 \text{ W/m}^2\text{ }^\circ\text{C}$, $I(t) = 850 \text{ W/m}^2$, $T_a = 22^\circ\text{C}$, $(MC)_f = 41,900 \text{ J/}^\circ\text{C}$, $U_L = 10.32 \text{ W/m}^2\text{ }^\circ\text{C}$, $\Delta t = 3600 \text{ s}$, $(\alpha\tau)_{\text{eff}} = 0.72$, $A_c = 2 \text{ m}^2$, $I_c = 790 \text{ W/m}^2$.
- 7.8 Calculate the thermal energy and exergy as well as the thermal-energy and exergy efficiency for Problem 7.7.

- 7.9 Estimate the instantaneous thermal-energy and exergy efficiency as well as the productivity of N-PVT-FPC-integrated active double-slope solar still. Given $I_c = 700 \text{ W/m}^2$, $I_{gE} = 600 \text{ W/m}^2$, $I_{gW} = 550 \text{ W/m}^2$, $T_a = 22^\circ\text{C}$, $N = 4$. Other specifications of different parts of the active system are given in Problem 5.11 of Chap. 5.

Objective Questions

- 7.1 The energy density of a solar thermal system is:
- greater than that of a PV module
 - lower than that of a PV module
 - equal to that of a PV module
 - none of these
- 7.2 Thermal energy is:
- high-grade energy
 - low-grade energy
 - both low- and high-grade energy
 - all of these
- 7.3 The 1 kWh is
- 36 MJ
 - 3.6 MJ
 - 0.36 MJ
 - 360 MJ
- 7.4 At a source of coal-based power generation, 1 kWh is equivalent to:
- 0.98 kg CO_2 emission
 - 9.8 kg CO_2 emission
 - 0.098 kg CO_2 emission
 - none of these
- 7.5 The solution of the previous differential equation, $\frac{dT_f}{dt} + aT_f = f(t)$, is as follows:
- $T_f = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] + T_{f0}e^{-a\Delta t}$
 - $T_f = \frac{\overline{f(t)}}{a} [1 - e^{-a\Delta t}] - T_{f0}e^{-a\Delta t}$
 - $T_f = \frac{\overline{f(t)}}{a} [1 + e^{-a\Delta t}] + T_{f0}e^{-a\Delta t}$
 - $T_f = \frac{\overline{f(t)}}{a} [1 - e^{a\Delta t}] + T_{f0}e^{a\Delta t}$

7.6 Which of the following condensing covers gives a better daily yield?

- (a) Glass cover
- (b) Copper cover
- (c) Plastic cover

7.7 Which of the following is correct expression of thermal energy of active double slope solar still?

- (a) $E_{\text{hourly, en}} = [h_{\text{ef, E}}(T_f - T_{\text{giE}}) - h_{\text{ef, W}}(T_f - T_{\text{giW}})] \left(\frac{A_b}{2}\right)$
- (b) $E_{\text{hourly, en}} = [h_{\text{ef, E}}(T_f + T_{\text{giE}}) + h_{\text{ef, W}}(T_f + T_{\text{giW}})] \left(\frac{A_b}{2}\right)$
- (c) $E_{\text{hourly, en}} = [h_{\text{ef, E}}(T_f - T_{\text{giE}}) + h_{\text{ef, W}}(T_f - T_{\text{giW}})] \left(\frac{A_b}{2}\right)$
- (d) $E_{\text{hourly, en}} = [h_{\text{ef, E}}(T_f + T_{\text{giE}}) - h_{\text{ef, W}}(T_f + T_{\text{giW}})] \left(\frac{A_b}{2}\right)$

7.8 Which of the following is the correct expression of the thermal exergy of an active single-slope solar still?

- (a) $E_{\text{hourly, ex}} = h_{\text{ef}} \left[(T_f - T_{\text{gi}}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{gi}} - 273} \right) \right]$
- (b) $E_{\text{hourly, ex}} = h_{\text{ef}} \left[(T_f - T_{\text{gi}}) - (T_a + 273) \ln \left(\frac{T_f - 273}{T_{\text{gi}} + 273} \right) \right]$
- (c) $E_{\text{hourly, ex}} = h_{\text{ef}} \left[(T_f - T_{\text{gi}}) + (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{gi}} + 273} \right) \right]$
- (d) $E_{\text{hourly, ex}} = h_{\text{ef}} \left[(T_f - T_{\text{gi}}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{gi}} + 273} \right) \right]$

Answers

7.1 (b) 7.2 (b) 7.3 (b) 7.4 (a) 7.5 (a) 7.6 (b) 7.7 (c) 7.7 (c) 7.8 (d)

References

1. R.V. Dunkle, in *Solar Water Distillation: The Roof Type Still and A Multiple Effect Diffusion Still*. International Development in Heat Transfer, ASME Proceedings, part 51961, pp. 895–902
2. P.I. Cooper, The maximum efficiency of single-effect solar stills. *Sol. Energy* **15**, 205–214 (1973)
3. V.K. Dwivedi, G.N. Tiwari, Annual energy and exergy analysis of single and double-slope passive solar stills. *Appl. Sci. Res.* **3**, 225–241 (2008)
4. P.T. Tsilingiris, Modeling heat and mass transport phenomena at higher temperatures in solar distillation systems—the Chilton-Colburn analogy. *Sol. Energy* **84**, 308–317 (2010)
5. R.V. Singh, R. Dev, M.M. Hasan, G.N. Tiwari, *Comparative energy and Exergy Analysis of Various Passive Solar Distillation Systems, Solar Thermal—Application*. World Renewable Energy Congress (Linkoping, Sweden), 8–13 May 2011
6. K.R. Ranjan, S.C. Kaushik, N.L. Panwar, *Energy and exergy analysis of passive solar distillation systems*. *Int. J. Low Carbon Technol.* **18**, 147–171 (2013)
7. G.N. Tiwari, J.K. Yadav, D.B. Singh, I.M. Al-Helal, A.M. Abdel-Ghaney, Exergoeconomic and enviroeconomic analyses of partially covered photovoltaic flat plate collector active solar distillation system. *Desalination* **367**, 186–196 (2015)

8. L. Fitzsimons, B. Corcoran, P. Young, G. Foley, Exergy analysis of water purification and desalination: a study of exergy model approaches. *Desalination* **359**, 212–224 (2015)
9. Y.A. Cengel, M.A. Boles, *Thermodynamics: An Engineering Approach*, 5th edn. (McGraw-Hill, New York, 2006)
10. J.B. Jones, R.E. Dugan, *Engineering Thermodynamics* (Prentice Hall, Upper Saddle River, 1996)
11. M.J. Moran, H.N. Shapiro, *Fundamentals of Engineering Thermodynamics*, 7th edn. (Wiley, New York, 2010)
12. G. Flavio, A. Segio, A.N. Silvia, Thermoeconomic evaluation of a gas turbine cogeneration system. *Energy Convers. Manag.* **41**, 1191–1200 (2000)
13. G. Zhang, B. Hua, Q. Chen, Exergoeconomic methodology for analysis and optimization of process systems. *Comput. Chem. Eng.* **24**, 613–618 (2000)
14. I. Dincer, The role of exergy in energy policy making. *Energy Policy* **30**, 137–149 (2000)
15. M.J. Moran, H.N. Shapiro, *Fundamentals of Engineering Thermodynamics, SI Version*, 6th edn. (Wiley India (P) Ltd., New Delhi, 2010)
16. N. Singh, S.C. Kaushik, R.D. Mishra, Exergetic analysis of a solar thermal power system. *Renew. Energy* **19**, 135–143 (2000)
17. S.C. Kaushik, V.S. Reddy, S.K. Tyagi, Energy and exergy analyses of thermal power plants: a review. *Renew. Sustain. Energy Rev.* **15**, 1857–1872 (2011)
18. G.N. Tiwari, A.K. Tiwari, *Solar Distillation Practice for Water Desalination Systems* (Anamaya Publishers, India, 2007)
19. M.A. Samee, U.K. Mirza, T. Majeed, Design and performance of a simple single basin solar still. *Renew. Sustain. Energy Rev.* **11**, 543–549 (2007)
20. V. Velmurugan, K. Srihar, Performance analysis of solar stills based on various factors affecting the productivity—a review. *Renew. Sustain. Energy Rev.* **15**, 1294–1304 (2011)
21. A.E. Kabeel, S.A. El-Agouz, Review of researches and developments on solar stills. *Desalination* **276**, 1–12 (2011)
22. G.N. Tiwari, *Solar Energy: Fundamentals, Designs, Modeling and Applications* (Narosa Publishing House, New Delhi, 2002)
23. R. Petela, Exergy of undiluted thermal radiation. *Sol. Energy* **74**, 469 (2003)
24. L. Sahota, G.N. Tiwari, Effect of nanofluids on the performance of passive double-slope solar still: a comparative study using characteristic curve. *Desalination* **388**, 9–21 (2016)
25. D.B. Singh, G.N. Tiwari, I.M. Al-Helal, V.K. Dwivedi, J.K. Yadav, Effect of energy matrices on life cycle cost analysis of passive solar stills. *Sol. Energy* **134**, 9–22 (2016)
26. R. Dev, G.N. Tiwari, Characteristic equation of a hybrid (PV-T) active solar still. *Desalination* **254**, 126–137 (2010)
27. G.N. Tiwari, L. Sahota, Review on the energy and economic efficiencies of passive and active solar distillation systems. *Desalination* **401**, 151–179 (2017)
28. D.B. Singh, J.K. Yadav, V.K. Dwivedi, S. Kumar, G.N. Tiwari, I.M. Al-Helal, Experimental studies of active solar still integrated with two hybrid PVT collectors. *Sol. Energy* **130**, 207–223 (2016)
29. D.B. Singh, G.N. Tiwari, Effect of energy matrices on life cycle cost analysis of partially covered photovoltaic compound parabolic concentrator collector active solar distillation system. *Desalination* **397**, 75–91 (2016)
30. B.J. Huang, T.H. Lin, W.C. Hung, F.S. Sun, Performance evaluation of solar photovoltaic/thermal systems. *Sol. Energy* **70**, 443–448 (2001)
31. R.V. Singh, S. Kumar, M.M. Hasan, M.E. Khan, G. Tiwari, Performance of a solar still integrated with evacuated tube collector in natural mode. *Desalination* **318**, 25–33 (2013)
32. S. Kumar, A. Dubey, G.N. Tiwari, A solar still augmented with an evacuated tube collector in forced mode. *Desalination* **347**, 15–24 (2014)

Chapter 8

Energy Matrices of Solar-Distillation Systems

8.1 Introduction

At the global level, fossil fuels are the main source of electricity. With their extensive and continuous use, fossil fuels are decreasing with time. This happens due to the rapid growth in population along with industrial progress. Moreover, burning fossil fuels also causes CO₂ emissions, which contribute to air contamination and environmental degradation. In addition, the constant use of conventional energy sources will cause the following hazards:

- (i) decrease of fossil-fuel reserves;
- (ii) global warming and other environmental concerns;
- (iii) geopolitical and military conflicts; and
- (iv) increased fuel prices.

Therefore, it is necessary to conserve fossil fuels and find other alternative energy sources. From this perspective, the awareness and appropriate use of renewable-energy sources has gained momentum worldwide.

A photovoltaic (PV) system has the potential to contribute much to a sustainable-energy system, and it is one of the most vital, reliable, and environmentally friendly technologies for energy conversion. It converts solar radiation into direct current (DC) electricity, and this DC current can be further converted to into alternative current (AC) electricity through an inverter. Therefore, it can significantly mitigate CO₂ emissions. The reported electrical efficiency of a PV module is approximately 10%, and it further decreases due to different factors, e.g., storage-battery involvement, converter, distributing wires, and efficiency of electrical appliances etc. In the above-mentioned vision, photovoltaic (PV) technology must meet two key criteria viz. (i) cost effectiveness and (ii) maximum net annual energy yield.

Here, a second criterion implies the sum of annual electrical and thermal energy (if any) obtained from the PV system. Various researchers have studied the energy analysis of PV systems [1–3].

A water pump is necessary to circulate the hot water between the solar still and the series/parallel-connected flat-plate collectors in an active solar-distillation system working under a forced mode of operation. This clearly suggests that this active system cannot function without electricity. Therefore, an ample and environmentally friendly source of energy, i.e., solar energy, is used through the photovoltaic (PV) module to fulfill the electricity requirement. By integrating the PV module into the flat-plate collector, an active solar-distillation system can be a viable substitute in a remote area of any low-economic and underdeveloped countries. In this case, the parameters viz. support structure, battery-replacement period, and balance-of-system (BOS) efficiency mentioned previously is not needed. However, it is important to estimate the energy matrices for such a system. In this chapter, embodied energy, energy matrices, and CO₂ mitigation of both passive and active solar-distillation systems are discussed in detail.

8.2 Embodied-Energy Analysis

Embodied energy is a relatively new concept of environmental assessment. It will soon be involved in the life cycle–energy estimation of any energy-generating technology. Embodied energy is defined as **“the quantity of energy required by all of the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making energy equipment and in other supporting functions i.e. direct energy plus indirect energy”** [4].

The analysis of embodied energy is performed to measure the amount of energy being used to manufacture a material, product, component, or element. It includes an assessment of the overall expenditure of energy required to extract the raw material, manufacture the products and components, and build and maintain the component element of what is being assessed. In addition, the compulsory embodied energy for the construction and maintenance of the item, component, or building over the entire life cycle must be assessed.

Similar to effective energy, embodied energy defines the level of energy depletion. System designers always try to minimize energy consumption through improved design and greater efficiency. Usually the portion of embodied energy is not been considered in this huge consumption. A common conviction is that the embodied energy portion of asset-energy consumption is insignificant and that the omission of embodied energy is due to non-availability of a clear assessment methodology, a lack of data, and a lack of understanding. However, the development of methodologies for assessment, data reliability, and access has improved over recent years. In addition, several environmental factors, such as CO₂ emission,

have been studied in the process of manufacturing all of the components of a system to facilitate life-cycle analysis.

8.2.1 *Energy Density*

Worldwide, energy analysis has been performed by various researchers and provides the values of energy densities (intensities). Given HE difficulties encountered in using different sources to confirm the values, it is necessary to explicate whether the values in terms of either primary/delivered energy or the definitions of technique boundaries. Regarding the materials incorporated into photovoltaic thermal (PVT) systems, it is difficult to obtain a fully authentic energy database. Therefore, it is necessary to acquire the exact and useful material quantities for the embodied-energy estimation for a system design. In addition, it is important to include the same with the present available energy-intensity values [5].

The following methods are given to execute energy analyses:

- (a) **Process analysis**—It method is often used to detect the system boundary around a meticulous process, and it can evaluate the needs for direct and indirect energy. The evaluation can be accomplished by way of the condition of other goods and services crossing the system boundary and capital equipment along with buildings. The system boundary is a crucial aspect in process analysis; consequently, it is essential to choose a proper system boundary that can give a significant range of results. A careful manufacturing process for the allocation of natural resources may comprise the needs “upstream,” in which the system boundary may be the factor hedge.
- (b) **Input–output analysis**—In different economic sectors, the economic flows of goods and services can be revealed by this analysis. This represents the inter-industry relationship, which shows the input–output nature of industrial sectors, i.e., the output from one industrial sector may be the input for another industrial sector. Government economists have compiled input–output matrices for economic analysis by collecting data from input–output analysis. The column entries in an inter industry matrix represent the input (i.e., monetary value of inputs to each sector) for the industrial sector, whereas row entries denote the output from a given sector. Therefore, this format clearly implies the dependence of one sector on the other. The columns indicate all of the purchases in dollars (input per \$100 of output), and rows indicate all of the sales of a sector in the matrix. The energy intensity of each sector is expressed in Giga-joules (10^9 J) of energy per \$100 of sector output (GJ/\$100), and it can be obtained by dividing the acquired purchases from individual sectors (energy supply) with suitable tariffs. In Australia, these input–output matrices have been published by the Australian Bureau of Statistics (ABS) at every fifth year for the 109 economic sectors.

- (c) **Hybrid analysis**—The direct energy and quantities of goods and services are determined by process analysis for the crucial aspects of the process, i.e., (1) an overview of process analysis as well as (2) a detailed quantification of the production process for all of the materials. Manufacture in the process analysis signifies the primary majority of the overall environmental influences. Then the input–output analysis requires the energy intensities of goods and services further upstream. Associated errors during input–output analysis can be much decreased with this approach, but this approach cannot be applied globally. However, the audited specific process/processes can be applied on the materials to derive the energy intensities and manufactured products.

It has been found that the net energy intensities were more conflicting compared with those obtained from the process analysis. Therefore, an input–output analysis was often used to derive the embodied energy intensities. Nevertheless, the accuracy of the input–output analyses is inherently unreliable, but it provides a basic level for comparison purposes. Therefore, for embodied-energy analysis, this method is preferred as the most favoured method that can minimize the errors associated with input–output analysis to a large extent. Manufacturing solar-energy technology requires the energy densities of different materials, which are given in Appendix F.

8.3 Energy Matrices

Growth in the design and manufacturing of renewable-energy technology has taken place with very fast pace in the recent past. It is predicted that this technology will play a major role in good and comfortable living, particularly in both developing and underdeveloped countries to meet the energy needs of humans. Energy matrices are significant for renewable technologies, and their use is sensible if the energy used during their manufacture is lower than the energy they can produce during their lifetime. Energy-payback time (EPBT) is one of the criteria considered for the comparison of feasibility of one renewable technology against another. From the analysis of a PV module, Hunt [6] reported the energy-payback time (EPBT) of a PV module as approximately 12 years, and these results have been found to be in good agreement with those of Kato et al. [7] for the crystalline silicon (c-Si) solar-cell module. Aulich et al. [8] concluded that the EPBT is 8 years for a crystalline silicon module. In the case of encapsulation of the Siemens C process, plastic materials are used. Under Indian climatic conditions, the EPBT duration is approximately 4 years for a crystalline silicon (c-Si) solar-cell module for annual peak load [9]. The EPBT for an amorphous silicon (a-Si) solar-cell module was predicted by Lewis and Keoleian [10]; and it has been reported that it is 7.4 years with an efficiency of 5% for Detroit (USA) climatic conditions. It has been perceived that the EPBT decreases to 4.1 years on increasing the module efficiency by 9%. Considering the hidden energy and gross-energy requirement (GER), Srinivas

et al. [11] investigated the EPBT for an amorphous silicon (a-Si) solar-cell module and reported a decrease of 2.6 years. Battisti and Corrado [12] examined the EPBT of a conventional multi-crystalline building-integrated system with 1530 kWh/m²—year annual solar radiation (global) on a horizontal plane for the climatic conditions of Rome (Italy). They reported that the EPBT has decreased from 3.3 years to 2.8 years.

From the previous discussion, the following considerations should be adopted for other renewable-energy technologies to decrease the EPBT of the PV module:

- (i) efficiency enhancement;
- (ii) use of low energy density—fabricated cost-effective materials for longer life span; and
- (iii) with minimum annual maintenance.

Energy matrices are discussed in detail as follows.

8.3.1 Energy Payback Time (EPBT)

The energy-payback time (EPBT) is the total time period essential to recover the total energy spent to prepare the materials (embodied energy) used for the fabrication of renewable-energy technologies. It depends on (i) the quantity of energy (embodied energy) expended to prepare the materials used for fabrication of the solar still and its components; and (ii) the annual energy yield (distillate output) attained from such a system. To estimate the embodied energy of an active solar still, the energy density of different materials is listed in Table 8.1.

It is important to know the values of energy densities of different materials for the estimation of the embodied energy of different components of the system. This is discussed in detail in the next section.

Energy-payback time is the ratio of embodied energy to the annual energy output from the system. Mathematically, it can be expressed as follows:

$$\text{EPBT} = \frac{\text{Embodied energy } (E_{\text{in}})}{\text{Annual energy output } (E_{\text{out}})} \tag{8.3.1}$$

To provide cost-effective renewable-energy technology for consumers, efforts should be made to lower the numerical values of EPBT as minimum as possible.

Table 8.1 Energy density of different materials

Materials	Energy density (kWh/kg)
Copper	36.87
FRP	25.64
Glass	8.72
GI angle	13.88

8.3.2 Energy-Production Factor (EPF)

This is defined as the ratio of output energy to input energy. It is used to predict the overall system performance.

(a) **On an annual basis**

$$\chi_a = \frac{E_{\text{out}}}{E_{\text{in}}} \quad (8.3.2a)$$

or

$$\chi_a = \frac{1}{T_{\text{epbt}}} \quad (8.3.2b)$$

If $\chi_a \rightarrow 1$, for $T_{\text{epbt}} \rightarrow 1$, the system is meaningful, or else it is not worthy from an energy point of view.

(b) **On a lifetime basis**

$$\chi_a = T \left(\frac{E_{\text{out}}}{E_{\text{in}}} \right) \quad (8.3.2c)$$

In this case, χ_a should be greater than unity, and it should be as maximum as for as long as possible for the cost-effectiveness of the system.

8.3.3 Life Cycle–Conversion Efficiency (LCCE)

The LCCE is the net energy output of a system with respect to the input (solar radiation) over the system's life span (T years). Mathematically, LCCE can be expressed as follows:

$$\phi(t) = \frac{(E_{\text{out}} \times T) - E_{\text{in}}}{E_{\text{sol}} \times T} \quad (8.3.3)$$

The numerical value of LCCE is always less than unity. However, for the best technology (from an energy point of view), the value of LCCE should approach unity.

It has been concluded that the embodied energy (E_{in}), the annual electrical output (E_{out}), and the life of renewable-energy technology all play a vital role to evaluate the energy matrices.

8.4 Embodied Energy and Annual Output of Renewable-Energy Technologies

It is straightforward to estimate the embodied energy of any given renewable-energy technology except for the photovoltaic (PV) module because it faces various high-technological processes unlike other renewable-energy technology. The embodied-energy calculation of a given renewable-energy technology (except PV module) can be attained as follows:

- (a) Multiply the mass of different materials (m_i) used for the manufacturing of the renewable-energy technology by the equivalent energy density (e_i) (Appendix D).
- (b) The sum of each numerical product expresses the total embodied energy.

8.4.1 Passive Solar Stills

The embodied energy of the fibre-reinforced plastic and annual yield from a still is required to estimate the energy-payback period (EPBT) of a passive single-slope solar still (basin area, 1 m^2). The materials, along with their quantity used for the solar-still fabrication, are given below:

- (a) Condensing or glass cover (thickness of 3 mm) = 1.2 m^2
- (b) Fibre-reinforced plastic (FRP) = 10 kg
- (c) Galvanized iron (G.I.) angles = 10 kg

The embodied energy of a passive solar still is evaluated as follows:

- (i) **Embodied energy of glass cover** = area $\times$ thickness $\times$ density $\times$ energy density = $1.2 \text{ m}^2 \times 0.003 \text{ m} \times 2500 \text{ kg/m}^3 \times 8.72 \text{ kWh/kg} = 73.33 \text{ kWh}$
- (ii) **Embodied energy of fibre-reinforced material** = $10 \text{ kg} \times 25.64 \text{ kWh/kg} = 256.4 \text{ kWh}$
- (iii) **Embodied energy of galvanized iron-angle stand** = $8 \text{ kg} \times 13.88 \text{ kWh/kg} = 111.04 \text{ kWh}$

Hence, the **total embodied energy of the still** = $73.33 \text{ kWh} + 256.4 \text{ kWh} + 111.04 \text{ kWh} = 441.21 \text{ kWh}$.

The annual energy available from the passive solar still for an average 2 kg annual yield/ m^2 (250 clear number of days) can be obtained as follows:

$$\text{Annual energy} = 2 \text{ kg} \times 250 \times 2.52 \times 10^6 \text{ J/kg} = 10^8 \text{ J} = 350 \text{ kWh}.$$

Therefore, from Eq. (8.3.1):

$$\text{Energy-payback time, EPBT} = \frac{\text{Embodied energy } (E_{in})}{\text{Annual energy output } (E_{out})} = \frac{441.21 \text{ kWh}}{350 \text{ kWh/year}} = 1.26 \text{ years}.$$

The estimated EPBT value of a passive solar still is low compared with its probable life span (25–30 years). Due to this fact, it has not been considered for life-cycle cost analysis.

8.4.2 Active Solar Stills

The Embodied energy and annual output of the different parts—i.e., a photovoltaic (PV) module, a conventional collector (FPC/ETC), and a hybrid collector—of an active solar still are discussed below:

(a) PV Module

Series-connected (by way of copper ribbon) 36 cells (matrix of 9×4 cells) of single crystalline silicon are imbedded to form a module. It has been assembled only after testing the solar cells under standard test conditions (STC: irradiance 1000 W/m^2 , cell temperature 25°C) and sorting to match the current and voltage. The main components of the module are given below:

- (i) front cover made of low iron-tempered glass;
- (ii) encapsulant, transparent, insulating, thermoplastic polymer foil (the most widely used one is EVA [ethylene vinyl acetate]);
- (iii) solar cells;
- (iv) copper ribbon;
- (v) back Tedlar cover foil; and
- (vi) aluminum channel.

The solar cells are implanted between the glass front plate and back Tedlar cover foil. The EVA is used for solar-cell plantation by way of heat and pressure, and all of the cells are sealed hermetically using state-of-the-art technology. Anodized aluminum channels are incorporated on the module's perimeter for its framing. A connection box is fixed under the module with an on/off switch, and it is operated by joining it to the battery by way of a cable. The amount of energy required to formulate a module of 1 m^2 area is 190 kWh.

It is challenging to estimate the total embodied energy necessary for manufacturing specific components of the PV module along with their manufacturing energy needs. The amount of energy required in various processes for the fabrication of a PV module is listed in Table 8.2.

The basic reasons behind the above-generated data are discussed below:

- (i) **Decrement in the mass of the solar cell:** The is due to the growth of new materials; case (C) has been considered as 10% of case (A).
- (ii) **Decrease in the energy of cell processing:** This decreased by 75% from case (A) to case (B).
- (iii) **The cell efficiency** is enhanced by 4%.

Table 8.2 Energy requirement (Energy density) in different processes for production of PV module

Process	Energy requirement
I. Silicon purification and processing	
(i) Czochralski Silicon (Cz-Si) production from EG-Si	290 kWh/kg of EG-Si
(ii) Electronic grade silicon (EG-Si) production from MG-Si	100 kWh/kg of EG-Si
(iii) Metallurgical grade silicon (MG-Si) production from silicon dioxide (quartz, sand)	20 kWh/kg of MG-Si
II. Fabrication of solar cell	120 kWh/m ² of Silicon cell
III. Assembly of PV module	190 kWh/m ² of PV module
IV. Roof top integrated PV system	200 kWh/m ² of PV module

Table 8.3 Embodied energy of PV module (excluding the embodied energy of BOS of PV system) for 1 m² of different specifications

Processes	MG-Si (kWh)	EG-Si (kWh)	Eg-Si for Cz-Si (kWh)	Fabrication (kWh)		Total module (kWh)
				Cell	Module	
Case (A)	48	230	483	120	190	1071
Case (B)	26.54	127.30	267.33	60.3	125.4	607
Case (C)	4.80	23.0	48.30	90	95	261

(iv) The removal of **wafer trimming and packaging**.

(v) **The embodied energy of the module** configuration is decreased by 50%.

The above-mentioned results clearly illustrate the significant decrease in embodied energy of a PV module from 1071 to 261 kWh/m² due to different reasons as discussed previously (Table 8.3).

Technically, the different components on the PV module are called balance of system (BOS) and The PV module itself is called the “system.” It involves wiring, electronic components, foundation, support structure, battery, installation, etc. In the case of open-field inauguration of the PV module, different materials (high energy) for the foundation and frame (concrete, cement and steel etc.) have been used. For example, the amount of energy required (energy density) for open-field installation or fitting of the panel is 500 kWh/m². However, the amount of energy required is decreased to 200 kWh/m² of panel in the case of a rooftop-integrated PV system; this decrease is due to the non-requirement of a foundation and frame in this case. Furthermore, the present embodied energy can be further decreased due to progress in the technology for the development of new materials used for BOS.

Thus, the total embodied energy of a PV module (including installation) will be: 1571 and 1271 kWh/m², respectively, for an open-field and a roof top-integrated building for case (A).

$$\text{The annual output of a PV module} = \eta_m \bar{I} A_m N n_0$$

where η_m is the electrical efficiency; A_m is the area of the PV module; N is the number of sunshine hours; and n_0 is the number of clear days in a year.

$\bar{I}$ is the average value of annual solar intensity, e.g., its value for Port Hedland (NW Australia), Sydney, and India are 2494, 1926 and 1800 kWh/m²/year, respectively.

For **Port Hedland (NW Australia)**, the climatic conditions are $\eta_m = 0.12$ and $A_m = 1 \text{ m}^2$.

The annual output of a PV module for $1 \text{ m}^2 = 0.12 \times 2494 \times 1 = 299.28 \text{ kWh}$. Similarly, for **Sydney and Indian**, the climatic conditions with the same design parameters are as follows:

The annual output of a PV module for 1 m^2 (Sydney) $= 0.12 \times 1926 \times 1 = 231.12 \text{ kWh}$, and the annual output of PV module for 1 m^2 (India) $= 0.12 \times 1800 \times 1 = 216 \text{ kWh}$.

For a PV-module life span of 30 years (assumed), the estimated values of energy matrices (EPBT have been expressed in Table 8.4).

Table 8.4 Energy matrices of a PV module for different climatic conditions

	Port headland			Sydney			India		
	EPBT	EPF	LCCE	EPBT	EPF	LCCE	EPBT	EPF	LCCE
Case (A)	3.60	8.30	0.105	4.64	6.47	0.101	4.96	6.05	0.100
Case (B)	2.0	15.0	0.112	2.62	11.45	0.109	2.81	10.68	0.109
Case (C)	0.87	34.50	0.116	1.13	26.55	1.115	1.21	24.79	0.115

The important role of an embodied energy (E_i), an annual electrical output (E_{out}), and a life of renewable-energy technology (T) can be realized from this table. Maximum values of EPF and LCCE, as well as lowest value of EPBT, for Port Hedland (NW Australia) clearly illustrates that the PV module is more appropriate for their climatic conditions [13].

(b) Flat-Plate Collector (FPC)

The embodied energy of various components of the active solar still, i.e., solar still, flat-plate collectors (FPC), PV module, and pump, are listed in Table 8.5. This table includes the embodied energy of two FPCs (each of area of 2 m^2) that have been estimated to be approximately 2315.10 kWh.

The embodied energy of a flat-plate collector (FPC) has an area of $2 \text{ m}^2 = 1157.55 \text{ kWh}$.

The annual solar radiation incident on an FPC of area $2 \text{ m}^2 = 400 \times 8 \times 2 \times 268 \text{ Wh} = 1715 \text{ kWh}$.

Table 8.5 Breakup of embodied energy of different components of hybrid (PV/T) active solar still

Components	Items	Quantity	Total weight (kg)	Embodied energy (MJ/kg)	Total embodied energy	
					(MJ)	(kWh)
Solar still (1 m ²)	Gaskets (8.9 m)	1	2.1	11.83	24.8	6.9
	GRP body	1	21.17	92.3	1954.0	542.8
	Glass cover (4 mm)	1	1.16	40,060 MJ/m ³	185.9	51.6
	Inlet/outlet nozzle	2	0.100	44.1	4.4	1.2
	M S clamping frame	1	5	34.2	171.1	47.5
	M S clamp	8	2	34.2	68.4	19.0
	Mild steel stand	1	14/20	34.2	478	133
Sub total					802	
Flat plate collector (quantity 2)	Aluminium box	2	10	199.0	1990.0	552.0
	Al frame (1")	12 m	2.5	170	425	118
	Al sheet 24 gauge		2.5	170	425	118
	Copper riser (0.5")	36 m	8.2	81.0	664.2	184.5
	Cu sheet	2	11	132.7	1460	405.6
	Glass cover toughened (4 mm)	2 (3.75 m ²)	0.01464 (m ³)	66,020 (MJ/m ³)	966.5	268.3
	Glass wool	13 (m ²)	0.064 (m ³)	139 (MJ/m ³)	8.89	2.5
	G I pipes (0.5")	*	9.5	44.1	418.9	116.4
	Header (1")	4.6 m	3.8	81.0	307.8	85.5
	Mild steel stand	1	40	34.2	1368	380
	Nozzle/flange	8	1	62.1	62.1	17.3
	Nuts/bolts/screws	32	1	31.06	31.06	8.6
	Paint	1 L	1 L	90.4	90.4	25.1
	Rubber gasket	18 m	4.2	11.83	49.7	13.8
	Union/elbow	8	1.5	46.8	70.2	19.5

(continued)

Table 8.5 (continued)

Components	Items	Quantity	Total weight (kg)	Embodied energy (MJ/kg)	Total embodied energy		
					(MJ)	(kWh)	
Sub total							2315.1
	PV module						
	BOS	*	*	475.2	475.2	132	
	Glass to glass	1	0.605 m ²	3612/m ²	2185.2	607	
Sub total							739
	Water pump						
	Bearings	2	0.030	*	*	*	
	Casing (brass)	1	0.300	62.0	18.6	5.2	
	Copper wire	*	0.150	110.19	16.5	4.6	
	Copper commutator	2	0.04	70.6	2.8	0.78	
	Impellers (plastic)	1	*	*	*	*	
	Motor body (SS)	1	0.100	36.1	3.61	1.0	
	Nuts/screws/flange		0.100	31.06	3.1	0.86	
	Si-steel armature	1	0.05	*	*	*	
	Steel shaft	1	0.050	12.5	0.625	0.17	
	Wire insulation	2	0.01	*	*	*	
Sub total							12.61
	Total embodied energy of hybrid active still						3868.6

For New Delhi climatic conditions with parameters viz. the annual efficiency of an FPC (η_c) = 0.70; the module area (A_m) = 2 m²; and the annual solar radiation received by the FPC = 1715 kWh.

An overall annual thermal energy for one FPC = $0.7 \times 1715 \text{ kWh} = 1205.5 \text{ kWh}$.

Now, the energy matrices of a single FPC can be estimated for a life span of 15 years using Eqs. (8.3.1)–(8.3.3) as follows:

$$\text{Energy-payback time (EPBT)} = \frac{1157.11}{1205.5} = 0.96 \text{ years}$$

$$\text{Energy-production factor (EPF)} = \frac{1205.5 \times 15}{1157.11} = 15.63$$

$$\text{Life cycle-conversion efficiency (LCCE)} = \frac{(1205.5 \times 15) - 1157.11}{1715 \times 15} = 0.66$$

It is more economical to incorporate the FPC due to their cost-effective and reasonable values of the energy matrices obtained on the basis of the annual thermal energy of the FPC'; it also fulfills all of the conditions discussed in Sect. 8.3.

(c) **Evacuated Tubular Collector (ETC)**

Annual useful energy

Design parameters:

The area of single tubular collector (A_c) = $3.14 \times 10.43 \times 11.067 = 0.144 \text{ m}^2$; $\alpha\tau = 0.81$; $U_L = 6 \text{ W/m}^2 \text{ }^\circ\text{C}$; and $\frac{A_t}{A_c} = 3.14$.

Climatic parameters:

Average annual solar intensity, $I(t) = 500 \text{ W/m}^2$; ambient temperature, $T_a = 25$; number of clear days in a year, $n = 250$; and number of sunshine hours per day, $t_T = 8$.

Thus, annual thermal energy can be obtained as follows:

$$\begin{aligned} Q_{\text{annual}} &= 0.0458 \times [(0.81 \times 500) - 0.77 \times 3.14 \times (30 - 25)] \times 8 \times 3600 \times 250 \\ &= 0.13 \times 10^9 \text{ J} = 36 \text{ kWh} \end{aligned}$$

Embodied energy

The materials, along with their specifications used for fabrication of single tubular solar collector, are given as follows:

The thickness of the copper tube = 0.003 m;

the surface area of the copper tube (A_L) = $3.14 \times A_c = 0.144 \text{ m}^2$;

the mass of the copper tube = $0.144 \times 0.003 \times 8795 = 3.8 \text{ kg}$ (density of copper = 8795 kg/m^3);

the thickness of the glass tube = 0.003 m;

the surface area of the glass tube = $3.14 \times 0.053 = 0.166 \text{ m}^2$;

and the mass of the glass tube $= 0.166 \times 0.003 \times 2700 = 13.5 \text{ kg}$ (density of copper $= 2700 \text{ kg/m}^3$).

The total embodied energy $= (3.8 \times 36.87) + (13.5 \times 8.72) = 257.82 \text{ kWh}$

(Note: 46% of the total embodied energy is given by the glass cover, and the remaining 54% is carried by the copper).

The energy-payback time for ETC can be evaluated as follows:

$$\text{EPBT} = \frac{257.82 \text{ kWh}}{36 \text{ kWh/years}} = 7.16 \text{ years}$$

From the above-mentioned calculation, it has been observed that the value of EPBT for the ETC is found to be greater than that of a flat-plate collector (FPC) due to the use of G.I. pipe and sheet in FPC. Unlike the FPC, the ETC is mostly used for industrial application. However, the EPBT of the ETC can be further decreased either by increasing the annual energy savings or decreasing the total embodied energy of the ETC. An annual energy savings can be improved by two ways viz. (i) by receiving more insolation and (ii) by increasing the number of sunshine hours. In contrast, the total embodied energy of the ETC can be decreased by lowering the copper tube's thickness by way of changing its design to have minimum copper use.

(d) Hybrid flat-plate collector

The embodied energy of single hybrid flat-plate collector with an area of 2 m^2 can be obtained by summing the embodied energy of (i) a single flat-plate collector with an area of 2 m^2 area (1157.11 kWh) and (ii) a single PV module with an area of 0.605 m^2 . The estimated value of the hybrid flat-plate collector is 1764.11 kWh (Table 8.5).

8.4.3 PV-Integrated Active Solar Still

The PV-integrated active solar still is discussed in detail in Chap. 5. It is essential to understand the complete scenario of energy analysis of a PV system for evaluation of its energy-payback time (EPBT). Consequently, the total amount of electrical energy has been used by each material for its preparation thorough different processes and energy attained in its lifetime.

The present analysis expresses the complete investigation for input and output energy involved in products. Moreover, through product manufacturing, energy flows in a life cycle of the product, from resource extraction to product use, can determine its overall energy performance. In the present case of a PV system, the sum of the energy input in the system components—as well as energy input during resource seizing, production, installation, operation, and maintenance of the PV

system—determines the gross-energy requirement (E_{in}). Moreover, then this gross-energy necessity is compared with the energy output (E_{out}).

8.4.3.1 Annual Output

The energy output of a PV system is reliant on the insolation, ambient temperatures, and various other factors. Proper design and size of the PV module is also important for a reliable and consistent performance over a longer period.

The energy output (E_{out}) of a PV system for different climatic zones (different insolation, varying number of sunshine hours/day, and efficiencies, etc.) can be estimated as follows:

Annual average insolation (kWh) = Insolation on inclined plane $\left(\frac{W}{m^2}\right) \times$ peak sunshine hours per day $\times$ number of clear days in a year = $400 \text{ W/m}^2 \times 6 \text{ (h)} \times 250 = 600 \text{ kWh/m}^2$ per year (India).

Hence, energy output of the PV system can be expressed as follows:

$$E_{out} = \text{Insolation} \times \text{system efficiency}$$

Under standard test conditions, the efficiency of a single crystalline silicon solar cell is assumed to be 14%. It decreases to 11% due to (i) enhanced cell temperature (ii) low solar intensity, and (iii) dust deposition.

8.4.3.2 Packing Factor

This is the ratio of area covered by the PV solar cells in a module to the actual area of the same module.

$$\text{Packing factor (PF)} = \frac{\text{Area of PV solar cell in a module}}{\text{Actual area of a module}}$$

There is a further decrease in efficiency if the solar-cell packing factor in the present case is assumed to be 82%. Hence,

$$\text{Efficiency of the PV system} = \text{Efficiency of the solar cell} \times \text{packing factor}$$

It directly decreases the annual average energy output. The electrical energy output from 1 m^2 PV panel will be:

$$\begin{aligned} E_{out} &= \text{Annual average insolation} \times \text{efficiency of solar cell} \times \text{packing factor} \\ &= 600 \text{ kWh/m}^2/\text{year (with 11\% uniform efficiency)} \end{aligned}$$

If the efficiency of the solar cell (decreases with time) is considered to be 8% in place of 11% of the PV system, then the electrical-energy output from a 1 m² PV panel will be as follows:

$$E_{\text{out}} = 600 \times 0.08 \times 0.82 = 39.36 \text{ kWh/m}^2/\text{year} \text{ (with 8\% uniform efficiency)}$$

The annual electrical energy available from a PV (single)-integrated FPC with an area of 0.606 m² will be 39.36 × 0.605 = 23.8 kWh/m²/year.

A water pump with a capacity of 60 W (operated with 18 V and draws a current of 0.68 A) will consume a total energy of 18 × 0.68 × 6 × 250/1000 = 18.36 kWh/m²/year in a single year. This consumed energy by the water pump is lower than annual electrical energy produced by a single PV module. This implies that the electrical energy produced by an FPC-integrated PV module is sufficient to run an active solar-distillation system.

The energy output (*E*_{out}) of a PV system on a basis of conversion efficiency of 11 and 8% for different climatic zones is listed in Table 8.6. The power capacity of a PV module depends on the amount of solar radiation it receives. Consequently, a PV module must be positioned in such a manner that it can retrieve the maximum solar radiation, i.e., perpendicular to its surface.

Eventually, the knowledge of embodied energy (kWh), as well as the energy output per year from the system, is needed to estimate the energy-payback time of a PV system. Alsema and Niluwlaar [1] discussed the various factors that must be taken into account while computing the energy-payback time and energy yield factor as discussed below:

- (i) **Evaluated process** in the life cycle of the system corresponding to the energy input and output.
- (ii) Behavior and handling of the **secondary energy** (remarkably electricity) in the analysis.
- (iii) Use of **common property** during the performance of energy supplies for PV modules.

Table 8.6 Energy output of 1 m² PV system for 300 clear sunny days in a year and two different values of sun shine hours (*n* = 6 and 8) per day

Efficiency (%)	Solar radiation (W/m ²)					
	<i>I</i> = 800 W/m ²		<i>I</i> = 1000 W/m ²		<i>I</i> = 1200 W/m ²	
	Sunshine hours (n)					
	6	8	6	8	6	8
	<i>E</i> _{out} (kWh/m ² /year)					
11	103	137	128	171	154	192
8	75	99	93	124	149	140

Table 8.7 Energy payback time (EPBT) for 1 m² PV module

Components	E_{in} (kWh/m ²)	E_{out} (kWh/m ² /year)		EPBT (years)	
		$\eta = 11\%$	$\eta = 8\%$	$\eta = 11\%$	$\eta = 8\%$
Cell fabrication	190	103	75	1.84	2.53
Cz-Si	423			4.11	5.64
EG-Si	201			1.95	2.68
MG-Si	42			0.41	0.56
Module assembly	120			1.16	1.60

The energy-payback time (EPBT) of a PV module with an area of 1 m² was evaluated using the data given in Table 8.6, and the embodied energy is compared with the energy output of the PV system.

Tables 8.6 and 8.7 clearly show that EPBT strongly depends on the solar cell and insolation (solar radiation). Generally, the life span of the PV system is considered in the range of 30–40 years.

8.5 CO₂ Mitigations

The socio-economic development of any country can be predicted from the energy consumed by that particular country. India is one of the countries that consume the lowest amount of electricity per capita, whereas per-capita electricity consumption is approximately 22% in Brazil. Per-capita Indian energy consumption is approximately 30% of that consumed in China and approximately 3.18% of that consumed in the USA. The energy consumption per capita is likely to be improved with development. In the present scenario, our energy production and consumption must be four time greater to achieve a per-capita energy consumption equivalent to that of Brazil. It should be approximately 6500 kWh/capita (European average). Therefore, it is essential for us to upturn both our energy production as well as consumption by approximately 15.5 times. Our annual economic progress rate is 8–10% per annum at present, and some other safe and reliable energy sources are essentially required to sustain this growth rate.

India is one of the countries that critically depends on natural resources, i.e., oil and gas imports, for energy. These natural sources have been consumed by approximately 65%, and it is predicted that this consumption is likely to increase further in the future considering the country’s economic development, increased living standards, rapid growth in population, and increasing prices. Among all natural resources, coal is used to produce >60% of India’s electricity at present. It is one of the major sources of emission of greenhouse gases as well as acid rains). Very soon India will become the third nation in the category of main polluters in the world after USA and China if the use of coal for electricity production is not abolished in the future. From the present scenario regarding the use of natural resources, India will exhaust its oil, gas, and coal reserves within 22, 30, and

80 years, respectively [14]. It will India <40 years to deplete its coal reserves if the nation grows continuously at a rate of 8% a year, which is the most alarming possible scenario.

Greenhouse gases play a vital role in controlling the Earth's temperature; and the planet would be so cold as to be uninhabitable without them. These gases are present in the Earth's atmosphere and decrease the loss of heat into space; consequently, it contributes to global temperatures by way of the greenhouse effect. In general, the temperature of a planet can increase to lethal levels with an excess of greenhouse gases, e.g., a 90-bar partial pressure of CO₂ can cause an increase in surface temperatures by approximately 467 °C on the planet Venus. Various natural and industrial processes directly and indirectly contribute to produce greenhouse gases in the atmosphere, which results in CO₂ levels of 380 ppmv (parts per million by volume). The present levels of CO₂ are almost 100 ppmv greater than during those immediately before industrial times on the basis of ice-core samples and records (neglecting direct human influences).

The average CO₂ equivalent intensity for electricity generation from coal is approximately 0.98 kg of CO₂/kWh [15]. Thus, the CO₂ emissions per year by each component for the 35-year lifetime of a PV system can be evaluated as follows:

$$\text{CO}_2 \text{ emission per year} = \frac{\text{Embodied energy} \times 0.98}{\text{Life time}} \quad (8.3.4)$$

The CO₂ emissions per year for a PV module (glass to glass) with effective area of 0.60534 m² and size of 1.20 m × 0.55 m × 0.01 m under the present conditions are given in Table 8.8. The CO₂ emissions for different PVT systems are presented in Fig. 8.1.

Example 8.1 Estimate the carbon-dioxide emission (CO₂) per year from a solar water heater with a lifetime of 10, 20, and 30 years when the total embodied energy required for manufacturing the system is 3550 kWh.

Solution

For a 10-year lifetime of the system, from Eq. (8.3.4), one can obtain the following:

$$\text{CO}_2 \text{ emission per year} = \frac{3550 \times 0.98}{10} = 347.9 \text{ kg of CO}_2$$

Table 8.8 CO₂ emissions per year from a PV module (glass to glass)

Components	Embodied energy (kWh)	CO ₂ emissions (kg)
Cz-Si	267.33	7.49
EG-Si	127.30	3.56
MG-Si	26.54	0.74
PV Module assembly	125.40	3.51
Solar cell fabrication	60.29	1.69
Total	606.86	16.99

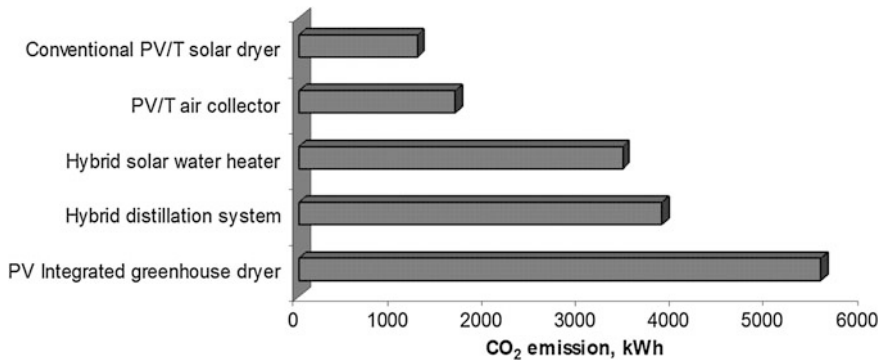


Fig. 8.1 CO₂ emissions for different PV/T systems

Similarly, CO₂ emissions per year are 173.9 and 115.9 kg of CO₂, respectively, for 20 and 30 years of lifetime.

8.5.1 Carbon Credit (C-Credit [CC])

The main motive behind the analysis of carbon credits (CC) is to minimize the influence of greenhouse-gas emission into the atmosphere by degreasing carbon footprints. It is defined as a key factor of a carbon-emissions trading scheme worldwide, which has been executed to mitigate CO₂ to decrease the level of global warming. It is based on an industrial scale by capping the total annual emissions. C-credits can be exchanged (sold/bought) at the usual market price (fixed by international agreement) in international markets. Different schemes of carbon reduction in the atmosphere can be sanctioned in trading partners on the basis of C-credits.

8.5.2 Formulation

If unit power (kWh) is used by a consumer, given the Lais electrical loss due to poor domestic appliances viz. tube light, fans, water pump, and fridge, the transmitted power should be $\frac{1}{1-L_a}$ units. For L_{td} (transmission and distribution), the generated power at a power-plant site is $\frac{1}{1-L_a} \times \frac{1}{1-L_{td}}$ units.

The average CO₂ emission for electricity generation of a unit energy (1 kWh) on site (source) from coal is approximately 0.98 kg of CO₂. Thus, the amount of CO₂ emission is $\frac{1}{1-L_a} \times \frac{1}{1-L_{td}} \times 0.98$ for a unit of power consumption on the user's end.

The annual CO₂ emission from the solar system can be expressed as

$$\begin{aligned}
 & \text{CO}_2 \text{ emission per year from the solar system} \\
 &= \frac{\text{Total CO}_2 \text{ emission by embodied energy}}{\text{Life of solar system}} \quad (8.3.5) \\
 &= \frac{E_{\text{in}}}{n_{\text{sys}}} \times \frac{1}{1 - L_a} \times \frac{1}{1 - L_{\text{td}}} \times 0.98 \text{ kg}
 \end{aligned}$$

where E_{in} and n_{sys} are the embodied energy and lifetime of the solar system, respectively.

$$\begin{aligned}
 & \text{Net CO}_2 \text{ emission over the life span of the system} \\
 &= \text{Total CO}_2 \text{ mitigation} - \text{total CO}_2 \text{ emission} \quad (8.3.6) \\
 &= (E_{\text{aout}} \times T_{\text{LS}} - E_{\text{in}}) \times \frac{1}{1 - L_a} \times \frac{1}{1 - L_{\text{td}}} \times 0.98 \text{ kg}
 \end{aligned}$$

where E_{aout} is an overall annual exergy gain.

$$\begin{aligned}
 & \text{Net CO}_2 \text{ mitigation over the life span in terms of CO}_2 \\
 &= (E_{\text{aout}} \times n_{\text{Sys}} - E_{\text{in}}) \times \frac{1}{1 - L_a} \times \frac{1}{1 - L_{\text{td}}} \times 0.98 \times 10^{-3} \quad (8.3.7)
 \end{aligned}$$

The environmental cost Z_{CO_2} is given as follows:

$$Z_{\text{CO}_2} = Z_{\text{CO}_2} \times \varphi_{\text{CO}_2} \quad (8.3.8)$$

where φ_{CO_2} is the amount of CO₂ emitted per annum.

8.6 Case Study: Energy Analysis of Solar Stills

Energy analysis of passive (single-slope and double-slope) and active solar-distillation (PVT-CPC) systems are discussed below.

8.6.1 Passive Solar Still

Singh et al. [16] studied the effect of energy matrices on the cost analysis of passive single-slope (SSSS) and double-slope (DSSS) solar stills. The comparative analysis of the stills was performed on the basis of annual exergy, energy matrices, exergoeconomic parameter, productivity, and efficiencies for different weather conditions (clear days [blue sky]), hazy days (fully), hazy and cloudy days (partially),

and cloudy days [fully] of New Delhi (India). The SSSS was placed facing south with a 15° inclination of the glass cover. The DSSS was placed facing east–west with a 15° inclination of the glass cover to retrieve the maximum solar radiation. The hourly variation of thermal energy and exergy of both stills for a typical day of the months January and May is presented in Fig. 8.2. Hourly thermal energy and exergy was found to be greater for SSSS for both months compared with DSSS. This is due to the absorption of more insolation (solar radiation) with respect to the orientation of SSSS, which ultimately enhances the temperature difference between the evaporative surface (basin water) and the inner surface of the top transparent glass cover.

The variation of energy-payback time (EPBT) and energy-production factor (EPF) of passive SSSS and DSSS systems is shown in Fig. 8.3. On the basis of energy, the EPBT was found to be 1.49 and 1.47 years, respectively, for passive SSSS and DSSS. The EPBT of passive SSSS is greater (1.38%) due to the greater embodied energy (14.61%) and annual energy (10.54%) of the SSSS compared with the DSSS. The EPF was found to be 0.67 and 0.70 years, respectively, for passive single-slope and double-slope solar stills on the basis of energy. The EPBT of passive single-slope is less (4.47%) due to the greater embodied energy (14.61%) and annual energy (10.54%) of SSSS compared with DSSS. Figure 8.4 shows the variation of life cycle–conversion efficiency (LCCE) of passive SSSS and DSSS with life span of the still.

On the basis of energy and exergy, it was found that LCCE of passive SSSS is greater than that of DSSS, which is due to greater annual exergy (17.68%), embodied energy (14.61%), and solar exergy (7.56%) of SSSS compared with DSSS. Moreover, it can be observed that the difference in LCCE between both solar stills increases with each still’s lifetime; this occurs due to gap of different values of

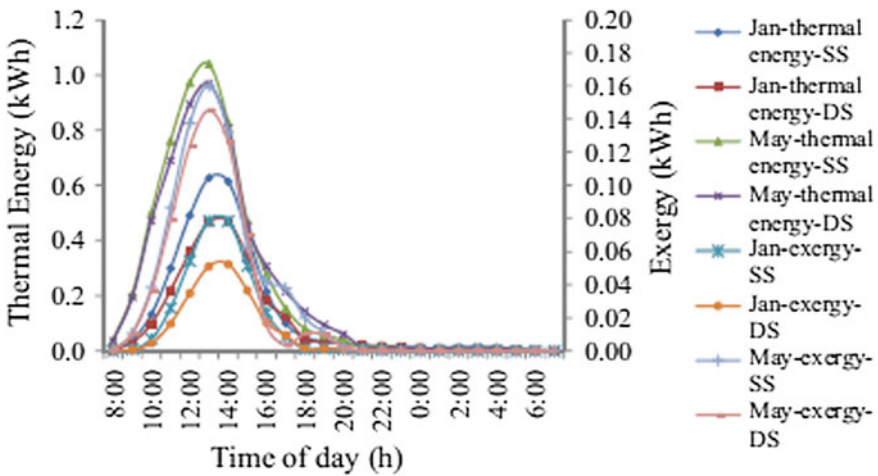


Fig. 8.2 Hourly variation of thermal energy and exergy of passive SSSS and DSSS for a typical day of the month January and May

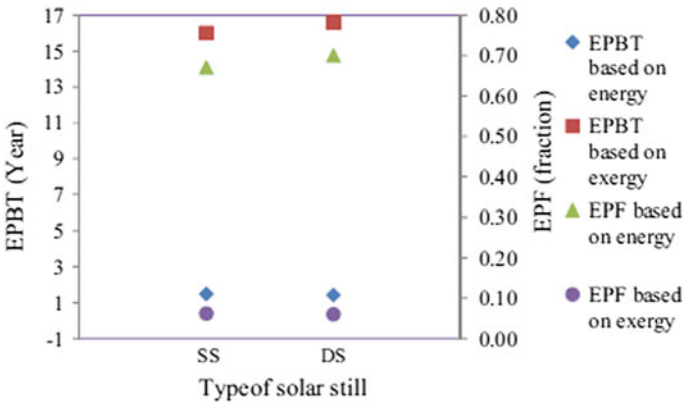


Fig. 8.3 Variation of energy payback time and energy production factor of passive single slope and double slope solar still on the basis of energy and exergy

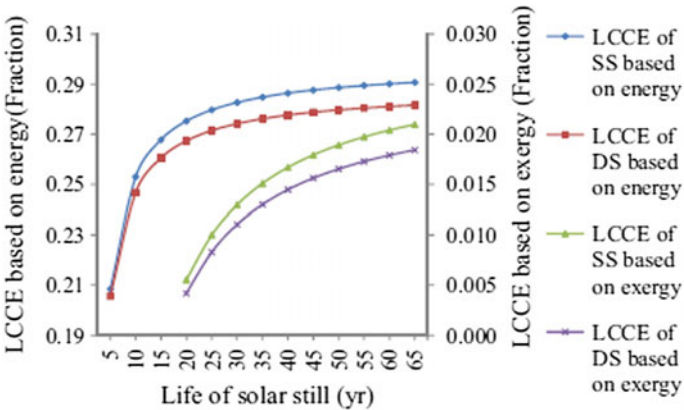


Fig. 8.4 Variation of life cycle conversion efficiency of passive single slope and double slope solar still with still's life time

available energy and embodied energy of SSSS and DSSS, which both increase with an increase in life of the system.

8.6.2 *N*-Photovoltaic Thermal Partially Covered Compound Parabolic Concentrator-Collector Active Solar Still (PVT-CPC)

The system of a single-slope and double-slope active solar still integrated with series-connected *N*-identical partially covered PVT-CPC collectors is discussed in

detail in Chap. 5. On the basis of energy matrices, Singh and Tiwari [17] compared the performance of a double-slope versus a single-slope N -PVT-CPC active solar still for optimum mass-flow rate and number of collectors at a basin depth of 0.4 m. They estimated the energy matrices for $N = 7$ number of collectors and $\dot{m}_f = 0.04$ kg/s (mass-flow rate of water inside the PVT-CPC).

From the analysis, it was found that the embodied energy for a single-slope is greater than that of a double-slope PVT-CPC active solar still for the same basin area of the still. This is ascribed to the fact that the amount of material required for the assembly of a single-slope PVT-CPC active solar still is greater due to the geometry of the system. On the basis of energy, the EPBT for an active double-slope is found to be lower (7.5%) than that of a single-slope PVT-CPC active solar still, which is due to the lower value (2.83%) of embodied energy and greater value (4.2%) of annual energy of a double-slope active solar still. In contrast, EPF is found to be greater (5.12%) for a double-slope than a single-slope PVT-CPC active solar still. This is due to the greater (4.2%) annual energy and lower value (2.83%) of embodied energy of a double-slope PVT-CPC compared with the single-slope active solar still.

On the basis of energy, it has been observed that the life cycle–conversion efficiency (LCCE) of a double-slope is greater than that of a single-slope PVT-CPC active solar still. This is due to the greater values of overall annual energy (4.2%), lower values of embodied energy (2.83%), and lower values of solar energy (1.56%) for a double-slope compared with a single-slope PVT-CPC active solar still. It implies that the numerator is greater (4.57%) and denominator lower (1.56%) in the LCCE equation (Eq. (8.3.3)) for a double-slope than a single-slope PVT-CPC active solar still. Therefore, the ratio that represents the LCCE based on energy is (5.55%) greater. Eventually, it has been concluded that the value of energy matrices, exergy, and energy at a basin depth of 0.14 m for a double-slope PVT-CPC is better than that of a single-slope active solar still.

Problems and descriptive questions

- 8.1 What is your understanding of the term “embodied energy”?
- 8.2 Calculate the embodied energy of different components of a passive solar still.
- 8.3 Calculate the embodied energy of different components of an active solar still.
- 8.4 Explain two different methods to execute the energy analysis of a renewable-energy system.
- 8.5 Explain the following energy matrices in detail:
 - (a) Energy-payback time (EPBT)
 - (b) Energy-production factor (EPF)
 - (c) Life cycle–conversion efficiency (LCCE)
- 8.6 Discuss the important role of energy matrices for the designing of solar stills.

8.7 Explain the environmental impact of CO₂ emission. How are renewable-energy systems consistent with CO₂ mitigation?

Objective questions

8.1 Which of the following method is executed in energy analysis?

- (a) process analysis
- (b) input-out analysis
- (c) hybrid analysis
- (d) all of these

8.2 Energy matrices include

- (a) Energy payback time
- (b) Energy production factor
- (c) life cycle conversion efficiency
- (d) all of these

8.3 Thermal energy is:

- (a) high-grade energy
- (b) low-grade energy
- (c) both low- and high-grade energy
- (d) all

8.4 Energy-payback time (EPBT) of a solar thermal system is:

- (a) lower than that of a PV module
- (b) greater than that of a PV module
- (c) equal to that of a PV module
- (d) none of these

8.5 Energy-payback time (EPBT) should be estimated under the:

- (a) standard test condition (STC)
- (b) real weather condition
- (c) both condition
- (d) all

8.6 Energy-payback time (EPBT) of active solar still is:

- (a) greater than the EPBT of a passive solar still
- (b) less than the EPBT of a passive solar still
- (c) equal to the EPBT of a passive solar still
- (d) none of these

- 8.7 The embodied energy of most renewable-energy technologies is always:
- (a) less than the energy density
 - (b) greater than the energy density
 - (c) equal to the energy density
 - (d) none of these
- 8.8 The energy-payback time (EPBT) should be preferably
- (a) <1
 - (b) >1
 - (c) $=1$
 - (d) $=0$
- 8.9 For wind energy–mechanical power, EPBT is:
- (a) <1
 - (b) >1
 - (c) $=1$
 - (d) $=0$
- 8.10 The energy-payback time (EPBT) for an FPC mainly depends on
- (a) ambient air
 - (b) wind velocity
 - (c) solar intensity
 - (d) none of these
- 8.11 The EPBT for a PV module with BOS is:
- (a) decreased
 - (b) increased
 - (c) constant
 - (d) none of these
- 8.12 The EPBT for a PV module at present is
- (a) less than unity
 - (b) greater than unity
 - (c) equal to unity
 - (d) zero
- 8.13 Which of the following relations between EPBT and EPF is correct?
- (a) $EPBT = \frac{1}{EPF}$
 - (b) $EPBT = \left(\frac{1}{EPF}\right)^2$
 - (c) $EPBT = \left(\frac{1}{EPF}\right)^{-1}$
 - (d) none of these

- 8.14 Which of the following is the correct expression of life cycle–conversion efficiency of a system?
- $\phi(t) = \frac{(E_{\text{out}} \times T) - E_{\text{in}}}{E_{\text{sol}} \times T}$
 - $\phi(t) = \frac{(E_{\text{out}} \times T) + E_{\text{in}}}{E_{\text{sol}} \times T}$
 - $\phi(t) = \frac{(E_{\text{in}} \times T) - E_{\text{out}}}{E_{\text{sol}} \times T}$
 - $\phi(t) = \frac{(E_{\text{in}} \times T) - E_{\text{out}}}{E_{\text{sol}} \times T}$
- 8.15 For the best technology (energy point of view), the value of LCCE should approach:
- >1
 - <1
 - =0
 - =1
- 8.16 The CO₂ emission for zero embodied energy is:
- <1
 - >1
 - 1
 - 0
- 8.17 At the source of coal-based power generation, 1 kWh is equivalent to
- 0.98 kg CO₂ emission
 - 98 kg CO₂ emission
 - 0.0098 kg CO₂ emission
 - none of these

Answers

- 8.1 (d) 8.2 (b) 8.3 (b) 8.4 (a) 8.5 (b) 8.6 (a) 8.7 (a) 8.8 (d) 8.9 (a) 8.10 (c) 8.11 (b) 8.12 (a) 8.13 (a) 8.14 (a) 8.15 (d) 8.16 (d) 8.17 (a)

References

- E.A. Alsema, E. Niluwlaar, Energy viability of photovoltaic systems. *Energy Policy* **28**, 999 (2000)
- S. Krauter, R. Ruther, Considerations for the calculations of green house gas reduction by photovoltaic solar energy. *Renewable Energy* **29**, 345–355 (2004)
- P. Frankl, A. Masini, M. Gamberale, D. Toccaceli, Simplified life cycle analysis of PV system in buildings present situations and future trends. *Prog. Photovoltaics Res. Appl.* **2**, 137 (1998)
- G.J. Treloar, *Energy Analysis of the Construction of Office Buildings*. Master of Architecture Thesis, Deakin University, Geelong (1994)
- I. Boustead, G.F. Hancock, *Handbook of Industrial Energy Analysis*, vol. 309 (Ellis Horwood Publishers, 1979)

6. L.P. Hunt, *IEEE PV Specialists Conference* (Piscataway, NJ, 1986), pp. 347–352
7. K. Kato, A. Murata, K. Sakuta, *Progress in Photovoltaic Research Applications*, vol. 6 (1998), pp. 105–115
8. H.A. Aulich, F.W. Schulz, B. Strake, *IEEE PV Specialist Conference* (Piscataway, NJ, 1986), pp. 1213–1218
9. R. Prakash, N.K. Bansal, *Energy Sources* **17**, 605–613 (1995)
10. G. Lewis, G. Keoleian, *National Pollution Prevention Center, School of Natural Resources and Environment*. University of Michigan (1996)
11. K.S. Srinivas, M. Vuknic, A.V. Shah, R. Tscharnner, *6th International Photovoltaic Science and Engineering Conference (PVSEC-6)* (New Delhi, India, 1992), pp. 403–413
12. R. Battisti, A. Corrado, Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. *Energy* **30**, 952–967 (2005)
13. R. Dones, R. Frischknecht, Life-cycle assessment of photovoltaic systems: results of swiss studies on energy chains. *Prog. Photovoltaics Res. Appl.* **6**, 117–125 (1998)
14. R. Kalshian, *Energy Versus Emissions: The Big Challenge of the New Millennium*. By Info Change News
15. M.E. Watt, A.J. Johnson, M. Ellis, H.R. Outhred, Life-cycle air emissions from PV power systems. *Prog. Photovoltaics Res. Appl.* **6**, 127–136 (1998)
16. D.B. Singh, G.N. Tiwari, I.M. Al-Helal, V.K. Dwivedi, J.K. Yadav, Effect of energy matrices on life cycle cost analysis of passive solar stills. *Sol. Energy* **134**, 9–22 (2016)
17. D.B. Singh, G.N. Tiwari, Effect of energy matrices on life cycle cost analysis of partially covered photovoltaic compound parabolic concentrator collector active solar distillation system. *Desalination* **397**, 75–91 (2016)

Chapter 9

Exergoeconomic Analysis of Solar-Distillation Systems

9.1 Introduction

Exergoeconomic analysis is the exergy-based economic analysis method for comparing two energy-conversion systems. In these systems, the identification and calculation of location, magnitude, causes, and costs of thermodynamic inefficiencies have been carried by way of exergoeconomic analysis. The exergy loss, time and capital cost-based correlation has been used in exergoeconomic analysis. This correlation clearly suggests that the system should be constructed to attain the overall optimal design corresponding to the exergy and economic characteristics. Different methods are available for exergoeconomic (exergetic-cost) analysis.

The main motive of the analysis is to achieve the optimal design of the system. For this purpose, mutual techniques of scientific disciplines (mainly thermodynamics) with economic disciplines (mainly cost accounting) are often used. Cost-accounting usually considers unit costs on the basis of energy for energy-conversion devices. Worldwide, various researchers recommend the better distribution of costs among the outputs if cost accounting is exergy-based (i.e., thermodynamic quantity) [1–16]. One basis for this declaration is that the consistent or reliable measure of economic value is exergy rather than energy, and different methodologies exist (exergoeconomics, thermoeconomics, etc.) to perform exergy-based economic analysis.

9.2 Modeling: Fundamental Equations

The exergoeconomic methodology is discussed using balance equations or fundamental equations for appropriate quantities [17]:

9.2.1 General Balance Equation (GBC)

For a quantity in a system, a general balance can be expressed as follows:

$$\text{Input} + \text{Generation} - \text{Output} - \text{Consumption} = \text{Accumulation} \quad (9.2.1)$$

where “input” refers to quantities entering through the system boundaries; and “output” refers to quantities exiting through the system boundaries. Within a system, quantities produced and quantities consumed refer to generation and consumption, respectively, and “accumulation” denotes the growth (either positive or negative) of the quantity.

The general-balance equation can be expressed in the forms of integral and differential. The differential balance describes the system behavior at a given instant of time, whereas the integral balance expresses the system behaviors between two instants of time, i.e., in a particular time interval. Generally, differential balances are applicable to continuous processes, whereas integral balances are applied to group processes. In the differential balance, the accumulation-rate term is zero for steady-state processes.

Different terms define the rates in Eq. (9.2.1) in differential form as follows:

$$\begin{aligned} &\text{Input rate} + \text{Generation rate} - \text{Output rate} - \text{Consumption rate} \\ &= \text{Accumulation rate} \end{aligned} \quad (9.2.2)$$

In contrast, these terms can be expressed in amounts in integral form as follows:

$$\begin{aligned} &\text{Amount input} + \text{Amount generated} - \text{Amount output} \\ &- \text{Amount consumed} = \text{Amount accumulated} \end{aligned} \quad (9.2.3)$$

9.2.2 Thermodynamic-Balance Equations (TBC)

Energy obeys the law of conservation (neglecting nuclear reactions), but exergy is consumed due to irreversibility during the process; hence, it is subject to a non-conservation law. Thus, in terms of energy and exergy, the general balance Eq. (9.2.1) can be expressed as follows:

$$\text{Energy input} - \text{Energy output} = \text{Energy accumulation} \quad (9.2.4)$$

and

$$\text{Exergy input} - \text{Exergy output} - \text{Exergy consumption} = \text{Exergy accumulation} \quad (9.2.5)$$

In the above-mentioned two Eqs. (9.2.4)–(9.2.5), the output terms can be divided into product and waste components as given below:

$$\text{Energy output} = \text{Product energy output} + \text{Waste energy output} \quad (9.2.6)$$

and

$$\text{Exergy output} = \text{Product exergy output} + \text{Waste exergy output} \quad (9.2.7)$$

For a solar still, the exergy-balance equation can be expressed as follows:

$$E_{x,\text{in}} - E_{x,\text{out}} = E_{x,\text{dest}}. \quad (9.2.7a)$$

In the previous equation, the input exergy ($E_{x,\text{in}}(W)$) can be obtained using the expression given by Petela [23] as follows:

$$\dot{E}_{\text{ex},\text{in}} = A_g I(t) \left[1 - \frac{4}{3} \left(\frac{T_a}{T_s} \right) + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right] \quad (7.2.11)$$

where

- T_s the Sun's temperature ($^{\circ}\text{C}$);
- T_a is the ambient temperature ($^{\circ}\text{C}$);
- A_g is the surface area of the glass cover (m^2);
- $I(t)$ is the solar intensity received by the solar still (W/m^2).

The exergy output ($E_{x,\text{out}}(W)$) can be obtained from the following expression [24]:

$$E_{x,\text{out}} = h_{\text{ef}} \left[(T_f - T_{\text{gi}}) - (T_a + 273) \ln \left(\frac{T_f + 273}{T_{\text{gi}} + 273} \right) \right] \quad (7.2.10)$$

where

- T_s is the Sun's temperature ($^{\circ}\text{C}$);
- T_f is the basin-fluid (water) temperature ($^{\circ}\text{C}$);
- T_{gi} is the temperature of the inner surface of the glass cover ($^{\circ}\text{C}$); and
- h_{ef} is the evaporative heat-transfer coefficient ($\text{W}/\text{m}^2 \text{ } ^{\circ}\text{C}$).

9.2.3 Economic-Balance Equations (EBC)

For the non-conserved quantity (cost), the general balance equation—Eq. (9.2.1)—can be expressed as follows:

$$\text{Cost input} + \text{Cost generation} - \text{Cost output} = \text{Cost accumulation} \quad (9.2.8)$$

where “input,” “output,” and “accumulation cost” signify, respectively, the cost associated with all inputs, outputs and accumulations for the system. “Cost generation” corresponds to the combination of appropriate capital and other costs of the system. These other costs include the manufacturing and maintenance of the system. In general, cost generation can be written as follows:

$$\text{Cost generation} = \text{Capital cost of equipment} + \text{All other creation and maintenance costs} \quad (9.2.9)$$

Other costs include interest and insurance costs. In a differential-cost balance, the “cost-generation rate” term defines the total cost generation balanced over the working lifespan of the system. In contrast, in an integral-cost balance, the term “amount of cost created” presents the part of the total cost generation accounted for between two instants of time under scrutiny.

9.3 Important Terms

Rosen and Dincer [17] studied two different types of thermodynamic losses. They described these losses with the help of differential forms of thermodynamic balances as discussed in the previous section Eqs. (9.2.4)–(9.2.7). For the sake of simplicity, the accumulation terms are assumed to be lossless in the energy and exergy balances Eqs. (9.2.4)–(9.2.5).

From Eqs. (9.2.4) to (9.2.6), the energy losses can be directly recognized. In the present analysis, the energy-loss rate (on the basis of energy) for a system is labeled L'_{en} for convenience. Thus, from Eq. (9.2.6), one obtains:

$$L'_{\text{en}} = \text{Waste exergy output rate} \quad (9.3.10)$$

Furthermore, the exergy losses (on the basis of exergy) can be identified from Eqs. (9.2.5) to (9.2.7). In general, there are two types of exergy losses viz. (a) waste-exergy output Eq. (9.2.7) and (b) exergy consumption Eq. (9.2.5). The term “waste-exergy output” defines the loss associated with exergy released from the system, whereas the term “exergy consumption” defines the internal-exergy loss due to the occurrence of irreversibilities during the process. These combined exergy losses gives the total exergy loss in the system.

Therefore, the exergy-based loss rate, L'_{ex} , can be expressed as follows:

$$L'_{\text{ex}} = \text{Exergy} - \text{consumption rate} + \text{Waste exergy} - \text{output rate} \quad (9.3.11)$$

Using the equations of cost balances [Eqs. (9.2.8) and (9.2.9)], the capital cost (K) is defined here as the part of cost generation credited to the equipment cost as follows:

$$K = \text{Capital cost of equipment} \quad (9.3.12)$$

Capital cost is the single economic term deliberated in the present analysis. From this approach, it has been found that there is no benefit to identify the costs related with inputs as well as cost distributions among outputs. It is predicted that the capital cost is more relevant to use (9.2.9) rather than the entire cost-generation term. This is credited to the fact that use of the cost-generation term considerably increases the complexity of the analysis by adding various other economic details (interest rates, component lifetimes, salvage values, etc.). Following are the two main clarifications for this overview:

- (i) Total cost generation's essential component is the capital costs. Therefore, the consideration of only capital costs closely estimates the results after considering the cost generation.
- (ii) Other than capital costs, the cost-generation components are proportional to capital costs. Therefore, good qualitative agreement has been found among the trends identified on considering capital cost only versus considering the entire cost generation.

It can be noted that the accumulation terms in Eqs. (9.2.1)–(9.2.5) and (9.2.8) are zero for a thermal system functioning normally in a continuous steady state (i.e., steady-flow process mode). Consequently, all losses are associated with the loss terms based on energy (L'_{en}) and exergy (L'_{ex}) as discussed previously. The energy- and exergy-loss rates can be attained through the following equations:

$$L'_{\text{en}} = \sum_{\text{input}} \text{Energy flow rates} - \sum_{\text{products}} \text{Energy flow rates} \quad (9.3.13)$$

$$L'_{\text{ex}} = \sum_{\text{input}} \text{Exergy flow rates} - \sum_{\text{products}} \text{Exergy flow rates} \quad (9.3.14)$$

The previously mentioned Eqs. (9.3.13)–(9.3.14) are obtained by rearranging Eqs. (9.2.4)–(9.2.7) and (9.3.10)–(9.3.11).

9.4 Ratio of Thermodynamic-Loss Rate to Capital Cost

A new parameter, “ R ”, is defined as the ratio of the thermodynamic-loss rate (L') to the capital cost (K) as follows:

$$R = \frac{L'}{K} \quad (9.4.15)$$

On the basis of energy-loss rate, it can be written as follows:

$$R_{\text{en}} = \frac{L'_{\text{en}}}{K} \quad (9.4.16)$$

and on the basis of exergy-loss rate, it can be written as follows:

$$R_{\text{ex}} = \frac{L'_{\text{ex}}}{K} \quad (9.4.17)$$

Rosen and Dincer [18, 19] considered the following thermodynamic loss rates viz.:

- (a) Energy (L'_{en}).
- (b) Exergy (L'_{ex}).
- (c) Internal exergy ($L'_{\text{ex},i}$) are consumptions of exergy due to irreversibility of the process inside the system.
- (d) External exergy ($L'_{\text{ex},e}$) are discarded outputs of exergy through the system boundary.

Note that $L'_{\text{ex},i} + L'_{\text{ex},e} = L'_{\text{ex}}$ for a system, as well as all energy losses, are associated with external-waste emissions. Furthermore, for the equipment in a system, capital-cost (K) values are taken into account, whereas other costs (interest and insurance costs) are ignored to simplify the economic part of the work. The value of “ R ” has been considered on the basis of energy- and exergy (total, internal, and external)-loss rate.

9.5 Exergoeconomic Analysis of Solar Stills

The exergoeconomic analysis of different thermal systems was investigated in the literature by the present author. In this section, the exergoeconomic analysis of a passive single-slope, passive double-slope, and partially covered PVT-FPC active solar still is discussed in detail as follows.

9.5.1 Exergoeconomic Analysis of a Passive Single-Slope and a Passive Double-Slope Solar Still

Singh et al. [20] analytically examined the exergoeconomic parameter for a passive single-slope and a double slope solar-distillation system on an annual basis. They executed the analysis for the climatic conditions of New Delhi (India). A passive single-slope solar still (area $1 \times 1 \text{ m}^2$ and inclination of the transparent glass cover 15°) was kept facing south to retrieve the maximum solar radiation. In contrast, a passive double-slope solar still (area $2 \times 1 \text{ m}^2$ and inclination of the glass cover 15°) was kept east–west for the same purpose. The variation of exergoeconomic parameter and productivity with a rate of interest for a 30-year lifespan of the proposed systems is presented in Fig. 9.1.

Figure 9.1 clearly shows that both the exergoeconomic parameter as well as the annual productivity decrease with an increase in interest rate. This is credited to the fact that the uniform annual cost (UAC) increases with an increase in the interest rate. Moreover, R_{gex} for a single-slope still was found to be 3.19% greater than that for the double-slope solar still ($n = 30$ year; rate of interest 2%), which is due to greater values of annual exergy gain (17.68%) and UAC (14.18%) in the case of a proposed single-slope solar still. In a similar manner, the annual productivity of a double-slope still has been found to be greater by 4.07% compared with the single-slope solar still ($n = 30$ year; rate of interest 2%), which is credited to the fact of the lower annual yield (11.78%) and the UAC (16.52%.) of a double-slope than a single-slope solar still.

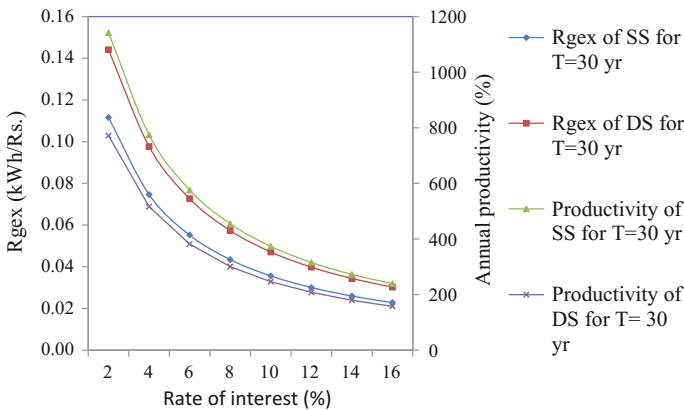


Fig. 9.1 Variation of exergoeconomic parameter (R_{gex}) and annual productivity (η_p) with rate of interest for 30 year life time for single slope and double slope passive solar still

9.5.2 Exergoeconomic Analysis of a Partially Covered PVT-FPC Active Solar Still

Tiwari et al. [21] performed an experiment on a partially covered PVT flat-plate collector solar-distillation system for a complete year for the climatic conditions of New Delhi. The system comprised two collectors (inclination 45°) each with an area of 2 m^2 , a PV module with a maximum power rating of 40 W , and a fibre-reinforced plastic-fabricated single-slope solar still with an area of $1 \times 1 \text{ m}^2$ with inclination of the glass cover at 30° .

As discussed previously, the exergoeconomic parameter can be expressed as follows:

$$R_{\text{ex}} = \frac{L_{\text{ex,ann.}}}{\text{UAC}} \quad (9.5.18)$$

where

R_{ex} the exergoeconomic parameter;
 $L_{\text{ex,ann.}}$ the annual exergy loss; and
 UAC (or K) the uniform annual cost.

According to Nag [22], the exergy-loss rate (L_{ex}) for the proposed system can be written as follows:

$$L_{\text{ex}} = \left[(h_{\text{cwg}} + h_{\text{rwg}}) \left\{ (T_{\text{w}} - T_{\text{g}}) - (T_{\text{a}} + 273) \ln \frac{(T_{\text{w}} + 273)}{(T_{\text{g}} + 273)} \right\} \right] + M_{\text{w}} C_{\text{w}} \left[(T_{\text{wf}} - T_{\text{wi}}) - (T_{\text{a}} + 273) \ln \frac{(T_{\text{wf}} + 273)}{(T_{\text{wi}} + 273)} \right] \quad (9.5.19)$$

where

h_{cwg} the convective heat-transfer coefficient between the water surface and the inner surface of the glass cover;
 h_{rwg} the radiative heat-transfer coefficient between the water surface and the inner surface of the glass cover;
 T_{g} the temperature of the glass cover;
 T_{w} the basin-water temperature;
 T_{wf} the final basin-water temperature; and
 T_{wi} the initial basin-water temperature.

The variation of monthly exergy is depicted in Fig. 9.2. The monthly exergy loss can be obtained by multiplying the daily exergy with the number of clear days in a typical month. The estimated annual exergy loss is presented in Fig. 9.3 and is found to be 4.38 kWh . The uniform end of annual cost for a given initial investment of a solar-distillation system is discussed in detail in the next chapter.

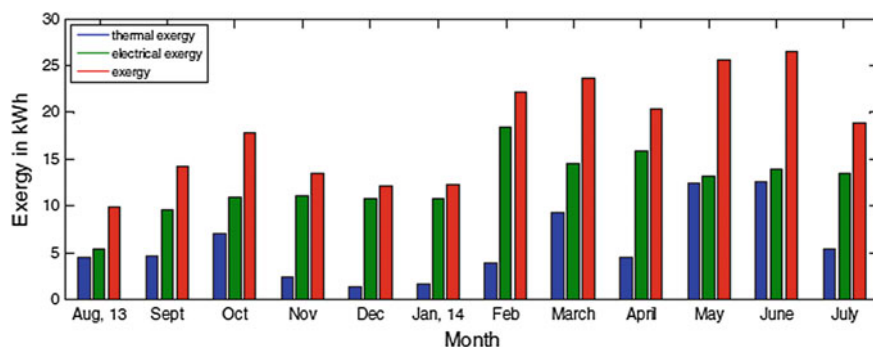


Fig. 9.2 Monthly variation of thermal exergy, electrical exergy, and overall exergy of active solar distillation system

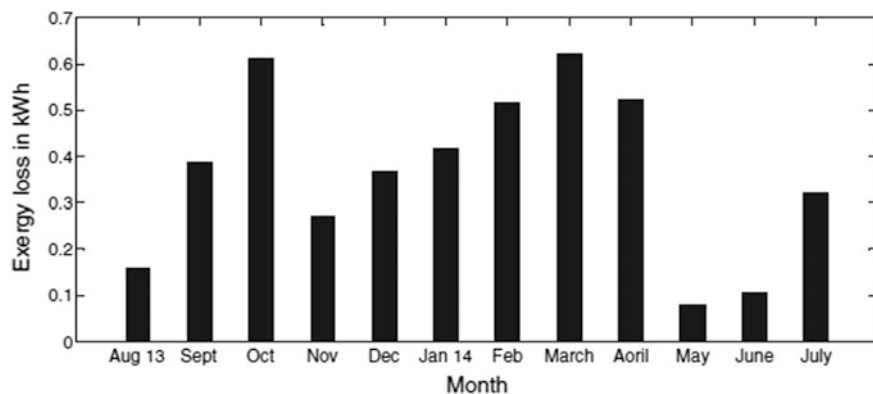


Fig. 9.3 Monthly variation of exergy loss

9.6 Exergoeconomic Analysis of a Glazed Hybrid Photovoltaic Thermal (PVT) Module Air Collector: A Case Study

Agarwal and Tiwari [25] performed an experimental and analytical study for the exergoeconomic analysis of a series-connected glazed hybrid photovoltaic thermal (PVT) module air collector for the climatic conditions of New Delhi (India) (year 2011). They found good agreements in the experimental and analytical results. In their experimental set-up, the glazed hybrid PVT module air collector comprised three PV modules (area 0.61 m^2 of each module, inclination 30°) of glass to Tedlar-type manufactured with crystalline silicon solar cells. A rectangular PVC (polyvinyl chloride) sheet air duct (area $0.54 \text{ m} \times 1.12 \text{ m}$; depth 0.02 m) was used to support the PV module. To extract the thermal energy available at the rear surface

of the PV module, a DC fan (24 W) was connected at the inlet of first PVT air collector to force the air flow (below the duct). The air flowed through one end of the collector's rectangular outlet, which had an area of 0.014 m^2 , and this outlet was connected to the inlet of the second PV module. The outlet of the second PV module was further connected to the inlet of the third PV module. The whole configuration was connected in series. Both a systematic view and the experimental set up-of the system are shown in Fig. 9.4.

The annual overall thermal energy and exergy gain was been found to be 1252.0 and 289.5 kWh, respectively, by a glazed hybrid PVT module air collector, and the annual net electrical energy savings was found to be 234.7 kWh. The device-parameter value for a PV module and a glazed hybrid PVT module air collector are listed in Table 9.1.

The values of various parameters—such as capital cost (K_c), thermodynamic-loss rate based on energy (L_{en}), thermodynamic-loss rate based on exergy (L_{ex}), and energetic (R_{en})/exergetic (R_{ex}) factor—for the glazed hybrid PVT module air collectors and PV module are listed in Table 9.1. An important parameter, R , is simply the ratio of thermodynamic loss rate (L) to the capital cost (K_c). The values of both R_{en} and R_{ex} were found to be greater for the PV module; this signifies that the glazed hybrid PVT module air collector offers a greater potential compared with the PV module in terms of energy saving.

Problems and descriptive questions

- 9.1 Discuss the following balance equations in detail:
 - (a) Energy-balance equation
 - (b) Thermodynamic-balance equation
 - (c) Economic-balance Eq.
- 9.2 Explain four main thermodynamic-loss rates of a system.
- 9.3 Discuss the behavior of the exergoeconomic parameter of a partially covered PVT flat-plate collector solar-distillation system.

Objective Questions

- 9.1 Which of the following is the correct expression of the general-balance equation?
 - (a) $\text{Input} + \text{Generation} - \text{Output} - \text{Consumption} = \text{Accumulation}$
 - (b) $\text{Input} - \text{Generation} - \text{Output} - \text{Consumption} = \text{Accumulation}$
 - (c) $\text{Input} + \text{Generation} + \text{Output} - \text{Consumption} = \text{Accumulation}$
 - (d) $\text{Input} + \text{Generation} - \text{Output} + \text{Consumption} = \text{Accumulation}$
- 9.2 Which of the following is the correct expression of the differential form of the general-balance equation?
 - (a) $\text{Input rate} + \text{Generation rate} - \text{Output rate} - \text{Consumption rate} = \text{Accumulation rate}$

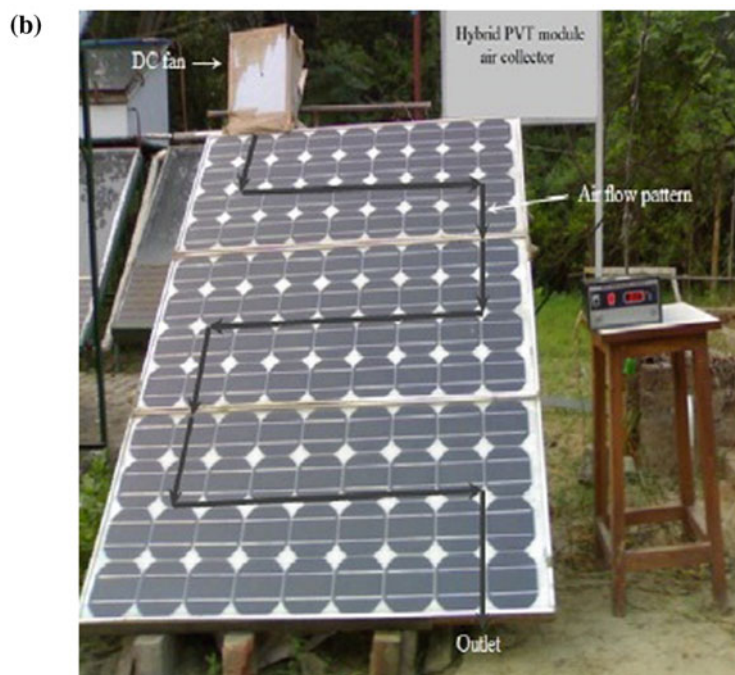
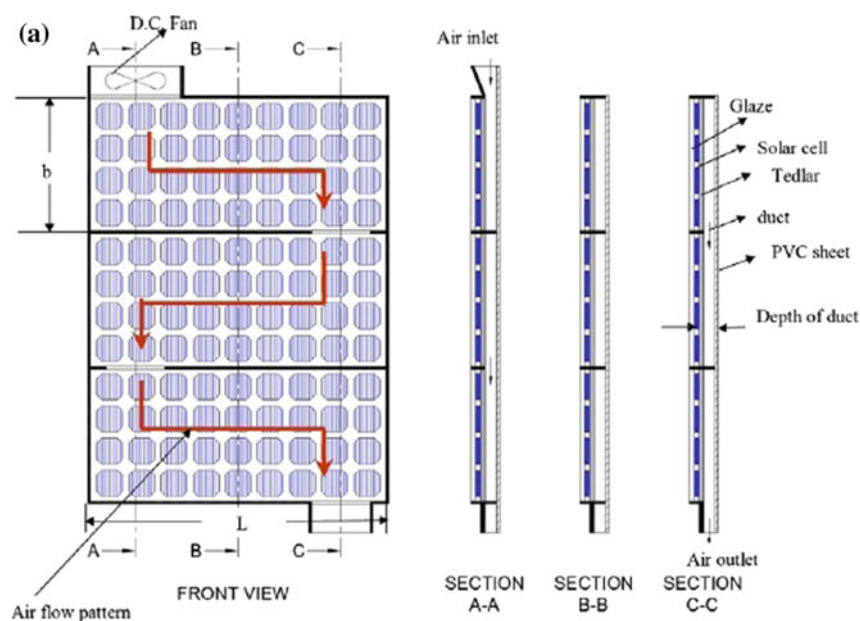


Fig. 9.4 a Schematic diagram and b experimental set up of the system [25]

Table 9.1 The values of device parameters for PV module and glazed hybrid PVT module air collectors

Device	K_c (Rs.)	L_{en} (kWh)	L_{ex} (kWh)	R_{en} (kWh/Rs.)	R_{ex} (kWh/Rs.)
Glazed hybrid PVT module air collector	13,800	621	670.42	0.045	0.049
PV module	12,500	768	691.30	0.061	0.055

- (b) Input rate + Generation rate + Output rate – Consumption
rate = Accumulation rate

(c) Input rate + Generation rate – Output rate + Consumption
rate = Accumulation rate

(d) Input rate – Generation rate – Output rate + Consumption
rate = Accumulation rate
- 9.3 Differential balances of the general-balance equation are applicable on which of the following processes?
- (a) Group processes

(b) Continuous processes

(c) Discontinuous processes

(d) All processes
- 9.4 Integral balances of the general-balance equation are applicable on which of the following processes?
- (a) Discontinuous processes

(b) Continuous processes

(c) Group processes

(d) All processes
- 9.5 What is the value of the accumulation-rate term in the differential balance of the general-balance equation for steady-state process?
- (a) >1

(b) <1

(c) 0

(d) 1
- 9.6 Which of the following is the correct expression of the general-balance equation in terms of exergy?
- (a) Exergy input + Exergy output – Exergy consumption = Exergy
accumulation

(b) Exergy input – Exergy output + Exergy consumption = Exergy
accumulation

- (c) Exergy input + Exergy output + Exergy consumption = Exergy accumulation
 (d) Exergy input – Exergy output – Exergy consumption = Exergy accumulation
- 9.7 Which of the following is the correct expression of the cost-generation term in the economic-balance equation?
- (a) Cost generation = Capital cost of equipment + All other costs
 (b) Cost generation = Capital cost of equipment – All other costs
 (c) Cost generation = Capital cost of equipment
 (d) None of the above
- 9.8 Which of the following is the correct expression of the exergy loss-rate term?
- (a) $L'_{\text{ex}} = \text{Exergy consumption rate} - \text{Waste exergy} - \text{output rate}$
 (b) $L'_{\text{ex}} = \text{Exergy consumption rate} + \text{Waste exergy} - \text{output rate}$
 (c) $L'_{\text{ex}} = \text{Exergy consumption rate}$
 (d) $L'_{\text{ex}} = \text{Waste exergy} - \text{output rate}$
- 9.9 The exergy losses in a system originate due to which of the following reasons?
- (a) Reversibility in the system
 (b) Irreversibility in the system
 (c) None of these
- 9.10 Which of the following represents the correct expression of the exergeconomic parameter?
- (a) $R_{\text{ex}} = \frac{K}{L'_{\text{ex}}}$
 (b) $R_{\text{ex}} = -\frac{L'_{\text{ex}}}{K}$
 (c) $R_{\text{ex}} = K L'_{\text{ex}}$
 (d) $R_{\text{ex}} = \frac{L'_{\text{ex}}}{K}$

Answers

- 9.1 (a) 9.2 (a) 9.3 (b) 9.4 (c) 9.5 (c) 9.6 (d) 9.7 (a) 9.8 (a) 9.9 (b) 9.10 (d)

References

1. R.B. Evans, G.L. Crellin, M. Tribus, in *Thermoeconomic Considerations of Sea Water Demineralization*, ed. by K.S. Spiegler. Principles of Desalination, second ed., Academic, New York (Chapter 1) (1980), pp. 1–54
2. Y.M. El-Sayed, M. Tribus, in *Strategic Use of Thermoeconomics for System Improvement*, ed. by R.A. Gaggioli. Efficiency and Costing: Second Law Analysis of Processes, ACS Symposium Series 235, American Chemical Society, Washington, DC (1983), pp. 215–238
3. Y.M. El-Sayed, R.B. Evans, *Hermoeconomics and the design of heat systems*. Trans. ASME J. Eng. Power **92**, 27–34 (1970)

4. R.A. Gaggioli, W.J. Wepfer, Exergy economics. *Energy Int. J* **5**, 823–838 (1980)
5. G.M. Reistad, R.A. Gaggioli, Available energy costing, in *Thermodynamics: Second Law Analysis*, ACS Symposium Series 122, ed. by R.A. Gaggioli (American Chemical Society, Washington, DC, 1980), pp. 143–159
6. G. Tsatsaronis, M. Winhold, Exergoeconomic analysis and evaluation of energy conversion plants. Parts 1& 2, *Energy The. Int. J* **10**, 69–94 (1985)
7. A. Poredos, A. Kitanovski, Exergy loss as a basis for the price of thermal energy. *Energy Convers. Manag* **43**, 2163–2173 (2002)
8. M.A. Rosen, The relation between thermodynamic losses and capital costs for a modern coal-fired electrical generation station. *Comput. Aided Eng. Syst. Anal. AES Am. Soc. Mech. Eng. N. Y* **21**, 69–78 (1990)
9. G. Tsatsaronis, in *A Review of Exergoeconomic Methodologies*, eds. by M.J. Moran, E. Sciubba. *Second Law Analysis of Thermal Systems*, American Society of Mechanical Engineers, New York (1987), pp. 81–87
10. M.J. Moran, in *Availability Analysis: A Guide to Efficient Energy Use*, revised ed. (American Society of Mechanical Engineers, New York, 1989)
11. T.J. Kotas, in *The Exergy Method of Thermal Plant Analysis*, reprint ed. (Krieger, Malabar, FL, 1995)
12. R.H. Edgerton, *Available Energy and Environmental Economics* (D.C. Heath, Toronto, 1982)
13. J. Szargut, D.R. Morris, F.R. Steward, *Exergy Analysis of Thermal, Chemical and Metallurgical Processes*, Hemisphere (New York, 1988)
14. A. Bejan, *Entropy Generation through Heat and Fluid Flow*. Wiley, Toronto, M.A. Rosen, I. Dincer. *Appl. Therm. Eng* **23**, 643–658 (2003)
15. V. El-Sayed, R.A. Gaggioli, A critical review of second law costing methods. Parts I and II *Trans. ASME J. Energ. Resour. Technol.* **111**, 1–15 (1989)
16. A. Valero, *On the energy costs of present day society—Thermodynamics and the Design, Analysis and Improvement of Energy Systems*, ed. by R.J. Krane. AES- American Society of Mechanical Engineers, New York, vol. 35, pp. 1–7 (1995)
17. M.A. Rosen, I. Dincer, Exergoeconomic analysis of power plants operating on various fuels. *Appl. Therm. Eng* **23**, 643–658 (2003)
18. M.A. Rosen, in *An investigation of the relation between capital costs and selected thermodynamic losses*, in: *Second Law Analysis—Industrial and Environmental Applications*. AES-Vol. 25/HTD-Vol. 191, American Society of Mechanical Engineers, New York, pp. 55–62 (1991)
19. M.A. Rosen, I. Dincer, Thermoeconomic analysis of power plants: an application to a coal-fired electrical generating station. *Energy. Convers. Manag* **44**, 1633–1651 (2003)
20. D.B. Singh, G.N. Tiwari, I.M. Al-Helal, V.K. Dwivedi, J.K. Yadav, Effect of energy matrices on life cycle cost analysis of passive solar stills. *Sol. Energy* **134**, 9–22 (2016)
21. G.N. Tiwari, J.K. Yadav, D.B. Singh, I.M. Al-Helal, A.M. Abdel-Ghany, Exergoeconomic and enviroeconomic analyses of partially covered photovoltaic flat plate collector active solar distillation system. *Desalination* **367**, 186–196 (2015)
22. P.K. Nag, in *Basic and Applied Thermodynamics*. Tata McGraw-Hill, ISBN 0-07- 047338-2 (2004)
23. R. Petela, Exergy of undiluted thermal radiation. *Sol. Energy* **74**, 469 (2003)
24. P.K. Nag, in *Basic and Applied Thermodynamics*. Tata McGraw-Hill, ISBN 0-07-047338-2 (2004)
25. S. Agrawal, G.N. Tiwari, Exergoeconomic analysis of glazed hybrid photovoltaic thermal module air collector. *Sol. Energy* **86**, 2826–2838 (2012)

Chapter 10

Economic Analysis of Solar-Distillation Systems

10.1 Introduction

Development of renewable technology reforms the change in the global climate, but the issue of economic and financial viability of new and smart renewable-energy systems (RES) is the main concern. In the area of techno-economic analysis (project-cost control, profitability analysis, planning, scheduling and optimization of operational research, etc.), as well as engineering judgment and experience, are broadly used in the application of scientific principles and techniques. From the user's point of view, it is essential to make renewable-energy systems economically viable for their proper use. Awareness of cost analysis can be used for the effective economic analysis of renewable-energy systems with different methods and cash-flow diagrams.

Some important factors are listed below for the techno-economic analysis of renewable-energy systems:

- (a) initial investment, present cost, and initial cost for the fabrication of renewable-energy systems (RES);
- (b) annual operational and maintenance cost of RES;
- (c) annual energy output (thermal energy or electrical energy);
- (d) repairing cost, if any, of RES; and
- (e) interest rate, life span, and salvage of the RES.

Apart from these important points, the following factors can also be considered for the economic analysis:

- (i) influence of embodied energy of RES on the environment due to CO₂ emission;
- (ii) annual energy used for the process of RES and pre-treatments; etc.; and
- (iii) CO₂ or carbon credit (CC) earned with the use of RES, etc.

Table 10.1 Capital cost of solar stills, United Nations (1970) ($1 \text{ ft}^2 = 0.029 \text{ m}^2$)

	Las Marian Still (9350 ft ²) (1966)	Daytona Beach still (2650 ft ²) (USA, 1961)			Patmos still (86,000 ft ²) (Greece, 1961)	Projected still (1 million ft ²) (USA)		
	Actual cost (\$/ft ²)							
		Material	Labor	Total		Material	Labor	Total
Aluminum frames					0.28			
Basin lining	0.502	0.32	0.19	0.51	0.26	0.15	0.10	0.25
Concrete beams	0.211	0.25	0.15	0.40		0.19	0.10	0.29
Contractor's fee				0.38				0.12
Distillate troughs		0.03	0.02	0.05		0.03	0.02	0.05
Electrical	0.178				0.19			
Glass cover		0.37	0.14	0.51	0.23	0.25	0.10	0.35
Land preparation	0.026	0.04	0.32	0.36		0.01	0.09	0.10
Masonry	0.063	0.07	0.04	0.11	0.09	0.16	0.04	0.10
Miscellaneous equipment	0.246				0.05			
Piping channels	0.188	0.03	0.01	0.04	0.06	0.03	0.01	0.04
Special works	0.146				0.19			
Subtotal		1.11	0.87	1.21	1.51	0.72	0.46	
Total	1.56			2.30				1.30

In this chapter, the basic knowledge of cost analysis, cash-flow diagram, pay-back time, and benefit–cost (B/C) analysis, etc., are discussed in detail for the effective economic analysis of renewable-energy systems.

Furthermore, the cost break-down different solar-distillation systems in different countries is listed in Table 10.1. The data clearly indicate that the cost of distilled water per liter is a function of labor cost, which exclusively depends on the region.

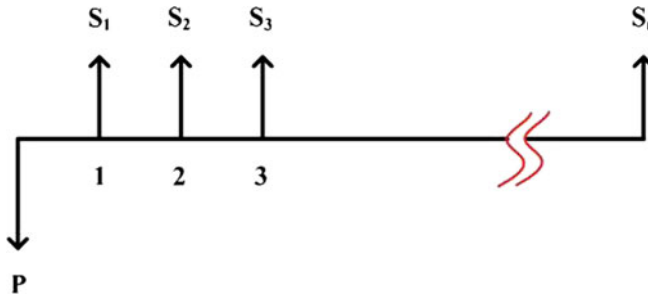
10.2 Important Terminology

For the financial estimation of renewable-energy technologies, it is essential to compare the combinations of different energy resources with each other for a given end use. Consequently, it is important that monetary values at different points in time be reduced to an equivalent basis for such comparisons.

10.2.1 Capital-Recovery Factor (CRF)

In financial-evaluation practices, cash flows cannot be compared directly with each other because cash flows have different values encountered at different points in time.

Let P be the present amount invested in the beginning ($n = 0$) at the interest rate of i per year, and S_n be its future value at the end of n years. Then the cash flow can be expressed as follows:



The time value of investment (P) at the end of 1 year ($n = 1$) can be written as follows:

$$S_1 = P + iP = (1 + i)P$$

Similarly, at the end of the second year ($n = 2$), it can be written as follows:

$$\begin{aligned} S_2 &= S_1 + iS_1 = P + iP + i(P + iP) \\ &= P(1 + i)^2 \end{aligned}$$

Similarly, at the end of third and n th year, it can be expressed as follows:

$$S_n = P(1 + i)^n$$

For simplicity, the previous equation can be re-expressed as follows:

$$S = P(1 + i)^n \quad (10.2.1)$$

where $S > P$ for $i > 0$ (law of compound interest).

Equation (10.2.1) can be simplified as follows:

$$S = PF_{PS}$$

It defines that the

$$\text{future value} = (\text{present value}) \times (\text{future-value factor}) \quad (10.2.2)$$

where F_{PS} can be designated as $F_{PS,i,n}$ and expressed as follows:

$$F_{PS,i,n} = (1 + i)^n \quad (10.2.3)$$

$F_{PS,i,n}$ is known as the “**compound-interest factor**” or the “**future-value factor**.” It estimates the future amount by determining the present value. Hence, the future value is obtained on multiplying the compound interest factor by the present value. The values of $F_{PS,i,n}$ for different values of n (from 1 to 20) at different interest rates ($i = 0.04, 0.06, 0.08$, and 0.10%) are listed in the second column of Table 10.2.

If 1 year is divided into p number of equal periods, then n becomes np and rate of interest, i become i/p (rate of return per unit period).

Using these values, Eq. (10.2.1) can be expressed as follows:

$$S = P \left(1 + \frac{i}{p} \right)^{np}$$

or

$$S = P \left[\left(1 + \frac{i}{p} \right)^p \right]^n \quad (10.2.4)$$

In the previous equation, the term $\left(1 + \frac{i}{p} \right)^p$ can be expressed as follows:

$$\left(1 + \frac{i}{p} \right)^p = 1 + \text{effective rate of return (ERR)}$$

or

$$\text{Effective rate of return (ERR)} = \left(1 + \frac{i}{p} \right)^p - 1 \quad (10.2.5)$$

For $p = 1$,

The effective rate of return becomes equal to i and remains greater than i if $p > 1$. In case of the simple interest rate, the future value S after n years can be expressed as follows:

Table 10.2 The values of conversion factors [1]

n	F_{PS}	F_{SP}	F_{RP}	F_{PR}	F_{RS}	F_{SR}	F_{PK}
$i = 0.04$							
1	1.04	0.962	0.962	1.04	1	1	26
2	1.082	0.925	1.886	0.53	2.04	0.49	13.255
3	1.125	0.889	2.775	0.36	3.122	0.32	9.009
4	1.17	0.855	3.63	0.275	4.246	0.235	6.887
5	1.217	0.822	4.452	0.225	5.416	0.185	5.616
6	1.265	0.79	5.242	0.191	6.633	0.151	4.769
7	1.316	0.76	6.002	0.167	7.898	0.127	4.165
8	1.369	0.731	6.733	0.149	9.214	0.109	3.713
9	1.423	0.703	7.435	0.134	10.583	0.094	3.362
10	1.48	0.676	8.111	0.123	12.006	0.083	3.082
11	1.539	0.65	8.76	0.114	13.486	0.074	2.854
12	1.601	0.625	9.385	0.107	15.026	0.067	2.664
13	1.665	0.601	9.986	0.1	16.627	0.06	2.504
14	1.732	0.577	10.563	0.095	18.292	0.055	2.367
15	1.801	0.555	11.118	0.09	20.024	0.05	2.249
16	1.873	0.534	11.652	0.086	21.825	0.046	2.146
17	1.948	0.513	12.166	0.082	23.697	0.042	2.055
18	2.026	0.494	12.659	0.079	25.645	0.039	1.975
19	2.107	0.475	13.134	0.076	27.671	0.036	1.903
20	2.191	0.456	13.59	0.074	29.778	0.034	1.84
$i = 0.06$							
1	1.06	0.943	0.943	1.06	1	1	17.667
2	1.124	0.89	1.833	0.545	2.06	0.485	9.091
3	1.191	0.84	2.673	0.374	3.184	0.314	6.235
4	1.262	0.792	3.465	0.289	4.375	0.229	4.81
5	1.338	0.747	4.212	0.237	5.637	0.177	3.957
6	1.419	0.705	4.917	0.203	6.975	0.143	3.389
7	1.504	0.665	5.582	0.179	8.394	0.119	2.986
8	1.594	0.627	6.21	0.161	9.897	0.101	2.684
9	1.689	0.592	6.802	0.147	11.491	0.087	2.45
10	1.791	0.558	7.36	0.136	13.181	0.076	2.264
11	1.898	0.527	7.887	0.127	14.972	0.067	2.113
12	2.012	0.497	8.384	0.119	16.87	0.059	1.988
13	2.133	0.469	8.853	0.113	18.882	0.053	1.883
14	2.261	0.442	9.295	0.108	21.015	0.048	1.793
15	2.397	0.417	9.712	0.103	23.276	0.043	1.716
16	2.54	0.394	10.106	0.099	25.672	0.039	1.649
17	2.693	0.371	10.477	0.095	28.213	0.035	1.591
18	2.854	0.35	10.828	0.092	30.906	0.032	1.539

(continued)

Table 10.2 (continued)

n	F_{PS}	F_{SP}	F_{RP}	F_{PR}	F_{RS}	F_{SR}	F_{PK}
19	3.026	0.331	11.158	0.09	33.76	0.03	1.494
20	3.207	0.312	11.47	0.087	36.786	0.027	1.453
$i = 0.08$							
1	1.08	0.926	0.926	1.08	1	1	13.5
2	1.166	0.857	1.783	0.561	2.08	0.481	7.01
3	1.26	0.794	2.577	0.388	3.246	0.308	4.85
4	1.36	0.735	3.312	0.302	4.506	0.222	3.774
5	1.469	0.681	3.993	0.25	5.867	0.17	3.131
6	1.587	0.63	4.623	0.216	7.336	0.136	2.704
7	1.714	0.583	5.206	0.192	8.923	0.112	2.401
8	1.851	0.54	5.747	0.174	10.637	0.094	2.175
9	1.999	0.5	6.247	0.16	12.488	0.08	2.001
10	2.159	0.463	6.71	0.149	14.487	0.069	1.863
11	2.332	0.429	7.139	0.14	16.646	0.06	1.751
12	2.518	0.397	7.536	0.133	18.977	0.053	1.659
13	2.72	0.368	7.904	0.127	21.495	0.047	1.582
14	2.937	0.34	8.244	0.121	24.215	0.041	1.516
15	3.172	0.315	8.559	0.117	27.152	0.037	1.46
16	3.426	0.292	8.851	0.113	30.324	0.033	1.412
17	3.7	0.27	9.122	0.11	33.75	0.03	1.37
18	3.996	0.25	9.372	0.107	37.45	0.027	1.334
19	4.316	0.232	9.604	0.104	41.446	0.024	1.302
20	4.661	0.215	9.818	0.102	45.762	0.022	1.273
$i = 0.10$							
1	1.1	0.009	0.909	1.1	1	1	11
2	1.21	0.826	1.736	0.576	2.1	0.476	5.762
3	1.331	0.751	2.487	0.402	3.31	0.302	4.021
4	1.464	0.683	3.17	0.315	4.641	0.215	3.155
5	1.611	0.621	3.791	0.264	6.105	0.164	2.638
6	1.772	0.564	4.355	0.23	7.716	0.13	2.296
7	1.949	0.513	4.868	0.205	9.487	0.105	2.054
8	2.144	0.467	5.335	0.187	11.436	0.087	1.874
9	2.358	0.424	5.759	0.174	13.579	0.074	1.736
10	2.594	0.386	6.145	0.163	15.937	0.063	1.627
11	2.853	0.35	6.495	0.154	18.531	0.054	1.54
12	3.138	0.319	6.814	0.147	21.384	0.047	1.468
13	3.452	0.29	7.103	0.141	24.523	0.041	1.408
14	3.797	0.263	7.367	0.136	27.975	0.036	1.357
15	4.177	0.239	7.606	0.131	31.772	0.031	1.315
16	4.595	0.218	7.824	0.128	35.95	0.028	1.278

(continued)

Table 10.2 (continued)

n	F_{PS}	F_{SP}	F_{RP}	F_{PR}	F_{RS}	F_{SR}	F_{PK}
17	5.054	0.198	8.022	0.125	40.545	0.025	1.247
18	5.56	0.18	8.201	0.122	45.599	0.022	1.219
19	6.116	0.164	8.365	0.12	51.159	0.02	1.195
20	6.728	0.149	8.514	0.117	57.275	0.017	1.175

$$S = P(1 + ni) = P + (iP)n \quad (10.2.6)$$

Equation (10.2.1) can be re-expressed as follows:

$$P = S(1 + i)^{-n} \quad (10.2.7)$$

On evaluating the future amount from Eq. (10.2.7) against the calendar as present value (i.e., at zeroth time), the greater value of the future amount (at n th year) will actually decrease assuming i to be positive. The previous equation can be expressed as follows:

$$P = SF_{SP}$$

It implies that

$$\text{Present value} = (\text{future value}) \times (\text{present-value factor}) \quad (10.2.8)$$

$F_{SP,i,n}$ is termed the “**compound-interest factor**” or the “**present-value factor**.” It is used to convert the future amount into the present amount such that the present value can be obtained from the product of the compound-value factor/present-value factor and the future value. The third column of Table 10.2 lists $F_{SP,i,n}$ for different values of n (from 1 to 20) at different interest rates ($i = 0.04, 0.06, 0.08$, and 0.10%).

Both the future value ($F_{PS,i,n}$) and the present value ($F_{SP,i,n}$) are the compound-interest factor, but for different purposes. They can be related as follows:

$$F_{PS,i,n} = \frac{1}{F_{SP,i,n}}$$

or

$$F_{PS,i,n} \times F_{SP,i,n} = 1 \quad (10.2.9)$$

Equations (10.2.1) and (10.2.8) can be used for evaluating the future value (S) of the initial investment (P) and vice versa, respectively. These can be expressed as follows:

$$S = P(1 + i)^n, \quad \text{when moving with the calendar.} \quad (10.2.10a)$$

$$P = S(1 + i)^{-n}, \quad \text{when moving against the calendar.} \quad (10.2.10b)$$

In generalized form,

$$A_{t2} = A_{t1}(1 + i)^n \quad (10.2.11)$$

In words, it can be expressed as

Amount at time t_2 = Amount at time t_1 (compound-interest operator)

Equation (10.2.11) concludes that n is positive value if estimated using Eq. (10.2.10a) and is negative if estimated against the calendar using Eq. (10.2.10b). Equation (10.2.11) is denoted as the equation of the time value–conversion relationship. The previous method is also referred to as the “life-cycle cost analysis.”

Example 10.1 What will be the rate of return if Rs. 20,000 compounds to Rs. 28,240 in 4 years?

Solution

The present value is $P = 20,000$, $n = 4$. Therefore, from Eq. (10.2.1), one can obtain the following:

$$28,240 = 20,000 (1 + i)^4$$

On simplifying, one can obtain the following:

$$i = 0.09$$

or

9% per year.

Example 10.2 For compounded annually at 10% per year, what would be the time period for the money to double in value?

Solution

Let us consider that the money doubles in n years, then $S = 2P$.

Using Eq. (10.2.1), one can obtain the following:

$$2P = P(1 + i)^n \quad \text{Or} \quad 2P = P(1 + 0.10)^n$$

On simplifying, one can obtain the following:

$n = 7.3$ years, i.e., the monetary value will double in 7.3 years.

Example 10.3 Evaluate the effective rate of return (ERR) for a 10% interest rate and $p = 5$, and 12.

Solution

From Eq. (10.2.5), one can obtain the following:

$$\text{Effective rate of return (ERR)} = \left(1 + \frac{i}{p}\right)^p - 1$$

For $p = 5$,

$$\text{ERR} = \left(1 + \frac{0.10}{5}\right)^5 - 1 = 0.104$$

For $p = 12$,

$$\text{ERR} = \left(1 + \frac{0.10}{12}\right)^{12} - 1 = 0.104$$

Example 10.4 What rate of interest (i) will a student pay if he or she borrows Rs. 2000 and returns Rs. 2100 at the end of 6 months?

Solution

Given that $S = 2100$, $P = 2000$ and $n = 6/12$.

Therefore, using Eq. (10.2.6)

$$S = P(1 + ni) \quad \text{Or} \quad 2100 = 2000 \left[1 + \left(\frac{6}{12}\right)i\right]$$

On simplifying, one can obtain the following:

$$i = 0.10 \quad \text{Or} \quad 10\%.$$

Example 10.5 A person borrows Rs. 10,000 at an interest rate of 10% for 4 years and 4 months. Evaluate the money paid by considering compound interest.

Solution

Using Eq. (10.2.6), the future amount after 4 months can be obtained as follows:

$$S = 10,000 \left[1 + \left(\frac{4}{12}\right)(0.10)\right] = \text{Rs. } 10,333$$

Now this obtained value become P for another 4 years. From the compound-interest equation, one can obtain the following:

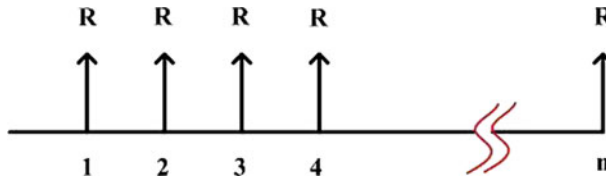
$$S = PF_{PS} = P(1+i)^n$$

$$S = (10,333)(1+0.10)^4 = \text{Rs. } 15,129$$

10.2.2 Uniform Annual Cost (UNACOST)

A graphical approach is mostly used in solving economic problems. In the diagram, expenses (debits) and receipts (credits) are denoted using vertical lines whereas the vertical line represents time. Conventionally, the debits and credits are marked in opposite directions, as is obvious, such that credits are indicated upside, whereas debits are indicated downside. The uniform annual amount is discussed on the basis of this concept.

It is implicit that the unknown value of amount is a time-dependent unit (year). Conveniently, it is understood that the amount is equally distributed for n number of years at the end of each year; consequently, it is known as a the “uniform end-of-year annual cost” for every year until the period of n years. It is denoted by R and known as the UNACOST for a period of n years. Graphically, it is presented as follows:



Let P represent the single present value at the beginning ($n = 0$). Using Eq. (10.2.8), one can obtain the following:

$$P = R \left[\frac{1}{1+i} + \frac{1}{(1+i)^2} + \frac{1}{(1+i)^3} + \cdots + \frac{1}{(1+i)^n} \right] \quad (10.2.12)$$

or

$$P = R \sum_{1}^n \frac{1}{(1+i)^n} \quad (10.2.13)$$

The previous equation represents a geometric series, and the summation terms can also be expressed as follows:

$$\sum_{1}^n \frac{1}{(1+i)^n} = \left(\frac{1}{1+i} \right) \left\{ \frac{1 - \left(\frac{1}{1+i} \right)^n}{1 - \frac{1}{1+i}} \right\} = \frac{(1+i)^n - 1}{i(1+i)^n}$$

On substituting this summation term in Eq. (10.2.13), one can obtain the following:

$$P = R \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right] = RF_{RP,i,n}$$

The previous equation represents the following:

$$\text{Present value} = (\text{UNACOST}) \times (\text{UNACOST present-value factor}) \quad (10.2.14)$$

where

$$F_{RP,i,n} = \frac{(1+i)^n - 1}{i(1+i)^n} \quad (10.2.15)$$

$F_{RP,i,n}$ is denoted as the “equal-payment series present-value factor” or the “annuity present-value factor.” The fourth column of Table 10.2 lists $F_{RP,i,n}$ for different values of n (from 1 to 20) at different interest rates ($i = 0.04, 0.06, 0.08$, and 0.10%).

Equation (10.2.14) can be re-expressed as follows:

$$R = P \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] \quad (10.2.16)$$

or

$$R = PF_{PR,i,n}$$

The previous equation represents the following:

$$\text{UNACOST} = (\text{present value}) \times (\text{capital-recovery factor}) \quad (10.2.17)$$

where

$$F_{PR,i,n} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (10.2.18)$$

This is also known as the “capital-recovery factor” (CRF). From Eqs. (10.2.15) and (10.2.18), respectively, the relation between the equal-payment series present-value factor and the capital-recovery factor can be attained as follows:

$$F_{RP,i,n} = \frac{1}{F_{PR,i,n}} \quad (10.2.19)$$

Example 10.6 Approximately USD\$4000 every year is saved in terms of fuel savings from a large-capacity water-heating system. For a discount rate of 12%, what is the present worth of fuel savings in the 5th, 10th, 15th, 20th, 25th, and 30th years (neglecting the effect of an increase in the price of fuel saved)?

Solution

Given, $i = 0.12$ and the amount of fuel saving = USD\$4000 per year.

For the desired years, the values of the present worth factors and the corresponding present worth of annual fuel savings are evaluated and listed in table below.

Year (n)	Present-worth factor (PWF) $\frac{1}{(1+i)^n}$	Present worth of fuel savings (4000 $\times$ PWF)
5	$1/(1.2)^5 = 0.5670$	2269.7
10	$1/(1.2)^{10} = 0.3220$	1287.8
15	$1/(1.2)^{15} = 0.1827$	730.7
20	$1/(1.2)^{20} = 0.1037$	414.6
25	$1/(1.2)^{25} = 0.0588$	235.2
30	$1/(1.2)^{30} = 0.0334$	133.5

From the previously tabulated values of the present worth of fuel savings, one can observe that it is rather small for the useful life of the domestic solar water-heating system in later years. Therefore, for a renewable-energy system with a longer useful life, the present-value analysis may not express its actual effectiveness to the user.

10.2.3 Sinking-Fund Factor (SFF)

As discussed previously, at the end of (n) years, the future value (S) can be distributed into an equal uniform end-of-year annual amount (R). Moreover, it denotes the uniform end-of-year annual amount but corresponding to the future value (S).

On substituting Eq. (10.2.7) in Eq. (10.2.16), one can obtain the following:

$$R = S(1+i)^{-n} \left[\frac{i(1+i)^n}{(1+i)^n - 1} \right] = S \left[\frac{i}{(1+i)^n - 1} \right]$$

or

$$R = SF_{SR,i,n}$$

The previous equation represents the following:

$$\text{UNACOST} = (\text{future amount}) \times (\text{sinking-fund factor}) \quad (10.2.20)$$

where

$$F_{SR,i,n} = \left[\frac{i}{(1+i)^n - 1} \right] = \text{SFF} \quad (10.2.21)$$

Generally, this equation is used to estimate the uniform end-of-year annual amount corresponding to the salvage value of any system in the future. Equation (10.2.20) can be re-expressed as follows:

$$S = R \left[\frac{(1+i)^n - 1}{i} \right] = RF_{RS,i,n}$$

The previous equation represents the following:

$$\text{Future amount} = (\text{UNACOST}) \times (\text{equal-payment series future-value factor}) \quad (10.2.22)$$

where

$$\text{Equal-payment series future-value factor, } F_{RS,i,n} = \left[\frac{(1+i)^n - 1}{i} \right] \quad (10.2.23)$$

Similarly, from Eqs. (10.2.21) and (10.2.23), the relation between the equal-payment series present-value factor and the shrinking-fund factor can be attained as follows:

$$F_{SR,i,n} = \frac{1}{F_{RS,i,n}} \quad (10.2.24)$$

A uniform beginning-of-year annual amount (R_b) can be expressed in terms of P and S as R and R_b , respectively, with the following relationship:

$$R = R_b(1+i) \quad (10.2.25)$$

Table 10.2 lists the estimated values of various conversion factors for a given number of years (n) and rate of interest (i).

Example 10.7 Derive the relation between R_b , P and S .

Solution

On putting the value of R from Eq. (10.2.12) into Eq. (10.2.22), one can obtain the following:

$$R_b(1+i) = P(F_{PR,i,n})$$

or

$$R_b = \frac{P(F_{PR,i,n})}{(1+i)}$$

Similarly, from Eq. (10.2.20),

$$R_b = \frac{S(F_{SR,i,n})}{(1+i)}$$

Example 10.8 For a discount rate of 10%, determine the present worth of a large-capacity PV/T solar water heater for an estimated salvage value of 5000 at the end of its useful lifetime of 20 years.

Solution

From Eq. (10.2.12),

$$P = S \left[\frac{1}{(1+i)^n} \right]$$

Given, $S = \text{USD\$}5000$, $n = 20$ years, and $i = 10\%$.

Hence, the present worth is given by the following:

$$P = 5000 \left[\frac{1}{(1+0.1)^{20}} \right] = \text{USD\$}743.22$$

10.3 Benefit–Cost Analysis

The benefit–cost ratio method is another method that can be used to make a judgment on investments. The term (benefits–cost [$B-C$] ratio) clearly suggests that it is based on the ratio of benefits to costs associated with a particular system or project. As a measure of financial or economic efficiency, this method is ideally simple and quite versatile and measures the cost efficiency. Initially, it is necessary to recognize the costs (construction, installation, operation, and maintenance, etc.) and benefits separately. In general, the benefits represent advantages expressed in monetary terms, whereas the disadvantages are related disadvantages. Government agencies frequently use this method for projects for which the costs are incurred by the government and the benefits accrued by the common public. The consequences of project implementation play a vital role in deciding whether an item is to be considered as a benefit, a disadvantage, or a cost. It is obvious that a project is

considered positive when its associated cost does not exceed the benefits derived from its execution. The conventional benefit-to-cost ratio can be evaluated as follows:

$$\frac{B}{C} = \frac{\text{Benifits} - \text{Disbenifits}}{\text{Cost}} = \frac{B - D}{C}$$

On including the operation and maintenance (O&M) costs into the disbenefits, the modified B/C ratio, which is gaining support, can be expressed as follows:

$$\frac{B}{C} = \frac{\text{Benifits} - \text{Disbenifits} - \text{O\&M cost}}{\text{Initial investment}}$$

The salvage value of the system can be considered in the cost term (denominator). The decision of project approval is based on the B/C ratio as follows:

If

$$B/C > 1 \quad \text{Approval}$$

$$B/C < 1 \quad \text{Refusal}$$

Hence, the B/C ratio gives a method to compare mutually exclusive projects against each other.

Benefits (B)	When the project under consideration involve advantages to the owner.
Dis-benefits (D)	When it involves disadvantages to the owner.
Costs	The anticipated expenditures for construction, operation, and maintenance, etc.
Owner	Incur all costs as the government.

Let B and C be the present values of the cash inflows (benefits) and outflows (costs) defined as follows:

$$B = \sum_{j=0}^n \frac{B_j}{(1+i)^j} \quad (10.3.26)$$

$$C = \sum_{j=0}^n \frac{C_j}{(1+i)^j} \quad (10.3.27)$$

where B_j and C_j , respectively, denote the benefits and costs at the end of j th period, and n is the useful life span of the project.

Moreover, the sum of Eqs. (10.3.26) and (10.3.27) gives the following:

$$B + C = \sum_{j=0}^n \frac{B_j}{(1+i)^j} + \sum_{j=0}^n \frac{C_j}{(1+i)^j} \quad (10.3.28)$$

Equation (10.3.27) expresses the equivalent present-value cost (C), which can be divided into two components viz. (a) initial capital expenditure and (b) annual costs accumulated in each successive period.

On considering the initial investment in first m periods and annual-costs accumulation in each year of this initial period until the end of the system's useful life (n periods), then these two components of C can be written as follows

$$C_0 = \sum_{j=0}^m \frac{C_j}{(1+i)^j} \quad (10.3.29)$$

$$C'' = \sum_{j=m+1}^n \frac{C_j}{(1+i)^j} \quad (10.3.30)$$

With

$$C = C_0 + C'' \quad (10.3.31)$$

Using the previously mentioned Eqs. ((10.3.29) through (10.3.31)), three different types of B/C ratios can be defined as follows:

(i) **Aggregate $B-C$ ratio**

This is the ratio of the present value of total benefits to total cost:

$$\left(\frac{B}{C}\right)_{\text{aggregate}} = \frac{B}{C} = \frac{B}{C_0 + C''}; \quad C > 0 \text{ (Or } C_0 + C'' > 0) \quad (10.3.32)$$

Or

$$\left(\frac{B}{C}\right)_{\text{aggregate}} = \frac{\sum_{j=0}^n \frac{B_j}{(1+i)^j}}{\sum_{j=0}^n \frac{C_j}{(1+i)^j} + \sum_{j=m+1}^n \frac{C_j}{(1+i)^j}}$$

$\left(\frac{B}{C}\right)_{\text{aggregate}} > 1$ for acceptance of the project.

(ii) **Net $B-C$ ratio**

In the net $B-C$ ratio, the initial capital investment is considered as a cash expenditure, and the corresponding benefits become the net benefits. Basically, these net benefits are the annual revenues minus annual outlays.

The net benefits–cost ratio is expressed as follows:

$$\left(\frac{B}{C}\right)_{\text{net}} = \frac{B - C'}{C_0}, \quad C_0 > 0 \quad (10.3.33)$$

$\left(\frac{B}{C}\right)_{\text{net}} > 1$ for a feasible or valid project.

The index obtained from the net B – C ratio specifies the benefits expected per unit of capital investment; consequently, it can be used as a cost-effectiveness or profitability index. In general, it is simply a comparison of the present value of net revenues with the present value of capital investment.

Advantage of B – C ratio

To evaluate different alternatives or replacements, this ratio offers the following advantage compared with other measures:

- (i) It compares alternatives on a common scale and authorizes the estimation of different-sized alternatives.
- (ii) It evaluates alternative projects in order to define the most profitable alternative, which helps the investor with limited budget.
- (iii) It determines the significance of the project.
- (iv) It can be used to determine the optimal size of a project.

Shortcomings of the B – C ratio

- (i) The B – C ratio depends on the item classified as a cost or a disbenefit, i.e., whether it comes in the denominator or numerator of the ratio. Often, it may be an arbitrary decision but can lead to inefficient leveling of investment alternatives.
- (ii) The efficient scale of a given project cannot be predicted using the simple B – C ratio method. For this purpose, an incremental analysis is undertaken.

The two methods do not produce the same results; consequently, the net present values of both alternatives are determined to determine the correct method.

Example 10.9 The manager of a hostel building under construction follows the latest building regulations and plans to incorporate solar-energy harvesting water-heating systems for all new students in the hostel. To supplement a natural gas-fired water-heating system, the manager considers two hybrid solar water-heating systems viz. double-glazed flat-plate collectors (alternative X) and evacuated tubular collectors (alternative Y). The life span of each of the systems is 20 years, and the corresponding associated costs and benefits are tabulated as follows:

	Amount (USD\$)	
	Alternative X	Alternative Y
Capital cost	3,200,000	2,700,000
Annual maintenance cost	50,000	80,000
Annual benefits due to fuel savings	600,000	560,000

Assuming the negligible salvage value of both the systems, which option should be preferred on the basis of incremental net benefit–cost ratio for an interest rate of 10%? On selecting the alternatives with their greater values of benefit–cost ratio, then what would be the option?

Solution

The incremental capital cost of alternative X over alternative Y is USD\$500,000 (USD\$3,200,000 – USD\$2,700,000). Similarly the incremental net annual benefits of alternative X compared with the those of alternative Y are

$$(600,000 - 50,000) - (560,000 - 80,000) = 550,000 - 480,000 = \text{USD\$}70,000.$$

For the incremental benefits of a useful life span over 20 years of alternative X compared with alternative Y , the cumulative present worth is as follows:

$$\begin{aligned}
 &= \sum_{j=1}^n \frac{70,000}{(1+i)^j} \\
 &= 70,000 \times (8.51) \\
 &= \text{USD\$}595,949.4
 \end{aligned}$$

Hence, the net incremental benefits to cost ratio = $595,949.4/500,000 \approx 1.19$.

A ratio of net incremental benefits-to-incremental capital cost greater than unity implies that the additional discounted benefits more than justify the extra capital cost of alternative X compared with alternative Y . Therefore, it is preferred to install alternative X in the hostel.

The evaluation for each alternative independent of each other for the net benefit-to-cost ratio is given as follows:

The net benefits-to-cost ratio for alternative X is as follows:

$$\begin{aligned}
 &= \frac{(60,000 - 50,000) \left[\frac{(1+0.1)^{20}-1}{0.1(1+0.1)^{20}} \right]}{3,200,000} \\
 &= \frac{50,000 \times 8.51}{3,200,000} = 1.463
 \end{aligned}$$

Similarly, for alternative Y

$$\begin{aligned}
 &= \frac{(56,000 - 80,000) \left[\frac{(1 + 0.1)^{20} - 1}{0.1(1 + 0.1)^{20}} \right]}{2,700,000} \\
 &= \frac{480,000 \times 8.51}{2,700,000} = 1.513
 \end{aligned}$$

It may be noted that an appraisal of the two alternatives using their net benefits-to-cost ratios would suggest that the alternative Y is selected. Because the results obtained with the two methods do not match, the net present value of both alternatives is determined to identify the correct method.

The NPV of alternative X is as follows:

$$\begin{aligned}
 (\text{NPV})_X &= -3,200,000 + (600,000 - 50,000) \left[\frac{(1 + 0.1)^{20} - 1}{0.1(1 + 0.1)^{20}} \right] \\
 &= 1,482,460 \$
 \end{aligned}$$

The NPV of alternative Y is as follows:

$$\begin{aligned}
 (\text{NPV})_Y &= -2,700,000 + (560,000 - 80,000) \left[\frac{(1 + 0.1)^{20} - 1}{0.1(1 + 0.1)^{20}} \right] \\
 &= 1,386,510 \$
 \end{aligned}$$

Hence, $(\text{NPV})_X > (\text{NPV})_Y$.

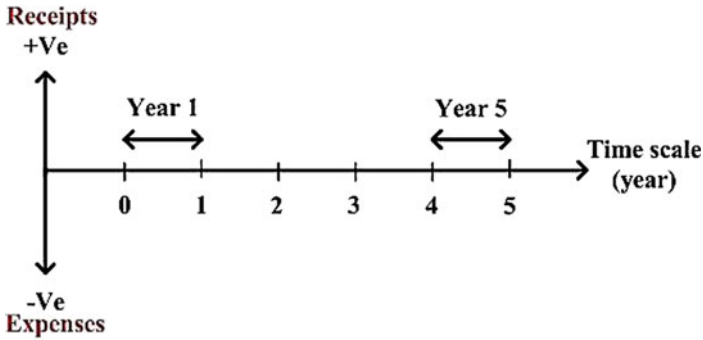
Thus, the evaluation on the basis of incremental costs and benefits is correct.

10.4 Cash-Flow Diagram

In any business, cash flow is the movement of money (both in and out), and it measures the growth of any healthy business. In other words, cash flow is the single greatest concern of any economic analysis [2, 3]. Cash flow can be understood on a timescale diagram known as a “cash-flow diagram.” The net cash flow is calculated as follows:

$$\text{Net cash flow} = \text{receipts (credits)} - \text{expenses (debits)} \quad (10.4.34)$$

Equation (10.4.34) can be represented by a cash-flow diagram as follows:

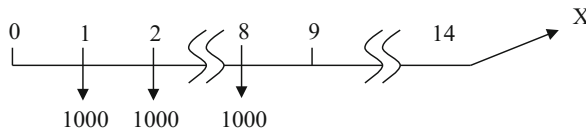


A uniform end-of-year annual amount (R) can be considered at the end of each year in the previously mentioned cash-flow diagram. It can be used in the following examples.

Example 10.10 A person deposits USD\$1000 at the end of each year for 8 years to create a forborne annuity. He desires to withdraw the money at the end of 14 years from now to purchase a hybrid solar water-heating system. If the money is worth 10% per year, then find the accumulated value at the end of 14th year.

Solution

Let the amount available be X at the 14th year (as a receipt). The cash-flow diagram for the payment is given below as follows:



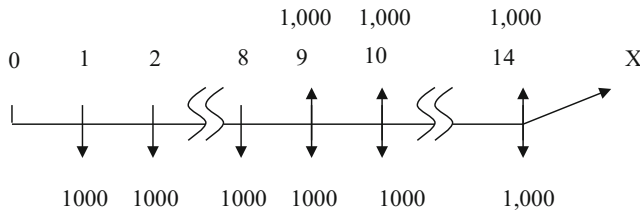
The present value (zero time) can be estimated using Eq. (10.2.12) as follows:

$$P = 1000 \times F_{RP,10\%,8} = 1000 \times 5.3349 = \text{USD\$}5334.90$$

On depositing the amount for 14 years, the future value at the end of 14 years can be obtained as follows:

$$S = 5334.90 \times F_{PS,10\%,14} = 5334.90 \times 3.79 = \text{USD\$}20,259$$

Moreover, the previously mentioned cash-flow diagram can be drawn by considering USD\$1000 paid for 14 years less USD\$1000 paid as annuity for the last 6 years.



Using Eq. (10.2.22), one can obtain the following:

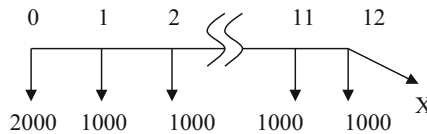
$$S = 1000 \left[\frac{(1.10)^{14} - 1}{0.10} - \frac{(1.10)^{16} - 1}{0.10} \right] = 1000 \times (27.9 - 7.71)$$

$$S = \text{USD\$}20,259$$

Example 10.11 A down payment of USD\$2000 is requested by a person for hybrid solar water-heating systems totaling an amount of USD\$10,000. For this, an amount of USD\$1174 annual end-of-year payment (R) is mandatory for 12 years. Conversely, the person chooses to pay USD\$1000 yearly, and the remaining payment in the last. What will be the balance payment (remaining payment) if the money is worth 10% interest.

Solution

Let the remaining payment at the end be X . The cash-flow diagram for this problem is given as follows:



From the cash-flow diagram and Eqs. (10.2.8) and (10.2.12), one can write the following:

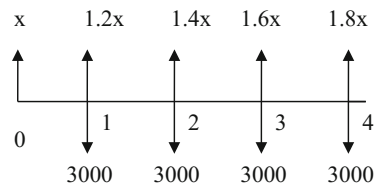
$$\begin{aligned} 10,000 &= 2000 + 1000(F_{RP,10\%,12}) + X(F_{SP,10\%,12}) \\ &= 2000 + 1000(6.8137) + X(0.31863) \end{aligned}$$

$X = 3723.10$; The remaining payment is USD\$3723.10.

Example 10.12 A person wants to purchase an energy-efficient piece of equipment and is ready to spend the amount of USD\$3000 on the first through fourth years and also decides to set aside a certain amount in the beginning as well as in each year thereafter until the fourth year. If the contribution arrangements have an arithmetical progression by 20% for all years increasing after the first year, evaluate the initial contribution by a person for 10% of the money.

Solution

Let us consider that the first contribution is x . The cash-flow diagram is given as follows:



Using the previous cash-flow diagram, one can obtain the following using the time value–conversion relation (consider 2 years from now as the focal point):

$$\begin{aligned} x(1.10)^2 + 1.2x(1.10)^{-1} + 1.4x(1.10)^0 + 1.6x(1.10)^1 + 1.8x(1.10)^2 \\ = 3000(1.10)^{-1} + 3000(1.10)^0 + 3000(1.10)^1 + 3000(1.10)^2 \end{aligned}$$

or

$$\begin{aligned} 7.2553x &= 3000 \times 4.2191 \\ x &= 1744.56 \end{aligned}$$

The first contribution will be USD\$1744.56.

10.5 Cost Comparison with Equal Duration

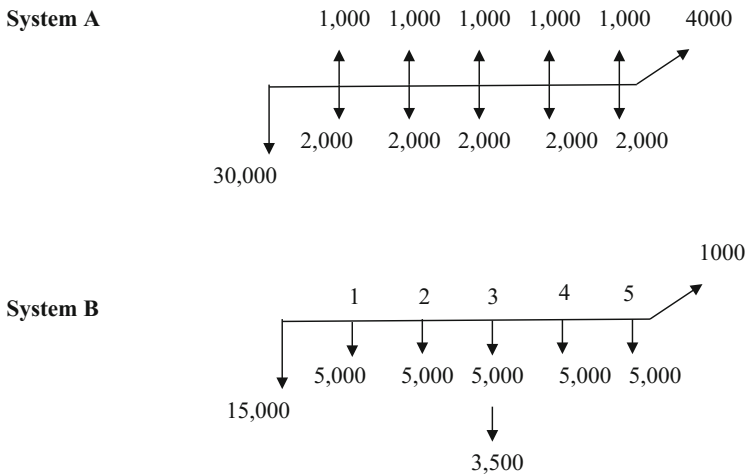
In this section, a uniform expense is referred to as the “uniform end-of-year cost.”

Example 10.13 The cost comparison of two hybrid PVT systems (system A and system B) is given below in a table. Determine the more economical system if the money is worth 10% per year.

Economic components	System (A)	System (B)
First cost (USD\$)	30,000	15,000
Uniform end-of-year maintenance per year (USD\$)	2000	5000
Overhaul at the end of the third year (USD\$)	–	3500
Salvage value (USD\$)	4000	1000
Life of the system (years)	5	5
Benefit from quality control as a uniform end-of-year cost per year (USD\$)	1000	–

Solution

A cash-flow diagram of both systems is given as follows:



From Eqs. (10.2.8) and (10.2.12), the present value of the costs for **system A** can be expressed as follows:

$$\begin{aligned}
 P_{AS} &= 30,000 + (2000 - 1000)(F_{RP,10\%,5}) - 4000(F_{SP,10\%,5}) \\
 &= 30,000 + 1000(3.7908) - 4000(0.62092) = \text{USD\$31,307.12}
 \end{aligned}$$

Similarly, for **system B**,

$$\begin{aligned}
 P_{BS} &= 15,000 + 5000(F_{RP,10\%,5}) + 3500(F_{SP,10\%,3}) - 1000(F_{SP,10\%,5}) \\
 &= 15,000 + 5000(3.7908) + 3500(0.75131) - 1000(0.62092) = \text{USD\$35,962.63}
 \end{aligned}$$

The previous evaluation clearly shows that **system A** is more economical compared with **system B**.

10.6 Cost Comparison with Unequal Duration

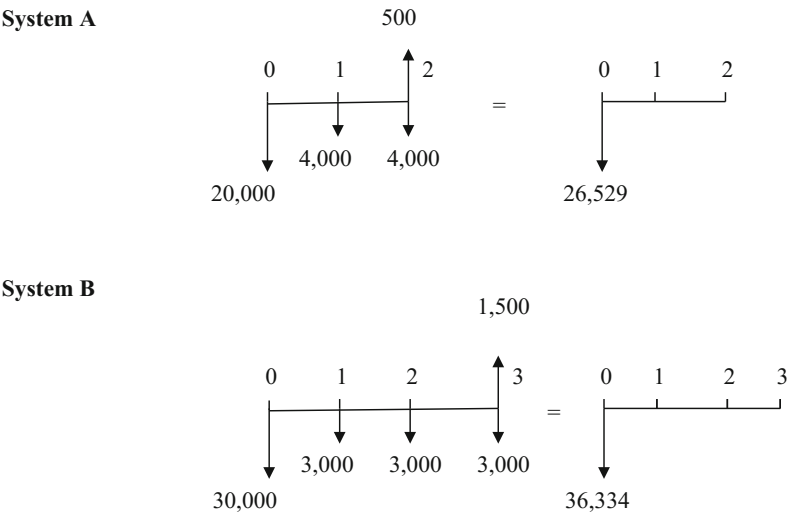
Only on the basis of equal duration can a fair comparison between two energy-efficient systems (with different life spans) be performed. One of the methods is to conduct a comparison of the single present value of costs on the basis of a common denominator of their service lives.

10.6.1 Single Present-Value Method (First Method)

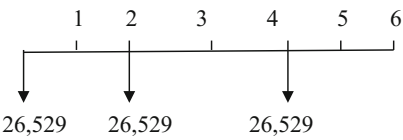
Example 10.14 The cost comparison of two energy-efficient systems is given below in a table. Determine the more economical system if the money worth is 10% per year.

Cost components (USD\$)	System A	System B
First cost	20,000	30,000
Uniform end-of-year maintenance	4000	3000
Salvage value	500	1500
Service life (years)	2	3

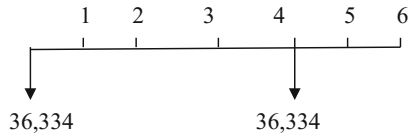
Solution
First, the cash-flow diagrams for both systems are reduced to a single present value of the cost as follows:



Now, to obtain the 6-year duration, the simplified diagrams are repeated. Note that the present value of **system A** at its time of installation is 26,529.



Similarly, at the time of installation, the present value of **system B** is USD \$36,334. The cash-flow diagram for 6-year duration is expressed as follows:



The present value of each of the preceding diagrams at 10% per year is obtained as follows:

$$\begin{aligned}
 P_{A6} &= 26,529 + 26,529(F_{SP,10\%,2}) + 26,529(F_{SP,10\%,4}) \\
 &= 26,559 + 26,559(1.10)^{-2} + 26,529(1.10)^{-4} \\
 &= \text{USD\$}66,573.4
 \end{aligned}$$

Similarly, $P_{B6} = \text{USD\$}63,332.2$

The ratio of cost is as follows:

$$\frac{P_{A6}}{P_{B6}} = \frac{66,573.4}{63,632.2} = 1.0462$$

Hence, **system B** is more economical compared with **system A**.

10.6.2 Annual-Cost Method (Second Method)

In this method, the uniform end-of-year annual amount can be estimated using Eq. (10.2.18) for $P_{A2} = \text{USD\$}26,529$ and, $P_{B3} = \text{USD\$}36,334$ of Example 10.8.

$$\begin{aligned}
 R_A &= P_{A2}(F_{PR,10\%,2}) = 26,529(0.57619) = \text{USD\$}15,285.74 \\
 R_B &= 36,334(F_{PR,10\%,3}) = 26,334(0.40211) = \text{USD\$}14,610.26
 \end{aligned}$$

The ratio of cost for the two systems becomes as follows:

$$\frac{R_A}{R_B} = \frac{15,285.74}{14,610.26} = 1.0462$$

This result implies that **System B** is still more economical as determined previously.

10.6.3 Capitalized-Cost Method (Third Method)

Capitalized cost is the present value on the basis of infinite time. For a system costing P_n and lasting n years, the present value replacing out to infinity is as follows:

$$K = P_n \sum_{x=0}^{\infty} \frac{1}{(1+i)^{xn}} = P_n \left[1 + \frac{1}{(1+i)^n} + \frac{1}{(1+i)^{2n}} + \frac{1}{(1+i)^{3n}} + \dots \right] \quad (10.6.35)$$

The sum of the previous geometric series can be expressed as follows:

$$\sum_{x=0}^{\infty} \frac{1}{(1+i)^{xn}} = 1 \left[\frac{1 - \left(\frac{1}{(1+i)^n} \right)^{\infty}}{1 - \frac{1}{(1+i)^n}} \right] = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (10.6.36)$$

Equation (10.6.35) can be re-expressed as follows:

$$K = P_n F_{PK,i,n}$$

Or

$$\text{Capitalized cost} = (\text{present-value basis } n \text{ year duration}) \times (\text{capitalized-cost factor}) \quad (10.6.36a)$$

The capitalized-cost factor is

$$F_{PK,i,n} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (10.6.37)$$

On comparing the previous equation with the value of $F_{PR,i,n}$ (Eq. (10.2.18)), one can obtain the following relationship:

$$F_{PR,i,n} = iF_{PK,i,n}.$$

or

$$\text{Capital-recovery factor} = (\text{rate of return}) \times (\text{capitalized-cost factor}) \quad (10.6.38)$$

Factors R and K can be related as follows:

$$R = iK$$

or

$$\text{UNACOST} = (\text{rate of return}) \times (\text{capitalized-cost factor}) \quad (10.6.39)$$

For this, Example 10.10 is solved below using the previous capitalized-cost method.

From Example 10.10, $P_{A2} = \text{USD\$}26,529$ and $P_{B3} = \text{USD\$}36,334$; using Eq. (10.6.36a), one can obtain the following:

$$\begin{aligned} K_A &= P_{A2}F_{PK,10\%,2} = 26,529(5.7619) = \text{USD\$}152,857.45 \\ K_B &= P_{B3}F_{PK,10\%,3} = 36,334(4.0211) = \text{USD\$}146,102.65 \end{aligned}$$

The ratio of the cost can be expressed as follows:

$$\frac{K_A}{K_B} = \frac{152,857.45}{146,102.65} = 1.0462$$

The previous results are similar to the solutions obtained earlier and clearly imply that **system B** is more economical compared with **system A**.

As a matter of fact, the present value P_{n1} of n_1 years' duration can be converted to an equivalent present value P_{n2} of n_2 years' duration as follows:

$$\begin{aligned} P_{n1}F_{PR,i,n_1} &= P_{n2}F_{PR,i,n_2} \\ P_{n2} &= P_{n1} \frac{F_{PR,i,n_1}}{F_{PR,i,n_2}} \end{aligned} \quad (10.6.40)$$

Hence, as reported previously, applying Eq. (10.6.36a) gives the following:

$$\begin{aligned} P_{A2} &= 2\text{-year duration} = \text{USD\$}26,529 \\ P_{B3} &= 3\text{-year duration} = \text{USD\$}36,334 \end{aligned}$$

Using Eq. (10.6.40), the present value of the **system B** can be converted to an equivalent value for a 2-year duration as follows:

$$\begin{aligned} P_{B2} &= P_{B3} \frac{F_{PR,10\%,3}}{F_{PR,10\%,2}} = (36,334) \left(\frac{0.40211}{0.57619} \right) = \text{USD\$}25,356.68 \\ \frac{P_{A2}}{P_{B2}} &= \frac{26,529}{25,356} = 1.0462 \end{aligned}$$

The previous results are similar to those obtained by various methods discussed earlier, and **system B** is still found to be more economical.

10.7 Net Present Value

The net present value (NPV) of the investment is the difference between the present value of the benefits and the costs resulting from a certain investment. A positive NPV value implies that the financial position of the investor will be improved by

undertaking the project, whereas a negative NPV value would indicate a financial loss. Zero or null NPV would mean that the present value of all benefits over the useful lifetime is equal to the present value of all of the costs [3]. Mathematically,

$$\text{NPV} = \sum_{j=0}^n \frac{B_j - C_j}{(1+i)^j} \quad (10.7.41)$$

where B_j is the benefits; C_j is the costs at the end of the period j ; n is the useful life of the project; and i is the rate of interest. Equation (10.7.41) involves subtracting of the cost from the benefits at any period and then multiplying the result by single-payment present-worth factor for that period. Eventually, the NPV is determined by algebraically adding the results for all of the periods under consideration.

It often happens that $(B_j - C_j)$ is constant for all j except for $j = 0$. In such a case, Eq. (10.7.41) can be modified as follows:

$$\text{NPV} = B_0 - C_0 + \sum_{j=1}^n \frac{B_j - C_j}{(1+i)^j}$$

Because B_0 , the benefits in the 0th year, are invariably zero, and $B_j - C_j$ is constant ($=B - C$) for $j = 1$ to n ,

$$\text{NPV} = -C_0 + (B - C) \sum_{j=1}^n \frac{1}{(1+i)^j}$$

or

$$\text{NPV} = -C_0 + (B - C) \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right] \quad (10.7.42)$$

where C_0 represents the initial capital investment in the project.

Example 10.15 The purchase and installation of a PV system for water pumping on a farmer's field costs USD\$10,000. The annual saving of diesel by the farmer is estimated to be approximately USD\$1200, and the annual maintenance cost is expected to be USD\$100. If the useful life of the system is 30 years, then what will be the NPV of the investment on the PV system for an 8% interest rate?

Solution

The net annual benefits of using a PV system = $1200 - 100 = \text{USD\$1100}$

Because the amount of net annual benefits is constant over the useful life of the system as defined in a problem, NPV can be obtained from Eq. (10.7.42) as follows:

$$\text{NPV} = -10,000 + (1100) \left[\frac{(1 + 0.08)^{30} - 1}{0.08(1 + 0.08)^{30}} \right] = 2384$$

Thus, the investment in the PV system is a financially viable for the farmer. Equations (10.7.41) and (10.7.42) are based on the assumption that the interest rate i remains constant over time. Furthermore, the NPV could be estimated with different rates of interest rate over j th period. Thus, from Eq. (10.7.41), it can be modified for NPV as follows:

$$\begin{aligned} \text{NPV} = & (B_0 - C_0) + \frac{B_1 - C_1}{(1 + i_1)} + \frac{B_2 - C_2}{(1 + i_1)(1 + i_2)} \\ & + \cdots + \frac{B_j - C_j}{(1 + i_1)(1 + i_2) \cdots (1 + i_j)} + \cdots + \frac{B_n - C_n}{(1 + i_1)(1 + i_2) \cdots (1 + i_n)} \end{aligned} \quad (10.7.43)$$

Eventually, on the basis of the NPV method, the acceptance criteria of an investment project is

NPV > 0: Agree to consider the project

NPV = 0: Remain indifferent

NPV < 0: Do not agree to consider the project

A positive NPV value represents a positive surplus as discussed previously; consequently, the project may be considered or accepted subject to the availability of funds. In contrast, a project should not be considered or rejected for negative NPV, and the funds can be profitably invested in the other projects. The project with greatest positive NPV should be preferred in the case of mutually exclusive alternative investments.

Limitations of the NPV Method

Following are the limitations of the NPV method:

- (a) The NPV method highlights only benefits. It does not differentiate between investments involving relatively large costs and benefits, as well as between much smaller costs and benefits, as long as the two projects results in equal NPV. Therefore, it does not give any suggestion or indications regarding the efforts required to achieve the results.
- (b) The results obtained by the NPV method are quite sensitive to the elected interest/discount rate. Therefore, it is very important to select an appropriate value of the rate of interest, otherwise the failure of this selected value incorporated in the evaluation of NPV may alter or even reverse the relative ranking of different alternatives being compared using this method. For example, with a very low value of rate of interest, an alternative with benefits spread far into the

future may unreasonably appear more beneficial compared with an alternative whose benefits are more quickly realized, but it is of a lower amount in undiscounted terms.

From Eq. (10.7.41), it may be noted that every cash flow in the future is discounted to the present by a factor of the general form $1/(1+i)^j$ with an increase in interest rate (i). As the rate of interest approach infinity, $1/(1+i)^j$ approaches zero. Mathematically, Eq. (10.7.41) for two extreme values of the interest rate gives the following:

$$\text{NPV} = \sum_{j=0}^n B_j - C_j \quad \text{for } i = 0$$

and

$$\text{NPV} = -C_0 \quad \text{for } i = \infty$$

Example 10.16 In addition to other routine maintenance costs of USD\$300 each year, replacement of the wooden duct in the 10th year is predicted to be approximately USD4000 during the useful life span of 20 years of a BIPVT air-circulating collector with a total cost of USD\$35,000. Find the equivalent annual cost of the BIPVT air-circulating collector given a 10% interest rate.

Solution

The present values of all of the costs associated with the BIPV air-circulating collector are evaluated as follows:

$$\begin{aligned} &= 35,000 + 300 \left[\frac{1}{(1+0.1)} + \frac{1}{(1+0.1)^2} + \cdots + \frac{1}{(1+0.1)^{10}} \right] + \frac{4000}{(1+0.1)^{10}} \\ &= 35,000 + 300 \left[\frac{(1+0.1)^{20} - 1}{0.1(1+0.1)^{20}} \right] + \frac{4000}{(1+0.1)^{10}} \\ &= \text{USD\$}39,095.4. \end{aligned}$$

Hence, the equivalent annual cost of the system is as follows:

$$\begin{aligned} &= (39,095.4) \left[\frac{0.1(1+0.1)^{20}}{(1+0.1)^{20} - 1} \right] \\ &= \text{USD\$}4574.1 \end{aligned}$$

10.8 Evaluating the Economic Feasibility of a Solar-Distillation System

Cost analysis of the system includes the initial investment required to purchase the system; administrative costs, and any operation and maintenance costs. Generally, there is no operation cost for utilities associated with solar-energy systems because the customers do not have to pay for the energy required to run the systems. Solar-distillation systems, being solar-energy systems, offer benefits such as supply of free potable water and reductions in consumption of conventional energy resources. Apart from this, other benefits may be found in the form of government incentives (tax benefits for capital investment and renewable systems and a subsidy for renewable-energy promotion) offered to promote the use of renewable energies.

The economic feasibility of a solar-distillation system can be estimated mainly on the basis of two points viz. (i) cost per liter of the produced potable water and (ii) payback period of the investment made for procuring the distillation system.

10.8.1 Cost Per Liter of Distilled Water

From the UNACOST concept, the net uniform end-of-year annual cost of the solar-distillation system for a given initial capital investment can be expressed as follows:

$$UA_{\text{net}} = P_s F_{PR,i,n} - P_s F_{PR,i,n} M_s - S_s F_{SR,i,n} \quad (10.8.44)$$

where UA_{net} is the net uniform end-of-year annual cost of the solar-distillation system with the values of known parameters, e.g., initial capital investment (P_s), interest rate (i), maintenance cost (M_s), life of system (n), salvage value (S_s) after the completion of the system life; $F_{PR,i,n}$ and $F_{SR,i,n}$ represent the capital-recovery factor and the sinking-fund factor, respectively (discussed previously).

The first and second terms at the right-hand side of Eq. (10.8.44) define the UNACOST corresponding to the initial capital investment (P_s) on a solar-distillation system and maintenance cost over this fraction, respectively. The third term describes the UNACOST of the salvage value of the system after completing a certain life of the system and hence is deducted.

The cost of unit mass of distilled water, or cost per liter (CPL), can be estimated on dividing the UA_{net} of the solar-distillation system by the annual yield of the distilled water (M_Y) obtained from the distillation system. Mathematically, it can be expressed as follows:

$$CPL = \frac{UA_{\text{net}}}{M_Y} \quad (10.8.45)$$

The annual yield (M_Y) can also be evaluated as follows:

$$M_Y = \sum_{m=1}^{12} M_D N_{d,m} \quad (10.8.46)$$

where M_D is the daily yield per unit area in liters; and $N_{d,m}$ is number of clear days in m th month.

10.8.2 Capital Cost of a Solar-Distillation System (P_s)

The initial capital investment to purchase a solar-distillation system varies according to the design, size, type, and material used for its construction, etc. Consequently, a simple single-slope basin-type passive solar-distillation system is considered for understanding the conceptual calculation of an initial capital investment. A similar approach can be implemented to evaluate the initial capital investment for any type and size of solar-distillation system. The initial capital cost of a distillation unit made of glass-reinforced plastic (GRP) can be expressed as follows:

$$\begin{aligned} P_s &= P_{\text{GRP}} + P_G + P_{\text{cl}} + P_{\text{st}} + P_{\text{Mi}} \\ &= \text{Cost of glass reinforced plastic} + \text{total cost of glass cover} \\ &\quad + \text{cost of clamping unit (frame and clamps)} + \text{cost of stand} \\ &\quad + \text{cost of other necessary miscellaneous items (glass ket etc.)} \end{aligned} \quad (10.8.47)$$

In the previous equation, the cost of different components constituting the distillation unit are in rupees per m^2 of basin area.

10.8.3 Interest Rate (i , %)

The possible interest rate at which to borrow funds for the capital investment could be as follows:

- (a) **4%**: Subsidized rate normally offered by government sectors to support the use of renewable energy.
- (b) **7–7.5%**: Rate normally offered by the government banks.
- (c) **10–12%**: Rate offered by private-banking sectors.
- (d) **12–16%**: Rate offered by any other private source.

Thus, any suitable interest rate from 4 to 16% can be deliberated for economic analysis.

10.8.4 Life of a Solar-Distillation System (n)

The “life” is the duration (years) for which the solar-distillation system successfully discharges its duty to produce potable water. This depends purely on the climatic circumstances to which it is subjected and the material used for its construction. The FRP-made distillation units reported a durability of >25 years. The GRP-made distillation units are expected to offer 1.5–2 times better durability than the FRP units. Therefore, for any evaluation, the life span of a solar-distillation system can take any value from the range 20–50 years depending on the situation under consideration.

10.8.5 Maintenance Cost (M_s , %)

The maintenance of a solar-distillation system under operation requires the following activities to be concerned:

- (i) Regular filling of brackish water into the distillation unit.
- (ii) Removal and collection of potable water from the measuring jar or collection container.
- (iii) Regular cleaning of glass cover to retrieve the maximum solar radiation.
- (iv) Periodical cleaning of the basin surface to remove the salt deposited whenever this is believed necessary.

A lower basin-water depth requires frequent refilling and thus causes greater maintenance cost. The frequency of basin-cleaning or scale-removal depends on the salt concentration of the feed water. Therefore, greater frequency results in a greater maintenance cost of the distillation unit. Therefore, the maintenance cost is expected to be in the range of 8–16% of the UNACOST corresponding to the initial capital investment. Thus, the maintenance cost can be estimated by considering its percentage value in this range depending on the conditions prevailing during the operation of the solar-distillation system.

10.8.6 Salvage Value (S_s)

The salvage value of a solar-distillation system is a future amount that can be gained by selling the solar-distillation system as scrap after completion of its successful life. Therefore, it is easy to understand that the salvage value solely depends on the material involved for making the solar-distillation system as well as on its condition at its end of life. Components made of iron give a better salvage value after the completion-of-life of the distillation unit if it has been cared for well by anti-corrosive painting; however, the concrete, FRP, and GRP do not contribute

Table 10.3 Capital cost of typical solar still (15° cover inclination and 0.04 m basin water depth) if produced on large scale for commercial purpose

Detail of components	Quantity	Amount (Rs.)	Scrap after 30 years (Rs.)	Scrap after 40 years (Rs.)	Scrap after 50 years (Rs.)
GRP body	1	2356	100	100	100
	$W_B = 11.78 \text{ kg}$ $R_{GRP} = \text{Rs. } 200$				
Glass cover	1	193	0	0	0
	$A_G = (1.03 \times 1.08) \text{ m}^2$ $R_{GRP} = \text{Rs. } 173/\text{m}^2$				
Sealing putty	3 kg @ Rs. 10/kg	30	0	0	0
Iron made stand	1	285	184 $R_{IS} = \text{Rs. } 20/\text{kg}$	230 $R_{IS} = \text{Rs. } 25/\text{kg}$	303 $R_{IS} = \text{Rs. } 33/\text{kg}$
	$6.12 \times 1.5 = 9.18 \text{ kg}$ $R_{FI} = \text{Rs. } 31/\text{kg}$				
Glass cutting and transportation	1	50	0	0	0
	$G_{Cut} = \text{Rs. } 50$				
P_{SCom} (1\$ = Rs. 46)		2914	284	330	403

much toward the salvage value. The scrap value of iron also increases with the passage of time because the value of scrap iron increases with time. Thus, the salvage value is evaluated by keeping the previously mentioned points in consideration. The cost break-down of a typical solar-distillation system for different life spans is listed in Table 10.3.

10.9 Payback Time/Payback Periods (n_p)

As discussed previously, the payback period is the minimum time taken for the system to recover the investment costs. The payback period for a system saving energy is evaluated as the total investment cost divided by the annual revenues from energy saved, displaced, or produced. The number of years to pay back the investment cost is the unit of measurement in payback analysis. In the case of a solar-distillation system, the amount of distilled water produced annually—rather than energy savings—is the main concern.

A simple payback analysis of a solar-distillation system takes into account only the initial capital costs and the distribution/selling cost of the produced distilled water. Understanding the payback period is also used as an approximate guide to cost-effectiveness. If the payback period is significantly less than the expected life of the distillation system, then it is likely to be considered a cost-effective system.

The variation in payback periods with selling price for different interest rates and with the capital cost of a commercially produced solar still (Table 10.3) is presented

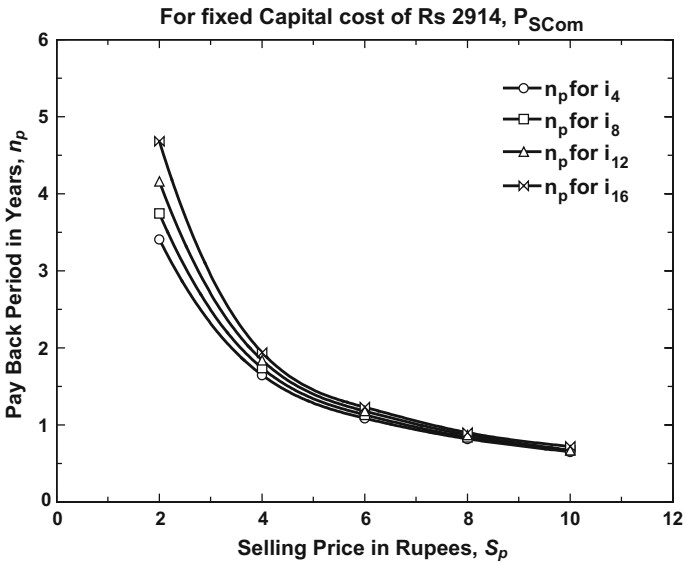


Fig. 10.1 Variation of payback period with selling price for different interest rates i

in Fig. 10.1. It has been observed that the payback period decreases significantly with an increase in selling price. It decreases from 4.68 to 0.72 years if the selling price is increased from Rs. 2 to Rs. 10/kg even at the highest rate interest rate (16%).

10.9.1 Understanding the Simple Payback Method

Payback considers the initial capital costs and the resulting annual cash flows. By definition, the payback period is the amount of time (usually measured in years) to recover the initial investment. Unfortunately, the payback method does not account for savings that may continue from a solar still after the initial investment has been recovered.

(a) Payback with equal annual savings

If annual cash flows are equal, the payback period is obtained by dividing the initial investment by the annual savings. Thus,

$$\text{payback period (years)} = \frac{\text{Initial capital cost}}{\text{Annual operating cash flow}}$$

Consider the example of a battery shop evaluating the purchase of a solar still to satisfy its need for distilled water. The shop owner analyses both (1) his current way of purchasing distilled water from the market and (2) the option of using a solar still. He observes that the installation of a solar-distillations system of 2 m² will cost Rs. 5000, but it will provide a net annual operational cash flow or savings of Rs. 1825. When the initial capital cost is divided by the net annual operational cash flow, the manager finds that the still will pay for itself in 2.7 years, while the life of a distillation system is supposed to be ≥ 30 years.

(b) Payback with unequal annual savings

The previous example assumes that the annual cash flow is the same each year. In reality, significant parameters—such as interest, maintenance cost, life, salvage value at the life, free distribution of distilled water, selling price of distilled water, etc.—cause variation of cash flows each year. If the annual cash flow differs from year to year, the payback period can be determined when the accrued cash savings become equal to the initial investment costs (i.e., when the cumulative cash-flow balance equals zero).

The payback period (n_p), i.e., the number of years necessary to exactly recover the initial capital investment for the solar distiller (P_s), is computed by summing the annual cash-flow values and estimating the value of n_p through the relation given below:

$$0 = -P_s + \sum_{t=1}^n CF_t(F_{SP,i,t}) \quad (10.9.48)$$

or

$$P_s = \sum_{t=1}^{n_p} [CF_t(1+i)^{-n_p}] \quad (10.9.49)$$

where CF_t is the net cash flow at the end of each year.

For the same value each year, it can be expressed as

$$P_s = CF(F_{RP,i,n}) \quad (10.9.50)$$

$F_{RP,i,n}$ is a factor described by Eq. (10.2.14) is multiplied with cash flow (CF) to take care about the interest rate and it is expressed below

$$F_{RP} = \frac{(1+i)^{n_p} - 1}{i(1+i)^{n_p}} \quad (10.9.51)$$

The previous equation can be simplified as follows:

$$n_p = \frac{\ln\left(\frac{CF}{CF - iP_s}\right)}{\ln(1+i)} \quad (10.9.52)$$

Case I—The distilled water is sold at the price it is produced

In this case the net cash flow is equal to the uniform end-of-year annual cost (UA_{net}) of the solar distiller, i.e., Eq. (10.9.52) can be modified as follows:

$$n_p = \frac{\ln\left(\frac{UA_{net}}{UA_{net} - iP_s}\right)}{\ln(1+i)} \quad (10.9.53)$$

Case II—The distilled water is sold at the market price.

In this case, the cash flow is estimated by the selling price, and it can be expressed as follows:

$$CF = M_Y S_p \quad (10.9.54)$$

The previously mentioned value of CF can be used in Eq. (10.9.52) to determine the payback period in case II.

Case III—The distilled water is sold at the market price considering a zero interest rate

In this case, Eq. (10.9.52) becomes as follows:

$$P_s = n_p CF$$

Or

$$n_p = \frac{P_s}{CF} \quad (10.9.55)$$

Problems and descriptive questions

- 10.1 Explain the following terms in detail:
 - (a) Capital-recovery factor (CRF)
 - (b) Uniform annual cost (UNACOST)
 - (c) Shrinking-fund factor (SFF)
- 10.2 Discuss the annual-cost and capitalized-cost methods.
- 10.3 Explain the concept of net present value (NPV) for acceptance/refusal criterion of the project.
- 10.4 Explain the concept of the payback period for a solar-distillation system in detail.
- 10.5 Discuss the payback period of a solar-distillation system for the following two cases:
 - (a) Payback period with equal savings
 - (b) Payback period with unequal savings
- 10.6 Calculate the future (F_{ps})- and present (F_{sp})-value factor for a given life of a solar-distillation system for a 10% interest rate, and show that $F_{ps}F_{sp} = 1$ for each case.
- 10.7 Calculate the effective rate of return for different values of p for a 10% interest rate.
- 10.8 Calculate the capital-recovery (F_{RP}) and sinking-fund (F_{SR}) factors for different numbers of years ($n = 1, 5, 10, 15$ and 20) for a given rate of interest $I = 0.05, 0.10, 0.15, 0.20\%$. In addition, prove that $F_{SR}F_{RS} = 1$.

- 10.9 A hybrid solar dryer purchased for USD\$1200 is expected to generate annual revenues of USD\$150 and have a salvage value of USD\$400 at the end of 15 years. If 18% per year required return is imposed on the purchase, compute the payback period. Use cash-flow diagram to solve the problem.
- 10.10 A non-profit organization is contemplating an investment of USD\$100,000 to install a hybrid solar water-heating system. The grant would extend over a 10-year period and would create an estimated saving of USD\$20,000/year. The organization uses a rate of return of 6%/year on all grant investments. An estimated USD\$4000/year would have to be released from other sources for expenses. In order to make this program successful, a USD\$2000/year operating expense will be incurred by the organization from its regular O&M budget. Use the following analysis methods to determine whether the program is justified over a 10-year period: (a) Conventional B/C (b) modified B/C , and $B-C$ analysis.

Objective questions

- 10.1 Which of the following is correct for the present-value factor?
- $F_{SP,i,n} = (1 + i)^{-n}$
 - $F_{SP,i,n} = (1 + i)^n$
 - $F_{SP,i,n} = (1 + i)^{-(n+1)}$
 - $F_{SP,i,n} = (1 + i)^{n+1}$
- 10.2 Which of the following is correct for the compound-interest factor or future-value factor?
- $F_{PS,i,n} = (1 + i)^n$
 - $F_{PS,i,n} = (1 + i)^{-n}$
 - $F_{PS,i,n} = (1 + i)^{n-1}$
 - $F_{PS,i,n} = (1 + i)^{n+1}$
- 10.3 Which of the following is the correct relationship between the present value and the UNACOST?
- $P = \frac{1}{R} \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right]$
 - $P = \frac{1}{R} \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right]^{-1}$
 - $P = R \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right]$
 - $P = \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right]$

10.4 Which of the following is the correct expression for the capital-recovery factor (CRF)?

- (a) $CRF = -\frac{i(1+i)^n}{(1+i)^n-1}$
- (b) $CRF = \frac{i(1+i)^{-n}}{(1+i)^n-1}$
- (c) $CRF = \frac{i(1+i)^n}{(1+i)^n+1}$
- (d) $CRF = \frac{i(1+i)^n}{(1+i)^n-1}$

10.5 Which of the following is the correct expression for the shrinking-fund factor (SFF)?

- (a) $SFF = \frac{1}{(1+i)^n-1}$
- (b) $SFF = -\frac{i}{(1+i)^n-1}$
- (c) $SFF = \frac{i}{(1+i)^n-1}$
- (d) $SFF = \frac{i}{(1+i)^n+1}$

10.6 Which of the following is a valid condition of net $B-C$ ratio for feasibility or acceptance of a project?

- (a) $\left(\frac{B}{C}\right)_{\text{net}} > 1$
- (b) $\left(\frac{B}{C}\right)_{\text{net}} < 1$
- (c) $\left(\frac{B}{C}\right)_{\text{net}} = 1$
- (d) $\left(\frac{B}{C}\right)_{\text{net}} > 0$

10.7 Which of the following is a valid condition of the net present value (NPV) for feasibility or acceptance of a project?

- (a) $NPV > 1$
- (b) $NPV < 1$
- (c) $NPV = 0$
- (d) $NPV > 0$

10.8 Which of the following represents the correct expression of the net uniform end-of-year annual cost?

- (a) $UA_{\text{net}} = P_s F_{PR,i,n}$
- (b) $UA_{\text{net}} = P_s F_{PR,i,n} - P_s F_{PR,i,n} M_s - S_s F_{SR,i,n}$
- (c) $UA_{\text{net}} = P_s F_{PR,i,n} + P_s F_{PR,i,n} M_s + S_s F_{SR,i,n}$
- (d) $UA_{\text{net}} = F_{PR,i,n} - P_s F_{PR,i,n} M_s - S_s F_{SR,i,n}$

10.9 Which of the following is the correct expression of the payback period on the basis of unequal annual savings?

$$(a) \quad n_p = \frac{\ln\left(\frac{UA_{\text{net}}}{UA_{\text{net}} + iP_s}\right)}{\ln(1+i)}$$

$$(b) \quad p = \frac{\ln\left(\frac{UA_{\text{net}}}{UA_{\text{net}} - iP_s}\right)}{\ln(1-i)}$$

$$(c) \quad n_p = \frac{\ln\left(\frac{UA_{\text{net}}}{UA_{\text{net}} - iP_s}\right)}{\ln(1+i)}$$

$$(d) \quad n_p = -\frac{\ln\left(\frac{UA_{\text{net}}}{UA_{\text{net}} - iP_s}\right)}{\ln(1+i)}$$

10.10 If the distilled or potable water is sold at the market price, then which of the following is the true relation of the cash flow and the selling price?

$$(a) \quad CF = M_Y S_p$$

$$(b) \quad CF = \frac{M_Y}{S_p}$$

$$(c) \quad S_p = M_Y CF$$

$$(d) \quad \text{none of these}$$

Answers

10.1 (a) 10.2 (c) 10.3 (a) 10.4 (d) 10.5 (c) 10.6 (a) 10.7 (d) 10.8 (b)
10.9 (c) 10.10 (a)

References

1. M.A. Hossain, J.L. Woods, B.K. Bala, *Optimisation Renewable Energy*, vol. 30, pp. 729–742 (2005)
2. G.N. Tiwari, *Solar Energy: Fundamentals, Design, Modeling and Applications* (Narosa Publishing House, New Delhi, India, 2004)
3. G.N. Tiwari, R.K. Mishra, *Advanced renewable energy resources* (RSC publishing, Cambridge, UK, 2012)

Appendix A

Conversion of units

(i) Length, m
1 yd (yard) = 3 ft = 36 in. (inches) = 0.9144 m
1 m = 39.3701 in. = 3.280839 ft = 1.093613 yd = 1650763.73 wavelength
1 ft = 12 in = 0.3048 m
1 in. = 2.54 cm = 25.4 mm
1 mil = 2.54×10^{-3} cm
1 μm = 10^{-6} m
1 nm = 10^{-9} m = 10^{-3} μm
(ii) Area, m²
1 ft ² = 0.0929 m ²
1 in. ² = 6.452 cm ² = 0.00064516 m ²
1 cm ² = 10^{-4} m ² = 10.764×10^{-4} ft ² = 0.1550 in. ²
1 ha = 10,000 m ²
(iii) Volume, m³
1 ft ³ = 0.02832 m ³ = 28.3168 l (litre)
1 in ³ = 16.39 cm ³ = 1.639×10^2 l
1 yd ³ = 0.764555 m ³ = 7.646×10^2 l
1 UK gallon = 4.54609 l
1 US gallon = 3.785 l = 0.1337 ft ³
1 m ³ = 1.000×10^6 cm ³ = 2.642×10^{12} US gallons = 109 l
1 l = 10^{-3} m ³
1 fluid ounce = 28.41 cm ³
(iv) Mass, kg
1 kg = 2.20462 lb = 0.068522 slug
1 ton (short) = 2000 lb (pounds) = 907.184 kg
1 ton (long) = 1016.05 kg
1 lb = 16 oz (ounces) = 0.4536 kg
1 oz = 28.3495 g
1 quintal = 100 kg

(continued)

(continued)

1 kg = 1000 g = 10,000 mg
1 μg = 10^{-6} g
1 ng = 10^{-9} g
(v) Density and specific volumes, kg/m³, m³/kg
1 lb/ft ³ = 16.0185 kg/m ³ = 5.787×10^{-4} lb/in. ³
1 g/cm ³ = 10 ³ kg/m ³ = 62.43 lb/ft ³
1 lb/ft ³ = 0.016 g/cm ³ = 16 kg/m ³
1 ft ³ (air) = 0.08009 lb = 36.5 g at N.T.P.
1 gallon/lb = 0.010 cm ³ /kg
1 $\mu\text{g}/\text{m}^3$ = 10^{-6} g/m ³
(vi) Pressure, Pa (Pascal)
1 lb/ft ² = 4.88 kg/m ² = 47.88 Pa
1 lb/in. ² = 702.7 kg/m ² = 51.71 mm Hg = 6.894757×10^3 Pa = 6.894757×10^3 N/m ²
1 atm = 1.013×10^5 N/m ² = 760 mm Hg = 101.325 kPa
1 in. H ₂ O = 2.491×10^2 N/m ² = 248.8 Pa = 0.036 lb/in. ²
1 bar = 0.987 atm = 1.000×10^6 dynes/cm ² = 1.020 kgf/cm ² = 14.50 lbf/in ² = 10^5 N/m ² = 100 kPa
1 torr (mm Hg 0 °C) = 133 Pa
1 Pascal (Pa) = 1 N/m ² = 1.89476 kg.
1 in. of Hg = 3.377 kPa = 0.489 lb/in ²
(vii) Velocity, m/s
1 ft/s = 0.3041 m/s
1 mile/h = 0.447 m/s = 1.4667 ft/s = 0.8690 knots
1 km/h = 0.2778 m/s
1 ft/min = 0.00508 m/s
(viii) Force, N
1 N (Newton) = 10^5 dynes = 0.22481 lb wt = 0.224 lb f
1 pdl (poundal) = 0.138255 N (Newton) = 13.83 dynes = 14.10 gf
1 lbf (i.e. wt of 1 lb mass) = 4.448222 N = 444.8222 dynes
1 ton = 9.964×10^3 N
1 bar = 10^5 Pa (Pascal)
1 ft of H ₂ O = 2.950×10^{-2} atm = 9.807×10^3 N/m ²
1 in H ₂ O = 249.089 Pa
1 mm H ₂ O = 9.80665 Pa
1 dyne = 1.020×10^{-6} kg f = 2.2481×10^{-6} lb f = 7.2330×10^{-5} pdl = 10^{-5} N
1 mm of Hg = 133.3 Pa
1 atm = 1 kg f/cm ² = 98.0665 k Pa
1 Pa (Pascal) = 1 N/m ²
(ix) Mass flow rate and discharge, kg/s, m³/s
1 lb/s = 0.4536 kg/s
1 ft ³ /min = 0.4720 l/s = 4.179×10^{-4} m ³ /s

(continued)

(continued)

$$1 \text{ m}^3/\text{s} = 3.6 \times 10^6 \text{ l/h}$$

$$1 \text{ g/cm}^3 = 10^3 \text{ kg/m}^3$$

$$1 \text{ lb/h ft}^2 = 0.001356 \text{ kg/s m}^2$$

$$1 \text{ lb/ft}^3 = 16.2 \text{ kg/m}^3$$

$$1 \text{ litre/s (l/s)} = 10^{-3} \text{ m}^3/\text{s}$$

(x) Energy, J

$$1 \text{ cal} = 4.187 \text{ J (Joules)}$$

$$1 \text{ kcal} = 3.97 \text{ Btu} = 12 \times 10^{-4} \text{ kWh} = 4.187 \times 10^3 \text{ J}$$

$$1 \text{ Watt} = 1.0 \text{ J/s}$$

$$1 \text{ Btu} = 0.252 \text{ kcal} = 2.93 \times 10^{-4} \text{ kWh} = 1.022 \times 10^3 \text{ J}$$

$$1 \text{ hp} = 632.34 \text{ kcal} = 0.736 \text{ kWh}$$

$$1 \text{ kWh} = 3.6 \times 10^6 \text{ J} = 1 \text{ unit}$$

$$1 \text{ J} = 2.390 \times 10^{-4} \text{ kcal} = 2.778 \times 10^{-4} \text{ Wh}$$

$$1 \text{ kWh} = 860 \text{ kcal} = 3413 \text{ Btu}$$

$$1 \text{ erg} = 1.0 \times 10^{-7} \text{ J} = 1.0 \times 10^{-7} \text{ Nm} = 1.0 \text{ dyne cm}$$

$$1 \text{ J} = 1 \text{ Ws} = 1 \text{ Nm}$$

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

$$1 \text{ GJ} = 10^9 \text{ J}$$

$$1 \text{ MJ} = 10^6 \text{ J}$$

$$1 \text{ TJ (Terajoules)} = 10^{12} \text{ J}$$

$$1 \text{ EJ (Exajoules)} = 10^{18} \text{ J}$$

(xi) Power, Watt (J/s)

$$1 \text{ Btu/h} = 0.293071 \text{ W} = 0.252 \text{ kcal/h}$$

$$1 \text{ Btu/h} = 1.163 \text{ W} = 3.97 \text{ Btu/h}$$

$$1 \text{ W} = 1.0 \text{ J/s} = 1.341 \times 10^{-3} \text{ hp} = 0.0569 \text{ Btu/min} = 0.01433 \text{ kcal/min}$$

$$1 \text{ hp (F.P.S.)} = 550 \text{ ft lb f/s} = 746 \text{ W} = 596 \text{ kcal/h} = 1.015 \text{ hp (M.K.S.)}$$

$$1 \text{ hp (M.K.S.)} = 75 \text{ mm kg f/s} = 0.17569 \text{ kcal/s} = 735.3 \text{ W}$$

$$1 \text{ W/ft}^2 = 10.76 \text{ W/m}^2$$

$$1 \text{ ton (Refrigeration)} = 3.5 \text{ kW}$$

$$1 \text{ kW} = 1000 \text{ W}$$

$$1 \text{ GW} = 10^9 \text{ W}$$

$$1 \text{ W/m}^2 = 100 \text{ lux}$$

(xii) Specific Heat, J/kg °C

$$1 \text{ Btu/lb °F} = 1.0 \text{ kcal/kg °C} = 4.187 \times 10^3 \text{ J/kg °C}$$

$$1 \text{ Btu/lb} = 2.326 \text{ kJ/kg}$$

(xiii) Temperature, °C and K used in SI

$$T_{(\text{Celsius}, ^\circ\text{C})} = (5/9) [T_{(\text{Fahrenheit}, ^\circ\text{F})} + 40] - 40$$

$$T_{(^{\circ}\text{F})} = (9/5) [T_{(^{\circ}\text{C})} + 40] - 40$$

$$T_{(\text{Rankine}, ^\circ\text{R})} = 460 + T_{(^{\circ}\text{F})}$$

$$T_{(\text{Kelvin}, \text{K})} = (5/9) T_{(^{\circ}\text{R})}$$

$$T_{(\text{Kelvin}, \text{K})} = 273.15 + T_{(^{\circ}\text{C})}$$

$$T_{(^{\circ}\text{C})} = T_{(^{\circ}\text{F})}/1.8 = (5/9) T_{(^{\circ}\text{F})}$$

(continued)

(continued)

(xiv) Rate of heat flow per unit area or heat flux, W/m²
1 Btu/ft ² h = 2.713 kcal/m ² h = 3.1552 W/m ²
1 kcal/m ² h = 0.3690 Btu/ft ² h = 1.163 W/m ² = 27.78 × 10 ⁻⁶ cal/s cm ²
1 cal/cm ² min = 221.4 Btu/ft ² h
1 W/ft ² = 10.76 W/m ²
1 W/m ² = 0.86 kcal/hm ² = 0.23901 × 10 ⁻⁴ cal/s cm ² = 0.137 Btu/h ft ²
1 Btu/h ft = 0.96128 W/m
(xv) Heat transfer coefficient, W/m² °C
1 Btu/ft ² h °F = 4.882 kcal/m ² h °C = 1.3571 × 10 ⁻⁴ cal/cm ² s °C
1 Btu/ft ² h°F = 5.678 W/m ² °C
1 kcal/m ² h °C = 0.2048 Btu/ft ² h °F = 1.163 W/m ² °C
1 W/m ² K = 2.3901 × 10 ⁻⁵ cal/cm ² sK = 1.7611 × 10 ⁻¹ Btu/ft ² °F = 0.86 kcal/m ² h °C
(xvi) Thermal Conductivity, W/m °C
1 Btu/ft h °F = 1.488 kcal/m h °C = 1.73073 W/m °C
1 Btu/ft ² h°F = 5.678 W/m ² °C
1 Btu in./ft ² h °F = 0.124 kcal/m h °C = 0.144228 W/m °C
1 Btu/in. h °F = 17.88 kcal/m h °C
1 cal/cm s °F = 4.187 × 10 ² W/m °C = 242 Btu/h ft °F
1 W/cm °C = 57.79 Btu/h ft °F
(xvii) Angle, rad
2π rad (radian) = 360° (degree)
1° (degree) = 0.0174533 rad = 60' (minutes)
1' = 0.290888 × 10 ⁻³ rad = 60" (seconds)
1" = 4.84814 × 10 ⁻⁶ rad
1° (hour angle) = 4 min (time)
(xviii) Illumination
1 lx (lux) = 1.0 lm (lumen)/m ²
1 lm/ft ² = 1.0 foot candle
1 foot candle = 10.7639 lx
100 lux = 1 W/m ²
(xix) Time, h
1 week = 7 days = 168 h = 10,080 min = 6,04,800 s
1 mean solar day = 1440 min = 86,400 s
1 calender year = 365 days = 8760 h = 5.256 × 10 ⁵ min
1 tropical mean solar year = 365.2422 days
1 sidereal year = 365.2564 days (mean solar)
1 s (second) = 9.192631770 × 10 ⁹ Hertz (Hz)
1 day = 24 h = 360° (hour angle)

(continued)

(continued)

(xx) Concentration, kg/m³ and g/m³
1 g/l = 1 kg/m ³
1 lb/ft ³ = 6.236 kg/m ³
(xxi) Diffusivity, m²/s
1 ft ² /h = 25.81 × 10 ⁻⁶ m ² /s

Appendix B

The value of $f_{0-\lambda T}$ for different $\lambda T, \mu\text{m K}$, for even increment of λT

$\lambda T, \mu\text{m K}$	$f_{0-\lambda T}$	$\lambda T, \mu\text{m K}$	$f_{0-\lambda T}$	$\lambda T, \mu\text{m K}$	$f_{0-\lambda T}$
1000	0.0003			8000	0.8562
1200	0.0021	4600	0.5793	8200	0.8639
1400	0.0077	4800	0.6075	8400	0.8711
1600	0.0197	5000	0.6337	8600	0.8778
1800	0.0393	5200	0.6579	8800	0.8841
2000	0.0667	5400	0.6803	9000	0.8899
2200	0.1009	5600	0.7010	9200	0.8954
2400	0.1402	5800	0.7201	9400	0.9005
2600	0.1831	6000	0.7378	9600	0.9054
2800	0.2279	6200	0.7451	9800	0.9099
3000	0.2730	6400	0.7692	10,000	0.9141
3200	0.3181	6600	0.7831	12,000	0.9450
3400	0.3617	6800	0.7961	14,000	0.9628
3600	0.4036	7000	0.8080	16,000	0.9737
3800	0.4434	7200	0.8191	18,000	0.9807
4000	0.4829	7400	0.8295	20,000	0.9855
4200	0.5160	7600	0.8390	50,000	0.9988
4400	0.5488	7800	0.8479	∞	1

Appendix C

Appendix C.1

Parameters on horizontal surface for sunshine hours = 10 for all four weather type of days for different Indian climates (Ref. [1] of Chap. 2).

(a) New Delhi:

Type of day	Parameters	Month											
		January	February	March	April	May	June	July	August	September	October	November	December
a	T_R	2.25	2.79	2.85	2.72	3.54	2.47	2.73	2.58	2.53	1.38	0.62	0.72
	α	0.07	0.10	0.17	0.23	0.16	0.28	0.37	0.41	0.29	0.47	0.59	0.54
	K_1	0.47	0.39	0.33	0.28	0.20	0.27	0.41	0.40	0.23	0.21	0.21	0.28
	K_2	-13.17	-6.25	5.61	38.32	65.04	31.86	-40.57	-55.08	39.92	32.77	30.62	9.73
	T_R	2.28	2.78	2.89	3.15	5.44	4.72	5.58	5.43	3.23	4.56	0.19	1.83
b	α	0.15	0.13	0.14	0.17	0.16	0.20	0.24	0.18	0.31	0.22	1.14	0.42
	K_1	0.51	0.54	0.49	0.46	0.45	0.45	0.53	0.39	0.37	0.42	0.35	0.40
	K_2	-21.77	-28.26	-9.22	-11.55	1.54	23.99	-51.61	9.46	14.07	-9.50	17.47	-0.07
	T_R	5.88	6.36	6.11	7.77	9.20	10.54	7.13	7.97	5.51	5.01	4.93	3.23
	α	0.27	0.37	0.37	0.31	0.07	0.06	0.41	0.51	0.49	1.26	1.06	0.64
c	K_1	0.39	0.36	0.33	0.35	0.56	0.48	0.47	0.35	0.39	0.36	0.31	0.43
	K_2	-14.73	-7.97	10.87	20.45	-56.00	-0.37	-52.27	47.70	35.64	-0.68	13.06	-7.04
	T_R	7.47	8.97	10.77	11.18	13.69	12.47	8.21	8.58	9.40	7.24	4.30	4.02
	α	0.96	1.04	0.24	0.07	0.07	0.61	1.26	1.10	0.84	1.29	1.43	1.70
	K_1	0.35	0.30	0.43	0.49	0.48	0.46	0.43	0.43	0.41	0.36	0.31	0.38
d	K_2	-25.89	-6.48	-36.46	-44.07	-42.58	-62.66	-56.75	-61.08	-27.09	3.90	20.10	-11.78

(b) Bangalore:

Type of day	Parameters	Month											
		January	February	March	April	May	June	July	August	September	October	November	December
a	T_R	3.36	3.27	3.63	5.05	4.24	4.32	5.18	4.75	4.10	2.28	1.66	1.65
	α	0.07	0.13	0.06	-0.06	0.10	0.19	0.10	0.18	0.13	0.33	0.35	0.36
	K_1	0.33	0.35	0.33	0.29	0.21	0.25	0.32	0.23	0.20	0.05	0.03	0.12
	K_2	-18.05	-22.11	-5.44	14.54	47.81	22.40	-26.04	10.14	38.54	107.04	103.64	47.70
b	T_R	3.24	5.25	6.21	5.72	5.90	7.35	4.12	5.27	4.83	2.43	1.89	3.68
	α	0.31	0.24	0.21	0.19	0.25	0.17	0.51	0.44	0.62	0.56	0.78	0.39
	K_1	0.50	0.45	0.48	0.50	0.41	0.50	0.46	0.50	0.33	0.26	0.37	0.41
	K_2	-60.12	-60.50	-80.04	-75.59	-28.55	-103.35	-90.54	-115.27	13.80	69.14	9.08	-33.76
c	T_R	3.70	4.51	7.74	5.83	4.95	4.39	5.68	2.67	6.64	4.71	5.68	2.02
	α	0.96	0.94	0.63	0.98	0.96	1.12	1.07	1.35	0.78	1.03	0.93	1.44
	K_1	0.46	0.57	0.36	0.50	0.53	0.58	0.50	0.55	0.48	0.43	0.36	0.43
	K_2	-63.02	-129.68	-20.76	-61.13	-103.14	-156.14	-108.34	-161.61	-52.93	-26.53	-15.95	-47.21
d	T_R	6.13	7.49	7.35	6.86	6.33	4.84	4.45	6.68	3.94	3.91	3.84	2.80
	α	1.61	1.31	1.41	1.48	1.59	2.00	2.32	1.69	2.16	2.00	2.04	2.58
	K_1	0.29	0.30	0.40	0.45	0.53	0.61	0.41	0.50	0.38	0.42	0.55	0.27
	K_2	36.80	83.73	-39.85	-72.22	-99.52	-213.29	-79.79	-146.94	-88.62	-125.35	-177.28	-12.29

(c) Jodhpur:

Type of day	Parameters	Month											
		January	February	March	April	May	June	July	August	September	October	November	December
a	T_R	1.26	1.33	1.59	2.82	3.72	3.87	3.25	3.39	3.20	2.26	1.56	1.54
	α	0.37	0.38	0.37	0.27	0.21	0.21	0.27	0.28	0.27	0.33	0.39	0.31
	K_1	0.22	0.14	0.18	0.21	0.20	0.13	0.10	0.17	0.26	0.24	0.23	0.26
	K_2	30.67	63.90	56.40	47.66	50.84	87.88	105.23	59.41	14.42	27.40	22.71	9.48
b	T_R	2.34	2.03	3.00	4.07	5.21	5.50	5.07	4.73	3.81	2.90	2.28	3.43
	α	0.46	0.55	0.42	0.31	0.23	0.28	0.37	0.40	0.35	0.38	0.46	0.24
	K_1	0.33	0.29	0.31	0.34	0.33	0.33	0.34	0.33	0.34	0.30	0.33	0.40
	K_2	12.89	43.13	42.22	23.50	31.22	33.40	35.81	29.57	8.71	24.12	12.35	-11.64
c	T_R	3.81	4.78	4.04	4.97	6.87	5.58	4.90	5.10	3.40	3.71	3.28	4.23
	α	0.93	1.32	0.98	0.64	0.61	0.67	1.02	0.88	0.97	2.05	1.31	1.06
	K_1	0.43	0.40	0.42	0.47	0.47	0.46	0.41	0.50	0.48	0.53	0.44	0.44
	K_2	-33.72	12.44	-19.11	-26.93	-44.76	-35.15	2.06	-60.42	-26.96	-62.06	-35.85	-32.84
d	T_R	2.25	5.20	7.09	9.33	8.01	3.52	9.62	3.17	1.63	7.67	1.71	1.94
	α	1.89	1.64	2.03	1.59	1.66	2.37	2.37	2.77	3.24	0.86	2.89	2.03
	K_1	0.44	0.46	0.42	0.44	0.43	0.28	0.52	0.44	0.44	0.52	0.36	0.39
	K_2	-19.31	-45.44	-89.92	-149.27	-117.01	60.69	-221.29	-87.34	-77.55	-26.47	-15.46	-14.88

(d) Mumbai:

Type of day	Parameters	Month											
		January	February	March	April	May	June	July	August	September	October	November	December
a	T_R	1.95	1.80	2.88	3.95	5.40	3.20	3.31	4.25	4.22	3.16	2.97	3.27
	α	0.34	0.37	0.23	0.14	-0.02	0.16	0.61	0.33	0.15	0.30	0.23	0.18
	K_1	0.26	0.19	0.28	0.34	0.28	0.25	0.09	0.12	0.24	0.24	0.26	0.30
	K_2	19.77	53.96	27.13	-0.75	30.06	4.55	27.28	47.27	30.02	15.87	9.11	-4.81
b	T_R	2.96	2.68	3.57	4.98	6.25	6.08	7.74	6.70	4.78	3.93	3.40	4.21
	α	0.43	0.49	0.37	0.25	0.15	0.19	0.20	0.37	0.47	0.47	0.45	0.24
	K_1	0.35	0.31	0.35	0.40	0.42	0.44	0.31	0.39	0.41	0.36	0.34	0.37
	K_2	-0.14	24.17	11.73	-13.57	-13.69	-19.52	61.35	22.16	-14.71	5.99	0.60	-14.17
c	T_R	3.06	2.26	3.24	4.39	5.91	5.97	8.17	4.24	5.36	3.16	2.97	3.75
	α	1.14	1.18	1.10	1.00	0.79	0.86	0.62	1.26	0.98	1.13	1.10	0.91
	K_1	0.59	0.58	0.52	0.54	0.60	0.52	0.54	0.43	0.44	0.47	0.57	0.54
	K_2	-59.86	-47.12	-58.09	-78.37	-111.97	-81.79	-95.21	-34.40	-39.31	-28.02	-48.41	-52.45
d	T_R	3.38	7.42	4.45	2.30	4.71	4.71	6.41	7.40	7.46	3.22	5.13	3.05
	α	1.71	1.73	2.29	2.08	2.95	2.66	2.68	1.81	2.14	2.15	1.53	1.51
	K_1	0.52	0.56	0.50	0.35	0.41	0.38	0.32	0.47	0.34	0.42	0.57	0.53
	K_2	-59.78	-26.16	-82.34	63.52	-101.81	-87.19	-61.50	-108.37	-38.68	-25.89	-78.03	-40.51

(e) Srinagar:

Type of day	Parameters	Month											
		January	February	March	April	May	June	July	August	September	October	November	December
a	T_R	1.45	5.37	3.31	4.25	5.41	3.63	5.77	6.45	4.06	2.61	4.03	0.72
	α	0.33	-0.36	-0.03	-0.03	-0.12	0.08	-0.09	-0.23	0.03	0.20	-0.37	0.53
	K_1	0.37	0.63	0.69	0.37	0.51	0.33	0.17	0.37	0.46	0.43	0.66	0.33
	K_2	-6.14	-82.86	-94.01	-10.95	-79.57	-13.73	68.06	-42.79	-60.27	-47.83	-37.00	-6.60
b	T_R	3.09	6.98	4.65	6.92	5.86	6.82	7.40	7.58	6.41	4.04	0.04	0.35
	α	0.38	-0.48	0.23	0.06	0.29	0.11	0.00	-0.13	-0.04	0.19	1.16	1.00
	K_1	0.39	0.83	0.59	0.42	0.32	0.63	0.48	0.38	0.48	0.52	0.37	0.41
	K_2	-23.08	-110.23	-107.74	-49.61	0.26	-167.86	-80.06	-13.91	-66.64	-62.52	-14.63	-12.20
c	T_R	2.35	6.59	6.31	7.57	8.69	8.00	9.72	8.23	7.36	5.02	1.86	0.76
	α	1.64	0.86	1.35	0.57	0.61	0.81	0.69	0.90	0.99	1.49	1.47	1.98
	K_1	0.41	0.42	0.48	0.54	0.50	0.39	0.56	0.49	0.44	0.52	0.41	0.31
	K_2	-37.87	-85.68	-180.45	-120.38	-146.97	-87.44	-228.91	-147.96	-62.10	-93.64	-40.07	-12.15
d	T_R	1.69	1.36	7.52	9.09	9.48	10.79	10.93	8.54	8.16	7.75	3.78	2.44
	α	2.63	2.97	1.87	1.35	1.13	1.56	3.08	1.71	3.15	1.70	1.74	2.04
	K_1	0.43	0.36	0.35	0.62	0.92	0.80	0.45	0.75	0.67	0.55	0.48	0.63
	K_2	-41.27	-44.68	-65.17	-254.24	-467.30	-421.63	-129.49	-356.92	-261.85	-119.53	-49.16	-64.02

Appendix C.2

The turbidity factor (T_R) for different months (Ref. [1] of Chap. 2).

Region	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
Mountain	1.8	1.9	2.1	2.2	2.4	2.7	2.7	2.7	2.5	2.1	1.9	1.8
Flat land	2.2	2.2	2.5	2.9	3.2	3.4	3.5	3.3	2.9	2.6	2.3	2.2
City	3.1	3.2	3.5	3.9	4.1	4.2	4.3	4.2	3.9	3.6	3.3	3.1

For cloudy condition the value of T_R will be more than 10.0

Appendix C.3

Model type	Model name	Model correlations	Remarks
Solar radiation model for calculation of hourly radiation	Hottel model [1]	$I_N = I_{ON}[a_0 + a_1 \exp(-k/\cos \theta_z)]$ $a_0 = 0.4237 - 0.00821(6 - A)^2$ $a_1 = 0.5055 - 0.00595(6.5 - A)^2$ $k = 0.2711 - 0.01858(2.5 - A)^2$	The constants a_0 , a_1 and k are functions of the altitude of the location, and A is the altitude in kilometres
	Kasten and Young model [2]	$I_N = I_{ON} \exp(-m \cdot \varepsilon \cdot T_R)$ $m = [\cos \theta_z + 0.15 \times (93.885 - \theta_z)^{-1.253}]^{-1}$ $\varepsilon = 4.529 \times 10^{-4} \text{ m}^2 - 9.66865 \times 10^{-3} \text{ m} + 0.108014$	m is air mass, ε is optical thickness of atmosphere and T_R Linke turbidity factor
	Perez et al. model [3]	$I_N = I_{ON} \exp[-T_R/(0.9 + 9.4 \cos \theta_z)]$	I_{ON} is solar radiation in extra-terrestrial region and T_R is Linke turbidity factor
	ASHRAE model [4]	$I = I_N \cos \theta_z + I_d$ $I_N = A \exp(-B/\cos \theta_z)$ $I_d = C I_N$	A , B and C are constants depends on locations
	Singh and Tiwari model [5]	$I_N = I_{ON} \exp\{- (m \cdot \varepsilon \cdot T_R + \alpha)\}$ $I_{HD} = K_1 (I_{ON} - I_N) \cos \theta_z + K_2$	α is atmospheric transmittance for beam radiation I_{HD} is diffuse radiation on horizontal surface K_1 and K_2 are atmospheric transmittances for diffuse radiation. Applicable to different weather conditions
	Jamil and Tiwari model [6]	$I_N = I_{ON} \exp\left\{-\left((m \cdot \varepsilon)^2 T_{RO} + (m \cdot \varepsilon) \cdot T_R + \alpha\right)\right\}$ $I_{HD} = K_0 \{(I_{ON} - I_N) \cos \theta_z\}^2 + K_1 (I_{ON} - I_N) \cos \theta_z + K_2$	Applicable to different weather conditions. Validated for composite climatic condition of New Delhi, India

(continued)

(continued)

Model type	Model name	Model correlations	Remarks
Radiation on horizontal surface (decomposition model)	Liu and Jordan model [7]	$k_D = 0.384 - 0.416k_t$ $k_t = \frac{I}{I_0}$, $k_d = \frac{I_d}{I}$, $k_D = \frac{I_d}{I_0}$, $k_b = \frac{I_b}{I_0}$	k_t is clearness index, k_d is diffuse fraction, k_D is diffuse coefficient and k_b is direct transmittance. I , I_b , I_d and I_0 being the global, direct, diffuse and extraterrestrial irradiances respectively, on a horizontal surface (all in MJ m ⁻²)
	Orgill and Hollands model [8]	$k_d = 1.557 - 1.846k_t$ for $0.35 \leq k_t \leq 0.75$, $k_d = 1.0 - 0.249k_t$ for $k_t < 0.35$, $k_d = 0.177$ for $k_t > 0.75$,	The model was based on the global and diffuse irradiance values registered in Toronto (Canada, 42.81 N) during the years 1967–1971
	Erbs et al. model [9]	$k_d = 0.951 - 0.1604k_t + 4.388k_t^2 - 16.638k_t^3$ + $12.336k_t^4$ for $0.22 \leq k_t \leq 0.80$ $k_d = 1.0 - 0.09k_t$ for $k_t \leq 0.22$ $k_d = 0.165$ for $k_t > 0.80$	Correlations developed using data from five stations in the USA with latitudes between 31° and 42°
	Spencer model [10]	$k_d = a_3 - b_3k_t$ for $0.35 \leq k_t \leq 0.75$ $a_3 = 0.94 + 0.0118 \phi $ $b_3 = 1.185 + 0.0135 \phi $	Correlations developed from five stations in Australia (20°S–45°S latitude) ϕ (degrees) is the latitude
	Muneer et al. model [11]	$k_d = 0.9698 + 0.4353k_t - 3.4499k_t^2$ + $2.1888k_t^3$ for $0.175 \leq k_t \leq 0.775$ $k_d = 0.95$ for $k_t < 0.175$ $k_d = 0.26$ for $k_t > 0.775$	Correlation developed using data from New Delhi, India
	Hawladar model [12]	$k_d = 1.135 - 0.9422k_t - 0.3878k_t^2$ for $0.225 < k_t < 0.775$ $k_d = 0.915$ for $k_t \leq 0.225$ $k_d = 0.215$ for $k_t \geq 0.775$	Correlation developed using data from a tropical site in Singapore
	Reindl et al. model [13]	First correlation: $k_d = 1.02 - 0.248k_t$ for $k_t \leq 0.30$ $k_d = 1.45 - 1.67k_t$ for $0.3 < k_t < 0.78$ $k_d = 0.147$ for $k_t \geq 0.78$	Correlations developed from five locations in the USA and Europe (28°N–60°N latitude)

(continued)

(continued)

Model type	Model name	Model correlations	Remarks
		Second correlation: $k_d = 1.02 - 0.254k_t + 0.0123 \sin \alpha$ for $k_t \leq 0.30$ $k_d = 1.4 - 1.749k_t + 0.177 \sin \alpha$ for $0.3 < k_t < 0.78$ $k_d = 0.486k_t - 0.182 \sin \alpha$ for $k_t \geq 0.78$	
	Chandrasekaran and Kumar model [14]	$k_d = 0.9686 + 0.1325k_t + 1.4183k_t^2 - 10.1862k_t^3 + 8.3733k_t^4$ for $0.24 < k_t \leq 0.80$ $k_d = 1.0086 - 0.178k_t$ for $k_t \leq 0.24$ $k_d = 0.197$ for $k_t > 0.80$	Correlation developed using data from a tropical environment in Chennai, India
	Lam and Li model [15]	$k_d = 0.977$ for $k_t \leq 0.15$ $k_d = 1.237 - 1.361k_t$ for $0.15 < k_t \leq 0.7$ $k_d = 0.273$ for $k_t > 0.7$	Correlations developed for Hong Kong (22.31°N latitude) with the measured data in 1991–1994
	Boland et al. model [16]	$k_d = \frac{1}{1+e^{3.997(k_t-0.586)}}$ for all values of k_t	Correlation developed using data from one location in Victoria, Australia
	Miguel et al. model [17]	$k_d = 0.724 + 2.738k_t - 8.32k_t^2 + 4.967k_t^3 + 12.336k_t^4$ for $0.21 < k_t \leq 0.76$ $k_d = 0.995 - 0.081k_t$ for $k_t \leq 0.21$ $k_d = 0.18$ for $k_t \geq 0.76$	Correlation developed using data from several countries in the North Mediterranean Belt area
	Oliveira et al. model [18]	$k_d = 0.97 + 0.8k_t - 3.0k_t^2 - 3.1k_t^3 + 5.2k_t^4$ for $0.17 < k_t < 0.75$ $k_d = 1.0$ for $k_t \leq 0.17$ $k_d = 0.17$ for $k_t > 0.75$	Correlation developed using data from Sao Paolo site, Brazil
	Karatasou et al. model [19]	$k_d = 0.9995 - 0.05k_t - 2.4156k_t^2 + 1.4926k_t^3$ for $0 < k_t \leq 0.78$ $k_d = 0.20$ for $k_t > 0.78$	Correlation developed using data from Athens, Greece
			(continued)

(continued)

Model type	Model name	Model correlations	Remarks
Models for predicting the mean hourly global radiation from daily summations	Soares et al. model [20]	$k_d = 0.90 + 1.1k_t - 4.5k_t^2 + 0.01k_t^3$ $+ 3.14k_t^4$ for $0.17 < k_t < 0.75$ $k_d = 1.0$ for $k_t \leq 0.17$ $k_d = 0.17$ for $k_t > 0.75$	Correlation developed with neural network technique using data from Sao Paolo site, Brazil
	Whillier/Liu and Jordan model [21]	$r_0 = (\cos \omega - \cos \omega_0) / kA(\omega_0)$ $A(\omega_0) = \sin \omega_0 - \omega_0 \cos \omega_0$ r_0 is the extraterrestrial hourly/daily ratio ω_0 is the sunrise hour angle (in radians) ω is the hour angle	It is assumed that global radiation follow the same hourly distribution as if there were no atmosphere
	Collares-Pereira and Rabl model [22]	$r_{CPR} = (a + b \cos \omega) r_0$ $a = 0.4090 + 0.5016 \sin(\omega_0 - 1.047)$ $b = 0.6609 + 0.4767 \sin(\omega_0 - 1.047)$	r_{CPR} is the extraterrestrial hourly/daily ratio
	Newell model [23]	$r_N = (1.5/S_0) \left[1 - 4(t - 12)^2 / S_0^2 \right]$ $S_0 = k\omega_0$, $k = 24/\pi$ ω_0 is the sunrise hour angle (in radians) $\cos \omega_0 = -\tan \phi \tan \delta$	ϕ is the site's latitude, δ is solar declination r_N is the extraterrestrial hourly/daily ratio
	Jain model [24]	$r_J = \frac{1}{\sigma_1 \sqrt{2\pi}} \exp \left[-\frac{(t-12)^2}{2\sigma_1^2} \right]$ $\sigma_1 = 0.461 + 0.192S_0$, $S_0 = k\omega_0$, $k = 24/\pi$ ω_0 is the sunrise hour angle (in radians) $\cos \omega_0 = -\tan \phi \tan \delta$	ϕ is the site's latitude, δ is solar declination r_J is the extraterrestrial hourly/daily ratio
	Gueymard model [25]	$r_{CPRG} = (a + b \cos \omega) r_0 / f$ $f = a + 0.5b(\omega_0 - \sin \omega_0 \cos \omega_0) / A(\omega_0)$ $a = 0.4090 + 0.5016 \sin(\omega_0 - 1.047)$ $b = 0.6609 + 0.4767 \sin(\omega_0 - 1.047)$	Modified Collares-Pereira and Rabl model r_{CPRG} is the extraterrestrial hourly/daily ratio
	Garg and Garg Model [26]	$r_G = r_0 - 0.008 \sin 3(\omega - 0.65)$	Corrected Whillier/Liu and Jordan model for Indian climatic condition r_G is the extraterrestrial hourly/daily ratio

(continued)

(continued)

Model type	Model name	Model correlations	Remarks
	Baig et al. model [27]	$r_B = \frac{1}{2\sigma_B\sqrt{2\pi}} \exp\left[-\frac{(\iota-12)^2}{2\sigma_B^2}\right]$ $\sigma_B = 0.26 + 0.21S_0$, $S_0 = k\omega_0$, $k = 24/\pi$ ω_0 is the sunrise hour angle (in radians) $\cos \omega_0 = -\tan \phi \tan \delta$	ϕ is the site's latitude, δ is solar declination It is corrected Jain model for better accuracy for values of solar radiation during sunrise and sunset r_B is the extraterrestrial hourly/daily ratio

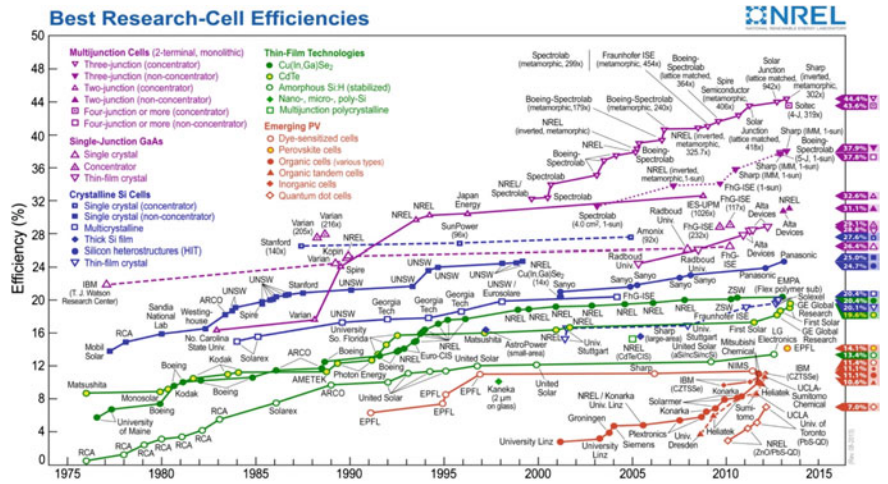
Appendix D

Specifications of solar cell material (at solar intensity 1000 W/m^2 and cell temperature 25°C) and cost (from Ref. [1] of Chap. 2).

Cell technology	Efficiency (%)	Fill factor (FF)	Aperture area ($10^{-4} \times \text{m}^2$)	Life time ^a (years)	Manufacturing cost (\$/kWp in 2007)	Selling price (\$/kWp in 2007)
Monocrystalline silicon	24.7 ± 0.5	0.828	4.0	30	2.5	3.7
Multicrystalline silicon	19.8 ± 0.5	0.795	1.09	30	2.4	3.5
Copper indium diselenide (CIS/ CIGS)	18.4 ± 0.5	0.77	1.04	5	1.5	2.5
Thin silicon cell	16.6 ± 0.4	0.782	4.02	25	2.0	3.3
Cadmium telluride (CdTe)	16.5 ± 0.5	0.755	1.03	15	1.5	2.5
Amorphous silicon (a-si)	10.1 ± 0.2	0.766	1.2	20	1.5	2.5

^aBased on experience

Source B. Agarwal, G.N. Tiwari, Development in environmental durability for photovoltaics, Pira International Ltd., UK, 2008



Courtesy NREL, USA.

Appendix E

See Tables [E.1](#), [E.2](#), [E.3](#), [E.4](#), [E.5](#), [E.6](#), [E.7](#), [E.8](#), [E.9](#), [E.10](#), [E.11](#), [E.12](#), [E.13](#) and [E.14](#).

Table E.1 Properties of air at atmospheric pressure

T (K)	P (kg/ m^3)	C_p (kJ/ kg K)	μ (kg/ m s) $\times 10^{-5}$	ν (m^2 / s) $\times 10^{-6}$	K (W/ m^2 K) $\times 10^{-3}$	α (m^2 / s) $\times 10^{-5}$	Pr
100	3.6010	1.0259	0.6924	1.923	9.239	0.2501	0.770
150	2.3675	1.0092	1.0283	4.343	13.726	0.5745	0.753
200	1.7684	1.0054	1.3289	7.490	18.074	1.017	0.739
250	1.4128	1.0046	1.488	9.49	22.26	1.3161	0.722
300	1.1774	1.0050	1.983	15.68	26.22	2.216	0.708
350	0.9980	1.0083	2.075	20.76	30.00	2.983	0.697
400	0.8826	1.0134	2.286	25.90	33.62	3.760	0.689

The value of μ , K , C_p and Pr are not strongly pressure-dependent and may be used over a fairly wide range of pressures

Table E.2 Properties of Water (saturated liquid)

Temperature		C_p (kJ/kg K)	ρ (kg/m ³)	μ_k (kg/m s)	K (W/m K)	Pr	$\frac{g \beta \rho^2 C_p}{\mu_k}$ (1/m ³ K)
°F	°C						
32	0.00	4.225	999.8	1.79×10^3	0.566	13.25	1.91×10^9
40	4.44	4.208	999.8	1.55	0.575	11.35	6.34×10^9
50	10.00	4.195	999.2	1.31	0.585	9.40	1.08×10^{10}
60	15.56	4.186	998.6	1.12	0.595	7.88	1.46×10^{10}
70	21.11	4.179	997.4	9.8×10^4	0.604	6.78	1.46×10^{10}
80	26.67	4.179	995.8	8.6	0.614	5.85	1.91×10^{10}
90	32.22	4.174	994.9	7.65	0.623	5.12	2.48×10^{10}
100	37.78	4.174	993.0	6.82	0.630	4.53	3.3×10^{10}
110	43.33	4.174	990.6	6.16	0.637	4.04	4.19×10^{10}
120	48.89	4.174	988.8	5.62	0.644	3.64	4.89×10^{10}
130	54.44	4.179	985.7	5.13	0.649	3.30	5.66×10^{10}
140	60.00	4.179	983.3	4.71	0.654	3.01	6.48×10^{10}
150	65.55	4.183	980.3	4.3	0.659	2.73	7.62×10^{10}
160	71.11	4.186	977.3	4.01	0.665	2.53	8.84×10^{10}
170	76.67	4.191	973.7	3.72	0.668	2.33	9.85×10^{10}
180	82.22	4.195	970.2	3.47	0.673	2.16	1.09×10^{10}
190	87.78	4.199	966.7	3.27	0.675	2.03	
200	93.33	4.204	963.2	3.06	0.678	1.90	
210	104.40	4.216	955.1	2.67	0.684	1.66	

Table E.3 Properties of metals

Metal		Properties at 20 °C			
		P (kg/m ³)	C_p (kJ/kgK)	K (W/mK)	α (m ² /s $\times 10^{-5}$)
Aluminum	Pure	2707	0.896	204	8.418
	Al-Si (Silumin, copper bearing) 86% Al, 1% Cu	2659	0.867	137	5.933
Lead	Pure	11400	0.1298	34.87	7.311
Iron	Pure	7897	0.452	73	2.034
	Steel (Carbon steel)	7753	0.486	63	0.970
Copper	Pure	8954	0.3831	386	11.234
	Aluminum bronze (95% Cu, 5% Al)	8666	0.410	383	2.330
Bronze	75% Cu, 25% Sn	8666	0.343	326	0.859
Red brass	85% Cu, 9% Sn 6% Zn	8714	0.385	61	1.804
Brass	70% Cu, 30% Zn	8600	0.877	85	3.412
German silver	62% Cu, 15% Ni, 22% Zn	8618	0.394	24.9	0.733
Constantan	60% Cu, 40% Ni	8922	0.410	22.7	0.612
Magnesium	Pure	1746	1.013	171	9.708
Nickel	Pure	8906	0.4459	90	2.266
Silver	Purest	10,524	0.2340	419	17.004
	Pure (99.9%)	10,524	0.2340	407	16.563
Tin	Pure	7304	0.2265	64	3.884
Tungsten	Pure	19,350	0.1344	163	6.271
Zinc	Pure	7144	0.3843	112.2	4.106

Table E.4 Properties of non-metals

Material	Temperature (°C)	K (W/mk)	ρ (kg/m ³)	C (kJ/kgK)	α (m ² /s) $\times 10^{-7}$
Asbestos	50	0.08	470	—	—
Building brick	20	0.69	1600	0.84	5.2
Common face	—	1.32	2000	—	—
Concrete, Cinder	23	0.76	—	—	—
Stone 1-2-4 mix	20	1.37	1900–2300	0.88	8.2–6.8
Glass, window	20	0.78 (avg)	2700	0.84	3.4
Borosilicate	30–75	1.09	2200	—	—
Plaster, Gypsum	20	0.48	1440	0.84	4.0
Granite	—	1.73–3.98	2640	0.82	8–18
Limestone	100–300	1.26–1.33	2500	0.90	5.6–5.9
Marble	—	2.07–2.94	2500–2700	0.80	10–13.6

(continued)

Table E.4 (continued)

Material	Temperature (°C)	K (W/mk)	ρ (kg/m ³)	C (kJ/kgK)	α (m ² /s) $\times 10^{-7}$
Sandstone	40	1.83	2160–2300	0.71	11.2–11.9
Fir	23	0.11	420	2.72	0.96
Maple or Oak	30	0.166	540	2.4	1.28
Yellow Pine	23	0.147	640	2.8	0.82
Cord board	30	0.043	160	1.88	2–5.3
Cork, regranulated	32	0.045	45–120	1.88	2–5.3
Ground	32	0.043	150	–	–
Sawdust	23	0.059	–	–	–
Wood shaving	23	0.059	–	–	–

Table E.5 Physical properties of some other materials

S. no.	Material	Density (kg/m ³)	Thermal conductivity (W/m K)	Specific heat (J/kg K)
1.	Air	1.117	40.026	1006
2.	Alumina	3800	29.0	800
3.	Aluminum	41–45	211	0.946
4.	Asphalt	1700	0.50	1000
5.	Brick	1700	0.84	800
6.	Carbon dioxide	1.979	0.145	871
7.	Cement	1700	0.80	670
8.	Clay	1458	11.28	879
9.	Concrete	2400	1.279	1130
10.	Copper	8795	385	–
11.	Cork	240	0.04	2050
12.	Cotton wool	1522	–	1335
13.	Fibre board	300	0.057	1000
14.	Glass-crown	2600	1.0	670
15.	Glass-window	2350	0.816	712
16.	Glass-wool	50	0.042	670
17.	Ice	920	2.21	1930
18.	Iron	7870	80	106
19.	Lime stone	2180	1.5	–
20.	Mudphuska	–	–	–
21.	Oxygen	1.301	0.027	920
22.	Plaster-board	950	0.16	840
23.	Polyesterene-expanded	25	0.033	1380
24.	P.V.C.—rigid foam	25–80	0.035–0.041	–
25.	P.V.C.—rigid sheet	1350	0.16	–
26.	Saw dust	188	0.57	–

(continued)

Table E.5 (continued)

S. no.	Material	Density (kg/m ³)	Thermal conductivity (W/m K)	Specific heat (J/kg K)
27.	Thermocole	22	0.03	–
28.	Timber	600	0.14	1210
29.	Turpentine	870	0.136	1760
30.	Water (H ₂ O)	998	0.591	4190
31.	Sea water	1025	–	3900
32.	Water vapour	0.586	0.025	2060
33.	Wood wool	500	0.10	1000

Table E.6 Absorptivity of various surfaces for sun's ray

Surface	Absorptivity	Surface	Absorptivity
White paint	0.12–0.26	Walls	
Whitewash/glossy white	0.21	White/yellow brick tiles	0.30
Bright aluminium	0.30	White stone	0.40
Flat white	0.25	Cream brick tile	0.50
Yellow	0.48	Burl brick tile	0.60
Bronze	0.50	Concrete/red brick tile	0.70
Silver	0.52	Red sand line brick	0.72
Dark aluminium	0.63	White sand stone	0.76
Bright red	0.65	Stone rubble	0.80
Brown	0.70	Blue brick tile	0.88
Light green	0.73	Surroundings	
Medium red	0.74	Sea/lake water	0.29
Medium green	0.85	Snow	0.30
Dark green	0.95	Grass	0.80
Blue/black	0.97	Light coloured grass	0.55
Roof		Sand Gray	0.82
Asphalt	0.89	Rock	0.84
White asbestos cement	0.59	Green leaf	0.85
Cooper sheeting	0.64	Earth (black ploughed field)	0.92
Uncoloured roofing tile	0.67	White leaves	0.20
Red roofing tiles	0.72	Yellow leaves	0.58
Galvanised iron, clean	0.77	Aluminium foil	0.39
Brown roofing tile	0.87	Unpainted wood	0.60
Galvanised iron, dirty	0.89		
Black roofing tile	0.92		

(continued)

Table E.6 (continued)

Surface	Absorptivity	Surface	Absorptivity
Metals			
Polished aluminium/copper	0.26		
New galvanised iron	0.66		
Old galvanized iron	0.89		
Polished iron	0.45		
Oxidized rusty iron	0.38		

Table E.7 Theoretical model for the thermal conductivity of nano-fluids found in literature

Models	Thermal conductivity (k) (W/m K)	Physical models
Maxwell-Eucken [28]	$k_{nf} = k_{bf} \times \frac{[k_p + 2k_{bf} + 2\phi_p(k_p - k_{bf})]}{[k_p + 2k_{bf} - \phi_p(k_p - k_{bf})]}$ Remarks: Spherical particles	Based on the conduction solution through a stationary random suspension of spheres
Bruggeman [29]	$k_{nf} = \frac{[(3\phi - 1)k_p + (2 - 3\phi)k_{bf} + k_{bf}\sqrt{\Delta}]}{4}$ $\Delta = \left[(3\phi_p - 1)\frac{k_p}{k_{bf}} + (2 - 3\phi)\right]^2 + 8\frac{k_p}{k_{bf}}$ Remarks: – Applicable to high volume fraction of spherical particles – Suspension with spherical inclusions	Based on the differential effective medium (DEM) theory to estimate the effective thermal conductivity of composites at high particle concentrations
Hamilton-Crosser [30]	$k_{nf} = k_{bf} \frac{[k_p + (n-1)k_{bf} + \phi(n-1)(k_p - k_{bf})]}{[k_p + (n-1)k_{bf} - \phi(n-1)(k_p - k_{bf})]}$ Remarks: Spherical and non-spherical particles, $n = 3$ (spheres), $n = 6$ (cylinders)	Based on the effective thermal conductivity of a two-component mixture when the ratio of thermal conductivity is more than 100
Wasp [31]	Remarks: Special case of Hamilton and Crosser's model with $n = 3$	Based on effective thermal conductivity of a two-component mixture

Table E.8 Correlation developed for thermal conductivity of nano-fluids

Khanafar and Vafai [32]	$k_{\text{nf}} = k_{\text{bf}} \times \left(1 + 1.0112\varphi_{\text{p}} + 2.4375\varphi_{\text{p}} \times \left(\frac{47}{d_{\text{p}}\text{nm}} \right) - 0.0248\varphi_{\text{p}} \left(\frac{k_{\text{p}}}{0.613} \right) \right)$ Remarks: At ambient temprature	Al ₂ O ₃ -H ₂ O CuO-H ₂ O
	$k_{\text{nf}} = k_{\text{bf}} \times \left[0.9843 + 0.398\varphi_{\text{p}}^{0.7383} \left(\frac{1}{d_{\text{p}}\text{(nm)}} \right)^{0.2246} \left(\frac{\mu_{\text{nf}}(T)}{\mu_{\text{bf}}(T)} \right)^{0.0235} \right. \\ \left. - (3.9517) \times \left(\frac{\varphi_{\text{p}}}{T} \right) + (34.034) \times \left(\frac{\varphi_{\text{p}}^2}{T^3} \right) + (32.509) \times \left(\frac{\varphi_{\text{p}}}{T^2} \right) \right]$ $\mu_{\text{bf}} = 2.414 \times 10^{-5} \times 10^{247.8/(T-140)}$ $0 \leq \varphi_{\text{p}} \leq 10\%, 11 \leq d_{\text{p}} \leq 150 \text{ nm}, 20 \leq T \leq 70 \text{ }^\circ\text{C}$ $\mu_{\text{nf}} = -0.4491 + \frac{28.837}{T} + 0.574\varphi_{\text{p}} - 0.1634\varphi_{\text{p}}^2 + 23.053 \times \left(\frac{\varphi_{\text{p}}^2}{T^2} \right) \\ + 0.0132\varphi_{\text{p}}^3 - 2354.735 \times \left(\frac{\varphi_{\text{p}}}{T^3} \right) + 23.498 \times \left(\frac{\varphi_{\text{p}}^2}{d_{\text{p}}^2} \right) - 3.0185 \times \left(\frac{\varphi_{\text{p}}^3}{d_{\text{p}}^2} \right)$ $1 \leq \varphi_{\text{p}} \leq 9\%, 13 \leq d_{\text{p}} \leq 131\text{nm}, 20 \leq T \leq 70 \text{ }^\circ\text{C}$	

Table E.9 Models of viscosity of nano-fluids

Models	Dynamic viscosity (μ) (kg/m s)	Physical model
Einstein [33]	$\mu_{nf} = \mu_{bf}(1 + 2.5\varphi_p)$ Remarks: – Infinitely dilute suspension of spheres (no interaction between the spheres) – Valid for relatively low particle volume fraction $\varphi_p < 5\%$	– Based on the phenomenological hydro dynamic equations – Considered a suspension containing n-solute particles in a total volume V
Brinkman [34]	$\mu_{nf} = \frac{\mu_{bf}}{(1 - \varphi_p)^{2.5}}$ Remarks: – Spherical particles, – Valid for high moderate particle concentrations – Used Einstein's factor: $(1 + 2.5\varphi_p)$	– Based on Einstein model – Derived by considering the effect of the addition of one solute-molecule to an existing solution
Batchelor [35]	$\mu_{nf} = \mu_{bf}(1 + 2.5\varphi_p + 6.2\varphi_p^2)$ $= \mu_{bf}(1 + \eta\varphi_p + k_H\varphi_p^2)$ Here, Huggins coefficient, $k_H = 6.2$ (5.2 from hydrodynamic effect and 1.0 from Brownian motion) Remarks: – Brownian motion – Isotropic structure	– Based on reciprocal theorem in Stokes flow problem to obtain an expression for the bulk stress due to the thermodynamic forces – Incorporated both effects: hydrodynamic effects and Brownian motion
Lundgren [36]	$\mu_{nf} = \frac{\mu_{bf}}{(1 - 2.5\varphi_p)}$ Remarks: – Dilute concentration of spheres – Random bed of spheres	Based on a Taylor series expansion in terms of φ_p

Table E.10 Viscosity models at room temperature based on experimental data (TiO₂–H₂O, CuO–H₂O and Al₂O₃–H₂O)

Reference	Viscosity, μ	Remarks
Maiga et al. [37]	$\mu_{\text{nf}} = \mu_{\text{bf}}(1 + 7.3\varphi_{\text{p}} + 123\varphi_{\text{p}}^2)$	Least-square curve fitting of Wang et al. [50] data, Al ₂ O ₃ –H ₂ O, $d_{\text{p}} = 28$ nm
Khanafer and Vafai [32]	$\mu_{\text{nf}} = \mu_{\text{bf}}(1 + 0.164\varphi_{\text{p}} + 302.34\varphi_{\text{p}}^2)$	Least-square curve fitting of experimental data (1993, 1999), Al ₂ O ₃ –ethylene glycol, $d_{\text{p}} = 28$ nm
Buongiorno [38]	$\mu_{\text{nf}} = \mu_{\text{bf}}(1 + 5.45\varphi_{\text{p}} + 108.2\varphi_{\text{p}}^2)$	Curve fitting of Pak and Cho [60] data, TiO ₂ –H ₂ O, $d_{\text{p}} = 27$ nm
Khanafer and Vafai [32]	$\mu_{\text{nf}} = \mu_{\text{bf}}(1 + 23.09\varphi_{\text{p}} + 1525.3\varphi_{\text{p}}^2)$	Curve fitting of Pak and Cho [60] data, Al ₂ O ₃ –H ₂ O, $d_{\text{p}} = 13$ nm, $0 \leq \varphi_{\text{p}} \leq 0.04\%$
Nguyen et al. [39]	$\mu_{\text{nf}} = \mu_{\text{bf}}[0.904 \times \exp(0.148\varphi_{\text{p}})]$, $d_{\text{p}} = 47$ nm $\mu_{\text{nf}} = \mu_{\text{bf}}(1 + 0.0025\varphi_{\text{p}} + 0.00156\varphi_{\text{p}}^2)$, $d_{\text{p}} = 37$ nm	Curve fitting of the experimental data, Al ₂ O ₃ –H ₂ O
Nguyen et al. [39]	$\mu_{\text{nf}} = \mu_{\text{bf}}(1.475 - 0.319\varphi_{\text{p}} + 0.051\varphi_{\text{p}}^2 + 0.009\varphi_{\text{p}}^3)$	Curve fitting of the experimental data, CuO–water, $d_{\text{p}} = 29$ nm
Tseng and Lin [40]	$\mu_{\text{nf}} = \mu_{\text{bf}}[13.47 \times \exp(35.98\varphi_{\text{p}})]$	TiO ₂ –H ₂ O, $\mu_{\text{nf}} = \mu_{\text{bf}}[13.47 \times \exp(35.98\varphi_{\text{p}})]$

Table E.11 Effect of temperature and volume fraction on dynamic viscosity of Al₂O₃–H₂O nanofluid

Reference	Viscosity, μ	Remarks
Khanafer and Vafai [32]	$\mu_{nf} = 0.44 - 0.254\phi_p^2 + 0.0368\phi_p^2 + 26.33\frac{\phi_p}{T} - 59.311\frac{\phi_p^2}{T^2}$	Curve fitting of Pak and Cho [60] data, and $d_p = 13$ nm, $20 < T(^{\circ}C) < 70$, $\phi_p = 1.34$ and 2.78% ; Units: mPa s
Nguyen et al. [39]	$\mu_{nf} = \mu_{bf}(1.125 - 0.0007 \times T(^{\circ}C)), \phi_p = 1\%$ $\mu_{nf} = \mu_{bf}(2.1275 - 0.0215 \times T(^{\circ}C) + 0.0002 \times T^2(^{\circ}C)), \phi_p = 4\%$	Units: mPa s
Namburu et al. [41, 42]	$\mu_{nf} = \exp[A \exp(-BT)]$ Here $A = -0.2995\phi_p^3 + 6.7388\phi_p^2 - 55.44\phi_p + 236.11$ $B = (-6.4745\phi_p^3 + 140.03\phi_p^2 - 1478.5\phi_p + 20341) \times 10^{-6}$	Experimental Al ₂ O ₃ –ethylene glycol and water mixture; $1\% < \phi_p < 10\%$, $d_p = 53$ nm, and $238 < T(K) < 323$, Units: mmPa s

Table E.12 Effect of temperature and volume fraction on the dynamic viscosity of TiO₂-H₂O and CuO-H₂O nanofluids

Reference	Viscosity, μ	Remarks
Duangthongsuk and Wongwises [43]	$\mu_{nf} = \mu_{bf}(1.0226 + 0.0477\varphi_p - 0.0112\varphi_p^2); T = 15^\circ\text{C}$ $\mu_{nf} = \mu_{bf}(1.013 + 0.092\varphi_p - 0.015\varphi_p^2); T = 25^\circ\text{C}$ $\mu_{nf} = \mu_{bf}(1.018 + 0.112\varphi_p - 0.0177\varphi_p^2); T = 35^\circ\text{C}$	– Experimental data, TiO ₂ -H ₂ O – $d_p = 21\text{ nm}$, $0.2\% \leq \varphi_p \leq 2\%$ – Units: mPa s
Khanafer and Vafai [32]	$\mu_{nf} = 0.6002 - 0.569\varphi_p + 0.0823\varphi_p^2 + 28.8763\frac{\varphi_p}{T} - 204.2202\frac{\varphi_p^2}{T^2} + 561.3175\frac{\varphi_p^3}{T^3}$	Curve fitting of Pak and Cho [60] data, TiO ₂ -H ₂ O, – $d_p = 27\text{ nm}$, $20 < T(^{\circ}\text{C}) < 70$, $\varphi_p = 0.99, 2.04, 3.16\%$ – Units: mPa-s
Namburu et al. [41, 42]	$\mu_{nf} = \exp[A \exp(-BT)]$ Here $A = 1.8375\varphi_p^2 + 29.643\varphi_p + 165.56$, $B = (4 \times 10^{-6}\varphi_p^2 - 0.001\varphi_p + 0.0186)$	CuO-ethylene glycol and water mixture $1 \leq \varphi_p \leq 6\%$, $d_p = 29\text{ nm}$, $238 < T(K) < 323$ – Units: mmPa s
Kulkarni et al. [44, 45]	$\mu_{nf} = \exp(\frac{A}{T} - B)$ Here $A = 20587\varphi_p^2 + 15857\varphi_p + 1078.3$, $B = -107.12\varphi_p^2 + 53.54\varphi_p + 2.8715$	CuO-H ₂ O, $0.5\% \leq \varphi_p \leq 0.15\%$ $d_p = 29\text{ nm}$ $238 < T(K) < 323$, – Units: mmPa s

Table E.13 Theoretical models and correlations for thermo-physical properties

Properties	References	Theoretical formulae	Correlations																								
Density (kg/m ³)	Pak and Cho [60]	$\rho_{nf} = \rho_p \phi_p + \rho_{bf} (1 - \phi_p)$	$\rho_{nf} = 1001.064 + 2738.6191 \phi_p - 0.2095T, \quad 0 \leq \phi_p \leq 0.4\%, \quad 5 < T(^{\circ}C) < 40$ Curve fitting of Ho et al. [46] measured the density of Al ₂ O ₃ —water nanofluid at different temperatures and nanoparticle volume fraction																								
Specific heat (J/kg K)	Pak and Cho [60]	$C_{nf} = \frac{\phi_p \rho_p C_{pp} + (1 - \phi_p) \rho_{bf} C_{bpf}}{\rho_{bf}}$ $(\rho C_p)_{nf} = (1 - \phi_p)(\rho C_p)_{bf} + \phi_p(\rho C_p)_p$	Vajjha and Das [48] for Al ₂ O ₃ and SiO ₂ , ZnO nanofluids $C_{pmf} = C_{pbf} \left[\frac{A \left(\frac{T}{T_0} \right) + B \left(\frac{C_{pbf}}{C_{pbf}} \right)}{(C + \phi_p)} \right]$ <table><tr><th>Nanofluids</th><th>A</th><th>B</th><th>C</th><th>Max error (%)</th><th>Avg. absolute error (%)</th></tr><tr><td>Al₂O₃</td><td>0.00089</td><td>0.5179</td><td>0.4250</td><td>5</td><td>2.28</td></tr><tr><td>SiO₂</td><td>0.00176</td><td>1.1937</td><td>0.8021</td><td>3.1</td><td>1.5</td></tr><tr><td>ZnO</td><td>0.00046</td><td>0.9855</td><td>0.299</td><td>4.4</td><td>2.7</td></tr></table> $0 \leq \phi_p \leq 0.1\%$ for Al₂O₃ and SiO₂-ethylene glycol and water mixture (60:40 by weight) $0 \leq \phi_p \leq 0.07\%$ for ZnO-ethylene glycol and water mixture (60:40 by weight) $315 < T(K) < 363$	Nanofluids	A	B	C	Max error (%)	Avg. absolute error (%)	Al ₂ O ₃	0.00089	0.5179	0.4250	5	2.28	SiO ₂	0.00176	1.1937	0.8021	3.1	1.5	ZnO	0.00046	0.9855	0.299	4.4	2.7
Nanofluids	A	B	C	Max error (%)	Avg. absolute error (%)																						
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SiO ₂	0.00176	1.1937	0.8021	3.1	1.5																						
ZnO	0.00046	0.9855	0.299	4.4	2.7																						
Thermal expansion coefficient (K ⁻¹)	Khanfer et al. [49] Wang et al. [50], Ho et al. [51]	$\beta_{nf} = \frac{(1 - \phi_p)(\rho \beta)_{bf} + \phi_p(\rho \beta)_p}{\rho_{nf}}$ $\beta_{nf} = (1 - \phi_p)\beta_{bf} + \phi_p\beta_p$	A correlation for the thermal expansion coefficient of Al ₂ O ₃ —water nanofluid as a function of temperature and volume fraction of nanoparticles based on the data presented in Ho et al. (2010) ³⁰ $\beta_{nf} = (-0.479\phi_p + 9.3149 \times 10^{-3}T - \frac{4.7211}{T^2}) \times 10^{-3}, \quad 0 \leq \phi_p \leq 0.04\%, 10 < T(^{\circ}C) < 40$																								
Thermal diffusivity (mm ² /s)		$\alpha_{nf} = \frac{k_{nf}}{\rho_{nf} C_{pmf}}$																									

$\alpha_{nf} = \frac{k_{nf}}{\rho_{nf} C_{pmf}}$ Volume fraction of nanoparticles, k_{nf} thermal conductivity of nanofluids, k_{bf} thermal conductivity of base fluid, k_p Thermal conductivity of nanoparticles, k_H 6.2, Huggins coefficient, n Empirical shape factor, r_p Particle radius, h Inter-particle spacing, t thickness of the nano-layer, T Temperature, $\phi_{p,max}$ maximum volume fraction of nanoparticles, k_{layer} thermal conductivity of the nano-layer
Sub-script f fluid, b / base fluid, p nanoparticle, nf nanofluid

Table E.14 Heat transfer coefficient of nanofluids

References	Nusselt number and heat transfer coefficient	Remarks																					
Seider–Tate equation [52]	$(Nu_{nf})_{th} = 1.86 \times \left(Re_{nf} Pr \frac{D}{L} \right)^{0.14} \left(\frac{\mu_{nf}}{\mu_{bf}} \right)$ $Re_{nf} = \frac{u_m D}{\mu_{nf}} Pr = \frac{(C_p)_{nf} \mu_{nf}}{K_{nf}}, Nu_{nf} = \frac{h_{nf} D}{K_{nf}}$	– Circular tube																					
Pak and Cho [53]	$Nu = 0.021 Re^{0.8} Pr^{0.5}$	– Circular tube – Limited to dilute concentration up to 3% – Ultrafine metallic oxide particles suspended in water (g-Al ₂ O ₃ , TiO ₂) – Mean diameter 13 nm (g-Al ₂ O ₃) and 17 nm (TiO ₂)																					
Xuan and Li [54]	$Nu_{nf} = c_1 (1 + c_2 \phi^m Pe_d^{m_2}) Re_{nf}^{m_3} Pr_{nf}^{m_4}$ $Pe_p = \frac{u_m d_p}{\alpha_{nf}} Re_{nf} = \frac{u_m D}{\mu_{nf}}$ $Pr_{nf} = \frac{\mu_{nf}}{\alpha_{nf}} \alpha_{nf} = \frac{K_{nf}}{(\rho C_p)_{nf}}$	<table><tr><th></th><th>C₁</th><th>C₂</th><th>m₁</th><th>m₂</th><th>m₃</th><th>m₄</th></tr><tr><td>Laminar flow</td><td>0.4328</td><td>11.285</td><td>0.754</td><td>0.218</td><td>0.333</td><td>0.4</td></tr><tr><td>Turbulent flow</td><td>0.0059</td><td>7.6286</td><td>0.6886</td><td>0.001</td><td>0.9238</td><td>0.4</td></tr></table> The case C₂=0 refers to zero thermal dispersion, which just corresponds to the case of the pure base fluid – limited to dilute up to 2%		C ₁	C ₂	m ₁	m ₂	m ₃	m ₄	Laminar flow	0.4328	11.285	0.754	0.218	0.333	0.4	Turbulent flow	0.0059	7.6286	0.6886	0.001	0.9238	0.4
	C ₁	C ₂	m ₁	m ₂	m ₃	m ₄																	
Laminar flow	0.4328	11.285	0.754	0.218	0.333	0.4																	
Turbulent flow	0.0059	7.6286	0.6886	0.001	0.9238	0.4																	
Maiga et al. [55]	Laminar flow $Nu = 0.086 Re^{0.55} Pr^{0.5}$ (For constant wall flux) $Nu_{nf} = 0.28 Re^{0.35} Pr^{0.36}$ (For constant wall temperature) Turbulent flow $(Nu_{nf})_{fd} = 0.085 \times Re^{0.71} Pr^{0.35}$	– Circular tube – Al ₂ O ₃ nanoparticles suspension in water																					
Fotukian and Estahany [56]	Turbulent flow $h_{nf} = \frac{C_{mf} \rho_{nf} u_{nf}^{1/4} (T_{12} - T_{11})}{\pi D L (T_w - T_b)_{LM}}$	– Circular tube CuO- H ₂ O – Turbulent convective heat transfer performance and pressure drop of very dilute (less than 0.24% volume) <table><tr><th>Nnao sized particle</th><th>Mean diameter (nm)</th><th>Density (kg/m³)</th><th>Thermal conductivity (J/kg K)</th><th>Specific heat (W/m K)</th></tr><tr><td>CuO</td><td>30-50</td><td>6350</td><td>69</td><td>535.6</td></tr></table>	Nnao sized particle	Mean diameter (nm)	Density (kg/m ³)	Thermal conductivity (J/kg K)	Specific heat (W/m K)	CuO	30-50	6350	69	535.6											
Nnao sized particle	Mean diameter (nm)	Density (kg/m ³)	Thermal conductivity (J/kg K)	Specific heat (W/m K)																			
CuO	30-50	6350	69	535.6																			

(continued)

Table E.14 (continued)

References	Nusselt number and heat transfer coefficient	Remarks
Qiang and Yimin [57]	Mourontseff numbers Laminar Flow $Mo = \left[1 + \left(11.285 \phi_p^{0.754} \left(\frac{d_p}{a_{pf}} \right)^{0.218} \left(\frac{\rho_p^{0.33} C_{p,p}^{0.4} K_{0.6}^{0.6}}{\mu_{pf}^{0.007}} \right) \right] \right]$	– Friction factor: $f_{pf} = \frac{2P_m D_g^2}{L \dot{m}}$ – Derived from equation of Xuan and Li [54] for fully developed internal laminar and turbulent flow at a specific velocity of 1 m/s.
	Turbulent Flow $Mo = \left[1 + \left(7.6286 \phi_p^{0.6886} \left(\frac{d_p}{a_{pf}} \right)^{0.001} \frac{\rho_p^{0.0238} C_{p,p}^{0.1} K_{0.6}^{0.6}}{\mu_{pf}^{0.2832}} \right) \right]$	
	For single phase flow $f = (1.58 \times \ln Re - 3.82)^{-2}$ $Nu_{pf} = \frac{(0.125f / (Re - 1000)) Pr}{1 + 12.7(0.125f)^{0.5} (Pr^{2/3} - 1)}$	
Duangthongsuk and Wongwises [59]	For each flow rate $f = 0.961 \times (Re^{-0.375} \phi_p^{0.052})$ $Nu_{pf} = 0.074 \times Re_{pf}^{0.707} Pr_{pf}^{0.385} \phi_p^{0.074}$ $Re = \frac{VD}{\mu} \quad Pe = \frac{VD}{a_{pf}} \quad Pr = \frac{\mu_{pf}}{a_{pf}} \quad a_{pf} = \frac{k_{pf}}{\rho_{pf}(C_p)_{pf}}$	Heat Exchanger Al ₂ O ₃ –H ₂ O TiO ₂ –H ₂ O
	$Nu = 1.75 \left(\frac{\mu_{pf}}{\mu} \right)^{0.14} \left[Gz_m + 0.0083 (Gr_m Pr_m)^{0.75} \right]^{1/3}$ Arithmetic mean Graetz number: $Gz_m = \frac{m_c C_{pf}}{k_{pf} L}$; Arithmetic mean Grashof number: $Gr_m = \frac{g D^2 \Delta T}{\mu_{pf}^2}$ where, T = Bulk temperature difference; D = tube diameter; L = length of heated section of the tube.	Heat Exchanger Al ₂ O ₃ –H ₂ O TiO ₂ –H ₂ O
Singh et al. [61]		Flat Plate Collector H ₂ O (basefluid)

(continued)

Table E.14 (continued)

References	Nusselt number and heat transfer coefficient	Remarks
Omid et al. [62]	$h_{FPC} = (Nu)_{nf} \frac{k_{nf}}{D_i}$, $(Nu)_{nf} = \frac{\left(\frac{d_i}{8}\right) \left((Re)_{nf} - 10^3\right) (Pr)_{nf}}{1 + 12.7 \sqrt{\left(\frac{d_i}{8}\right)} \left((Pr)_{nf}^{2/3} - 1\right)}$ for $3 \times 10^3 \leq (Re)_{nf} \leq 5 \times 10^5$ and $0.55 \leq (Pr)_{nf} \leq 2 \times 10^3$ $(Re)_{nf} = \frac{4\dot{m}_{w-}}{\pi D_i \mu_{nf}}$; $(Pr)_{nf} = \frac{\mu_{nf} C_{p,f}}{k_{nf}}$ $\dot{m}_w$ = Mass flow rate in any riser and f = Darcy friction factor. Petukhov correlation for smooth tubes [63] $f = \left[0.79 \ln(Re)_{nf} - 1.64\right]^{-2}$ Colebrook correlation for roughness of the tubes [64] $\frac{1}{\sqrt{f}} = -2 \log \left(\frac{\epsilon/D_i}{3.7}\right) + \frac{2.51}{(Re)_{nf} \sqrt{f}}$ (relative roughness)	Flat Plate Collector Al ₂ O ₃ -H ₂ O TiO ₂ -H ₂ O CuO-H ₂ O
Khairul et al. [65]	$(Nu)_{nf} = \left(2.153 + 0.318(De)^{0.643}\right) Pr^{0.177}$ For $20 < De < 2 \times 10^3$ and $0.7 < Pr < 200$ Deans number: $(De)_{nf} = (Re)_{nf} \sqrt{\frac{d_i}{d_c}}$; Reynold number; $(Re)_{nf} = \frac{4\dot{m}_w}{\pi d_i \mu_{nf}}$ d_c = coil diameter; $d_i = r_{11}$ = Inner tube diameter	Heat Exchanger H ₂ O (basefluid)

(continued)

Table E.14 (continued)

References	Nusselt number and heat transfer coefficient	Remarks
Xin and Ebdian [66]	$(Nu)_{nf} = 3.67 (De)^{0.57} \delta^{0.009} \varphi^{1.004}$ $h_{nf} = \frac{(Nu)_{nf} k_{eff}}{d_i}; k_{eff} = k_{static} + k_{brownian}$ $k_{static} = k_{bf} \left[\frac{k_{np} + 2k_{bf} - 2\varphi(k_{bf} - k_{np})}{k_{np} + 2k_{bf} + \varphi(k_{bf} - k_{np})} \right] \text{ and }$ $k_{static} = (5 \times 10^4) \left(\beta \varphi \rho_{bf} C_{bf} \sqrt{\frac{k_b T}{2 \rho_{np} R_{np}}} \right) f(T, \varphi)$ $\beta = 8.44 \times (100\varphi) e^{-1.07304} \text{ for } 1 \leq \varphi \leq 10\% \text{ (Al}_2\text{O}_3 \text{ nanoparticles)}$ Modeling function: $f(T, \varphi) = (2.82 \times 10^{-2} \varphi + 3.91 \times 10^{-3}) \left(\frac{T}{T_0} \right) - (3.069 \times 10^{-2} \varphi + 3.911 \times 10^{-3})$ Where, φ = Concentration of nanoparticles; and $\delta = \frac{d_i}{u_c}$ T_0 = Reference temperature	Heat Exchanger Al ₂ O ₃ -H ₂ O TiO ₂ -H ₂ O CuO-H ₂ O

$(P_e)_p$ Particle Pecletnumber of the nanoparticle, Re_{nf} Reynolds number of nanofluids, Pr_{nf} Prandlt number of nanofluids, α_{nf} Thermal diffusivity of nanofluids, K_{nf} Thermal conductivity of nanofluids, D Tube diameter, d_p Particle diameter, u fluid velocity, A cross-section area of the tube, D diameter of the tube, L tube length, T_{b1} inlet bulk temperature (K), T_{b2} exit bulk temperature (K), T_w wall temperature of the tube (K), $(T_w - T_b)_{LM}$ logarithmic mean temperature difference in which T_w is the wall temperature that is the average of ten measured temperatures on tube wall at different positions. P_{nf} Pressure drop of the pressure drop test section, L Length of the pressure drop test section, g Acceleration gravity, f friction factor, volume concentration is $\varphi_v [1/100/\varphi_m ((\rho_p/\rho_w) + 1)] \times 100\%$

Appendix F

List of Embodied Energy Coefficients

Material	MJ/kg	MJ/m ³
Aggregate, general	0.10	150
Virgin rock	0.04	63
River	0.02	36
Aluminium, virgin	191	515,700
Extruded	201	542,700
Extruded, anodised	227	612,900
Extruded, factory painted	218	588,600
Foil	204	550,800
Sheet	199	537,300
Aluminium, recycled	8.1	21,870
Extruded	17.3	46,710
Extruded, anodised	42.9	115,830
Extruded, factory painted	34.3	92,610
Foil	20.1	54,270
Sheet	14.8	39,960
Asphalt (paving)	3.4	7140
Bitumen	44.1	45,420
Brass	62.0	519,560
Carpet	72.4	–
Felt underlay	18.6	–
Nylon	148	–
Polyester	53.7	–
Polyethylterephthalate (PET)	107	–
Polypropylene	95.4	–
Wool	106	–
Cement	7.8	15,210
Cement mortar	2.0	3200
Fibre cement board	9.5	13,550

(continued)

(continued)

Material	MJ/kg	MJ/m ³
Soil-cement	0.42	819
Ceramic		–
Brick	2.5	5170
Brick, glazed	7.2	14,760
Pipe	6.3	–
Tile	2.5	5250
Concrete		–
Block	0.94	–
Brick	0.97	–
GRC	7.6	14,820
Paver	1.2	–
Pre-cast	2.0	–
Ready mix, 17.5 MPa	1.0	2350
30 MPa	1.3	3180
40 MPa	1.6	3890
Roofing tile	0.81	–
Copper	70.6	631,160
Earth, raw		–
Adobe block, straw stabilised	0.47	750
Adobe, bitumen stabilised	0.29	–
Adobe, cement stabilised	0.42	–
Rammed soil cement	0.80	–
Pressed block	0.42	–
Fabric		–
Cotton	143	–
Polyester	53.7	–
Glass	66.2	–
Float	15.9	40,060
Toughened	26.2	66,020
Laminated	16.3	41,080
Tinted	14.9	375,450
Insulation		–
Cellulose	3.3	112
Fibreglass	30.3	970
Polyester	53.7	430
Polystyrene	117	2340
Wool (recycled)	14.6	139
Lead	35.1	398,030
Linoleum	116	150,930
Paint	90.4	118 per litre

(continued)

(continued)

Material	MJ/kg	MJ/m ³
Solvent based	98.1	128 per litre
Water based	88.5	115 per litre
Paper	36.4	33,670
Building	25.5	–
Kraft	12.6	–
Recycled	23.4	–
Wall	36.4	–
Plaster, gypsum	4.5	6460
Plaster board	6.1	5890
Plastics		–
ABS	111	–
High density polyethylene (HDPE)	103	97,340
Low density Polyethylene (LDPE)	103	91,800
Polyester	53.7	7710
Polypropylene	64.0	57,600
Polystyrene, expanded	117	2340
Polyurethane	74.0	44,400
PVC	70.0	93,620
Rubber		–
Natural latex	67.5	62,100
Synthetic	110	–
Sand	0.10	232
Sealants and adhesives		–
Phenol formaldehyde	87.0	–
Urea formaldehyde	78.2	–
Steel, recycled	10.1	37,210
Reinforcing, sections	8.9	–
Wire rod	12.5	–
Steel, virgin, general	32.0	251,200
Galvanised	34.8	273,180
Imported, structural	35.0	274,570
Stone, dimension		–
Local	0.79	1890
Imported	6.8	1890
Straw, baled	0.24	30.5
Timber, softwood		–
Air dried, roughsawn	0.3	165
Kiln dried, roughsawn	1.6	880
Air dried, dressed	1.16	638

(continued)

(continued)

Material	MJ/kg	MJ/m ³
Kiln dried, dressed	2.5	1380
Mouldings, etc.	3.1	1710
Hardboard	24.2	13,310
MDF	11.9	8330
Glulam	4.6	2530
Particle bd	8.0	–
Plywood	10.4	–
Shingles	9.0	–
Timber, hardwood		–
Air dried, roughsawn	0.50	388
Kiln dried, roughsawn	2.0	1550
Vinyl flooring	79.1	105,990
Zinc	51.0	364140
Galvanising, per kg steel	2.8	–

Appendix G

Heating Values of Various Combustibles and their Conversion Efficiencies

Fuel	Heating value (kJ/kg)	Efficiency of device
Coal coke	29,000	70
Wood	15,000	60
Straw	14,000–16,000	60
Gasoline	43,000	80
Kerosene	42,000	80
Methane (natural gas)	50,000	80
Biogas (60% methane)	20,000	80
Electricity	–	95

Appendix H

Steam table for saturation vapor pressure

Temp. (K)	P (N/m ²)	Temp. (K)	P (N/m ²)	Temp. (K)	P (N/m ²)
273	610.8	304	4491.0	334	20,860.0
274	656.6	305	4743.0	335	21,840.0
275	705.5	306	5029.0	336	22,860.0
276	757.6	307	5318.0	337	23,710.0
277	812.0	308	5622.0	338	25,010.0
278	871.8	309	5940.0	339	26,150.0
279	934.5	310	6274.0	340	27,330.0
280	1001.2	311	6624.0	341	28,560.0
281	1072.0	312	6991.0	342	29,840.0
282	1147.2	313	7375.0	343	31,160.0
283	1227.0	314	7777.0	344	32,530.0
284	1311.6	315	8198.0	345	33,960.0
285	1401.4	316	8639.0	346	35,430.0
286	1496.5	317	9100.0	347	36,960.0
287	1597.3	318	9583.0	348	38,550.0
288	1703.9	319	10,086.0	349	40,190.0
289	1816.8	320	10,612.0	350	41,890.0
290	1936.2	321	11,162.0	351	43,650.0
291	2062.0	322	11,736.0	352	45,470.0
292	2190.0	323	12,335.0	353	47,360.0
293	2337.0	324	12,961.0	354	49,310.0
294	2485.0	325	13,613.0	355	51,350.0
295	2642.0	326	14,340.0	356	53,420.0
296	2808.0	327	15,002.0	357	55,570.0
297	2982.0	328	15,641.0	358	57,800.0
298	3166.0	329	16,511.0	359	60,110.0
299	3360.0	330	17,313.0	360	62,490.0
300	3564.0	331	18,147.0	361	64,950.0

(continued)

(continued)

Temp. (K)	P (N/m ²)	Temp. (K)	P (N/m ²)	Temp. (K)	P (N/m ²)
301	3778.0	332	19,016.0	362	67,490.0
302	4004.0	333	19,920.0	363	70,110.0
303	4241.0				

Appendix I

Physical properties of some liquids

Liquid	Density (kg/m ³)	Viscosity $\times 10^3$ (Ns/m ²)	Melting point (K)	Boiling point (K)	Thermal conductivity (W/m K)	Specific heat (J/Kg K)	Latent heat $\times 10^4$ (J/kg)	Heat of vaporization $\times 10^4$ (J/kg)
Acetic acid	1049	1.219	290	391	0.180	1960	18.1	39
Acetone	780	0.329	178	330	0.161	2210	8.2	52
Ammonia	665	–	–	–	0.558	4606	–	–
Crude oil	800	1.379	–	–	0.155	–	–	–
Ethyl alcohol	789	1.197	156	352	0.177	2500	10.4	85
Glycerine	1262	1495	293	563	0.270	2400	19.9	83
Mercury	13,546	1.552	234	630	7.6	140	1.17	29
Olive oil	920	85	–	570	0.17	1970	–	–
Paraffin oil	800	1000	–	–	0.15	2130	–	–
Turpentine	870	1.49	263	429	0.136	1760	–	29
Sea water	1020	1.02	264	377	–	3900	33.0	–
Water	998	1.00	273	373	0.591	4190	33.4	226

Appendix J

Derivation of exergy formulae [67] (Fig. J.1).

$$(\Delta S)_{\text{body}} = \int_T^{T_a} \frac{C_p dT}{T} = C_p \ln\left(\frac{T_a}{T}\right) \quad (\text{J.1})$$

$$(\Delta S)_{\text{HE}} = 0 \quad (\text{J.2})$$

$$(\Delta S)_{\text{ambient}} = \frac{Q - W}{T_a} \quad (\text{J.3})$$

On adding Eqs. (J.1)–(J.3), one can get

$$\begin{aligned} (\Delta S)_{\text{body}} + (\Delta S)_{\text{HE}} + (\Delta S)_{\text{ambient}} &= C_p \ln\left(\frac{T_a}{T}\right) + \frac{Q - W}{T_a} \\ (\Delta S)_{\text{universe}} &= C_p \ln\left(\frac{T_a}{T}\right) + \frac{Q - W}{T_a} \end{aligned} \quad (\text{J.4})$$

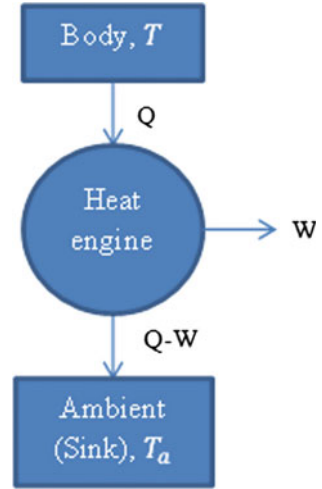
By entropy principle, $(\Delta S)_{\text{universe}} \geq 0$

Therefore, from Eq. (J.4), one can get

$$\begin{aligned} C_p \ln\left(\frac{T_a}{T}\right) + \frac{Q - W}{T_a} &\geq 0 \\ W &\leq Q + T_a C_p \ln\left(\frac{T_a}{T}\right) \\ W_{\text{max}} &= C_p \left[(T - T_a) - T_a \ln\left(\frac{T_a}{T}\right) \right] \end{aligned} \quad (\text{J.5})$$

Hence, W_{max} between glass and ambient can be expressed as

Fig. J.1 Maximum work obtainable



$$W_{\max 1} = C_p \left[(T_g - T_a) - T_a \ln \left(\frac{T_a}{T_g} \right) \right] \quad (\text{J.6})$$

Similarly, $W_{\max}$ between basin water and ambient can be expressed as

$$W_{\max 2} = C_p \left[(T_w - T_a) - T_a \ln \left(\frac{T_a}{T_w} \right) \right] \quad (\text{J.7})$$

Eqs. (J.7)–(J.6) gives,

$$W_{\max 1} - W_{\max 2} = C_p \left[(T_w - T_g) - T_a \ln \left(\frac{T_w}{T_g} \right) \right] \quad (\text{J.8})$$

$$\text{Exergy} = C_p \left[(T_w - T_g) - T_a \ln \left(\frac{T_w}{T_g} \right) \right] \quad (9)$$

Since, $C_p = hA$; Therefore,

$$\text{Exergy} = h \left[(T_w - T_g) - T_a \ln \left(\frac{T_w}{T_g} \right) \right] A \quad (10)$$

where,

A area, C_p specific heat, HE-heat engine, h heat transfer coefficient, m mass, Q heat taken from the system, ΔS entropy change, T -body temperature, T_a ambient temperature, T_g glass cover temperature, T_w water temperature, $W_{\max 1}$ maximum work output for $(T_g - T_a)$, $W_{\max 1}$ maximum work output for $(T_g - T_a)$, $W_{\max 2}$ maximum work output for $(T_w - T_a)$.

Glossary

Absorber plate A component of the solar flat-plate collector that absorbs solar radiation and converts it into heat.

Absorptance The ratio between the amount of radiation absorbed by a surface (absorber) and the total amount of solar radiation striking the surface.

Acceptance angle Half of the angular aperture of an optical system.

Active solar still Water in a basin is heated through the glass cover as well as by an external source such as flat-plate collector.

Albedo Ratio of the amount of light reflected by a surface to the light falling onto it.

Altitude Height of the Sun in a vertical plane at altitude angle.

Altitude angle The Sun's rays make an angle above the horizontal plane as measured in a vertical plane

Ampere Electrical current a measure of flowing electrons.

Anemometer An instrument used for measuring the wind speed.

Antifreeze A substance added to water to lower its freezing point. Solar water heaters usually use a mixture of water and propylene glycol instead of water to prevent freezing.

Angle of incidence An angle formed by a ray incident on a surface and a perpendicular to the surface at the point of incidence.

Annual solar saving The annual energy savings due to using solar-energy devices.

Aperture In optics, a hole or an opening through which solar radiation travels.

Array Any number of photovoltaic modules connected together electrically to provide a single electrical output. An array is a mechanically integrated assembly of modules or panels together with a support structure (including foundation and other components, as required) to form a free-standing field-installed unit that produces DC power.

Atmosphere of Earth A layer of gases surrounding the planet Earth and retained by Earth's gravity. The atmosphere protects (i) living organism (life on Earth) by absorbing ultraviolet solar radiation (UV radiation), (ii) warming the surface

through heat retention (greenhouse effect), and (iii) reducing temperature extremes between day and night (*i.e.*, diurnal temperature variation).

Audit An energy audit seeks energy inefficiencies and prescribes improvement.

Azimuth The horizontal angle between the Sun and due south in the northern hemisphere or between the Sun and due north in the southern hemisphere.

Balance of system (BOS) A term used in the field of photovoltaics that represents all components and costs other than the PV modules.

Battery A collection of cells that store electrical energy each cell converts chemical energy into electricity or *vice versa* and is interconnected with other cells to form a battery for storing useful quantities of electricity.

Beam radiation This is radiation propagating along the line joining the receiving surface and the Sun. It is also known as direct radiation.

Black body A perfect absorber and emitter of radiation. A cavity is a perfect black body. Lampblack is close to a black body, whereas aluminium (polished) is both a poor absorber and emitter of radiation.

Blackbody radiation This is energy converted electro-dynamically from the black body's pool of internal thermal energy at any temperature greater than absolute zero.

Blackened surface See **absorber plate**.

Capital-recovery factor (CRF) The ratio of a constant annuity to the present value of receiving that annuity for a given length of time.

Carbon dioxide (CO₂) A colorless, odorless gas formed during normal human breathing. It is also emitted by combustion activities used to produce electricity. CO₂ is a major cause of the greenhouse effect, *i.e.*, the trapping of radiant energy near the Earth's surface.

Cash-flow diagram This is a tool used by accountants and engineers to represent the transactions that will take place over the course of a given project by including initial investments, maintenance costs, projected earnings or savings resulting from the project, as well as salvage and resale value of equipment at the end of the project.

Cell A device that generates electricity traditionally consisting of two plates or conducting surfaces placed in an electrolytic fluid.

Celsius The international temperature scale in which water freezes at 0 [°] and boils at 100 [°] and named after Anders Celsius.

Circuit A system of conductors (*i.e.*, wires and appliances) capable of providing a closed path for electric current.

Clear sky A sky condition with few or no clouds usually taken as the sky being covered only two tenths by clouds. Clear skies have high luminance and high radiation and create strong shadows relative to more cloudy conditions. The sky is brightest nearest the Sun, whereas away from the Sun it is approximately three times brighter at the horizon than at the zenith.

Cogeneration The joint production of heat and work, most often electricity and heat.

Collector The name given to a device that converts incoming solar radiation to heat.

Collector efficiency The ratio of useful (heat) energy converted by the solar collector to the radiation incident on the device.

Collector-efficiency factor (F') The ratio of actual rate of heat transfer to the rate of heat transfer if the absorber plate were at fluid temperature.

Collector plate A component of the solar flat-plate collector that absorbs solar radiation and converts it into heat.

Collector-tilt angle The angle between the horizontal plane and the surface of the solar collector.

Concentrating collector A solar collector that reflects solar radiation (direct) to an absorber plate to produce high temperatures.

Concentration ratio The ratio of aperture area to receiver area.

Condensation The process of vapor changing into the liquid state. Heat is released in the process.

Conductivity The quality or power of conducting electricity or heat.

Convection The mode of heat transfer due to the motion of the fluid itself.

Convective zone The range of the radii of a star, Sun in which energy is transported primarily by convection.

Conservation of energy The total amount of energy in any closed system remains constant.

Crystalline silicon A type of PV cell made from a single crystal or polycrystalline slices of silicon.

Cost-benefit analysis (B/C) A process by which business decisions are analyzed.

Current The flow of electrons through the conductor.

Dark current The constant response (current) exhibited by a receptor of radiation (e.g., a solar cell) during periods when it is not actively being exposed to light.

Declination The angle of the Sun north or south of the equatorial plane.

Density Weight (mass [kg]) per unit volume.

Diffuse radiation The solar radiation reaching the surface due to reflection and scattering effect.

Diffusion length The mean distance through which a free electron or hole is moved before recombining with another holes or electrons.

Direct current (DC) The complement of AC, or alternating current, presents one unvarying voltage to a load. This current is standard in automobiles.

Direct radiation The radiation from the Sun's rays this radiation can be focused.

Earth The third planet from the Sun and the densest and fifth largest of the eight planets in the solar system.

Efficiency The ratio of output power (or energy) to input power (or energy) expressed as a percentage.

Electromagnetic spectrum The entire range of wavelengths or frequencies of electromagnetic radiation extending from gamma rays to the longest radio waves including visible light.

Elevation The height of a geographic location above a fixed reference point, i.e., the Earth's sea level as an equipotential gravitational surface.

Emissivity The ratio of the radiant energy emitted by a body to that emitted by a perfect black body.

Embodied energy The amount of energy required to produce an object in its present form, e.g., an inflated balloon's embodied energy includes the energy required to manufacture it and inflate it.

Energy The ability to do work.

Energy density Energy per unit area.

Energy intensity The ratio of energy use in a sector to the activity in that sector, e.g., the ratio of energy used for constant dollar production in manufacturing.

Energy storage A device or a physical medium that stores some form of energy to perform some useful operation at a later time.

Evacuated-tube collector A solar collector that uses a vacuum to insulate the absorber plate. The collector fluid flows through an absorber tube, which is contained inside an evacuated glass cylinder.

EVA Ethylene-vinyl-acetate foil, a material used in module production for covering the cells.

Exergy The available energy to be used for work. It refers to the second law of thermodynamics.

Extra-terrestrial region An enclosure (space) between the top of the atmosphere and the Sun.

Flat-plate collector A solar-collection device for gathering the Sun's heat that consist of a shallow metal container covered with one or more layers of transparent glass or plastic; either air or a liquid is circulated through the cavity of the container, the interior of which is painted black and the exterior well insulated.

Fill factor (FF) For an I–V curve, the ratio of the maximum power to the product of the open-circuit voltage and the short-circuit current. “Fill factor” is a measure of the “squareness” of the I–V curve.

Focusing collector A solar collector that reflects solar radiation (direct) to an absorber plate to produce high temperatures.

Forced circulation The same as **forced mode**.

Forced convection A type of heat transport in which fluid motion is generated by an external source (e.g., a pump, fan, suction device, etc.).

Forced mode Hot water from a flat-plate collector is moved to an insulated storage tank by a water pump.

Frequency $f = c/\lambda$ or $f = E/h$.

Free convection (natural convection) A type of heat transport only by density differences in the fluid occurring due to temperature gradients.

Glazing A transparent sheet that allows solar radiation to pass through but restricts the passage of heat.

Global radiation The sum of direct, diffuse, and reflected radiation.

Greenhouse (glasshouse) A building (house) made of transparent materials where plants are grown. These structures range in size from small sheds to very large buildings.

Greenhouse effect Global warming resulting from the absorption of infrared solar radiation by carbon dioxide and other traces of gases present in the atmosphere. (The term is a misnomer in that in actual greenhouses the warming comes primarily from a restriction of air flow.)

Greenhouse gases These are gases that contribute to the greenhouse effect by absorbing infrared radiation in the atmosphere. These gases include carbon dioxide, nitrous oxide, methane, water vapor, and a variety of chlorofluorocarbons (CFCs).

Heat capacity or thermal capacity The quantity of heat required to raise 1 kg of a substance by 1 °C.

Heat exchanger A device that passes heat from one substance to another. In a solar hot-water heater, for example, the heat exchanger takes heat harvested by a fluid circulating through the solar panel and transfers it to domestic hot water.

Heat loss An unwanted decrease in the amount of heat contained in a space.

Heat pipe (heat pin) A heat-transfer device that combines the principles of both thermal conductivity and phase transition to efficiently manage the transfer of heat between two solid interfaces.

Heat-removal factor (F_R) The ratio of actual rate of heat transfer to the rate of heat transfer if the absorber plate were at fluid-inlet temperature.

Heat transfer A discipline (mechanism) of thermal engineering that concerns the exchange of thermal energy from one physical system to another.

Heat-transfer coefficient The proportionality constant coefficient between the heat flux (a heat flow per unit area [q/A]) and the temperature difference, ΔT (the thermodynamic driving force for the flow of heat). It is also inverse of thermal resistance.

Hour angle The angular displacement of the Sun east or west of the local meridian due to rotation of the Earth on its axis at $15^\circ/\text{h}$ with morning being a negative number and afternoon being a positive number.

I–V curve The plot of current versus voltage characteristics of a solar cell, module, or array. I–V curves are used to compare various solar cell modules and to determine their performance at various levels of insolation and temperatures.

Incident radiation The quantity of radiant energy striking a surface per unit time and unit area.

Inflation rate The rate of increase of a price index (consumer price index) or the percentage rate of change in price level over time. The rate of decrease in the purchasing power of money is approximately equal.

Infrared radiation (IR) The part of the electromagnetic radiation (waves) whose wavelength lies between 0.75 and 1000 μm .

Insolation (or incident solar radiation) The amount of sunlight falling on a surface.

Instantaneous efficiency The ratio of the rate of useful energy to the rate of input energy.

Insulation A material that keeps energy from crossing from one place to another: on electrical wire, it is the plastic or rubber that covers the conductor; in a building, insulation makes the walls, floor, and roof more resistant to the outside (ambient) temperature.

Inverter An electrical device that changes direct current (DC) into alternating current (AC).

Irradiance This term is used when the electromagnetic radiation is incident on the surface. It has an SI unit of W/m^2 . In this case, the total amount of radiation present at all frequencies.

Irradiation Same as **irradiance**.

Irreversible process A process that is not reversible is referred to as “irreversible.” It refers to the second law of thermodynamics.

Joule The unit of energy or work. One joule is equal to one Watt-second.

Kilowatt (kW) 1000 W; energy consumption at a rate of 1000 J/s.

Kilowatt-hour (kWh) This is 1 kilowatt of power used for 1 hour. A typical house uses 750 kWh/mo.

Laminar flow (streamline flow) This occurs when a fluid flows in parallel layers with no disruption between the layers.

Latent-heat storage This uses a phase-change material (PCM) as a storage medium.

Latitude The angular position of a location north or south of the equator.

Life-cycle costing A method for estimating the comparative costs of alternative energy or other systems. Life-cycle costing takes into consideration such long-term costs as energy consumption, maintenance, and repair.

Life-cycle costs The entire cost of an energy device, including the capital cost in present dollars and the cost and the benefits, discounted to the present.

Local time (mean solar time) Our clocks use mean solar time (local time), which is uniform, being averaged out over 1 year (365.243... days).

Longitude The angular position east or west of Greenwich.

Mean solar time (local time) Our clocks use **mean solar time**, which is uniform, being averaged out over 1 year (365.243... days).

Medium-temperature solar collector A solar-thermal collector designed to operate in the temperature range of 80–100 °C.

Megawatt (MW) 1,000,000 watts.

Module The smallest self-contained, environmentally protected structure housing interconnected photovoltaic cells providing a single direct current (DC) electrical output.

Monthly mean daily insolation The average solar energy per square meter available per day of a given month.

Natural convection (same as free convection) The natural convection of heat through the fluid in a body that occurs when warm, less dense fluid rises and cold, dense fluid sinks under the influence of gravity.

Night-sky radiation A reversal of the daytime-insolation principle. Just as the Sun radiates energy during the day through the void of space, so also heat energy can travel unhindered at night from the Earth's surface back into space. On a clear night, any warm object can cool itself by radiating long-wave heat energy to the cooler sky. On a cloudy night, the cloud cover acts as an insulator and prevents the heat from travelling to the cooler sky.

Nonrenewable energy sources Energy derived from finite and static stocks of energy.

Nuclear fusion This is the process by which two or more atomic nuclei of hydrogen join together, or "fuse," to form a single heavier nucleus of helium. This occurs at the centre core of the Sun and is usually accompanied by the release of large quantities of energy.

Number of transfer units (NTU) A method used to calculate the rate of heat transfer in counter-current heat exchangers.

Nusselt number The ratio of convective to conductive heat transfer across (normal to) the boundary.

Open-circuit voltage (V_{oc}) The maximum possible voltage across a solar module or array. Open circuit voltage occurs in sunlight when no current is flowing.

Orientation The arrangement of windows on a building or solar device along a given axis to face in a direction best suited to absorb solar radiation.

Overall heat-transfer coefficient The inverse of total thermal resistance across all boundary layers.

Overall thermal efficiency The ratio of useful energy to the input energy for a given period. It can be expressed on a hourly, daily, monthly, and yearly basis.

Parabola Reflective material manufactured in a geometrically curved shape to focus sunlight on a single point.

Parabolic mirror A device with a large, shiny, curved surface that focuses solar radiation on a specific point.

Passive solar still In this case, the water in the basin is only heated through the glass cover of solar still.

Passive solar water heater A solar water-heating system with natural/thermosyphon circulation.

Payback period (payback time/payment time) The length of time required to recover the cost of an investment.

Payback time Same as **payback period/payment time**.

Payout time Same as **payback period/payback time/payment time**.

Peak sunshine hours The number of hours per day during which solar radiation averages 1000 W/m^2 .

Peak watt (W_p) Power output of a PV module under standard test condition, i.e., 1000 W/m^2 and 25°C .

Photon The elementary particle of electromagnetic energy; light (Greek photos, light).

Photovoltaic array A number of PV modules that are electrically connected in series or in parallel to provide the required rated power.

Photovoltaic-conversion efficiency The ratio of the electric power produced by a photovoltaic device to the power of the sunlight incident on the device.

Photovoltaic device A device that converts light directly into DC electricity.

Photovoltaic effect Same as **photovoltaic device**.

Photovoltaic module This is the basic building block of a photovoltaic device, which consists of a number of interconnected solar cells.

Photovoltaics (PVs) A technology for using semiconductors to directly convert light into electricity.

Photovoltaic thermal A system to produce electrical as well as thermal energy

Phase-change materials (PCM) These are substances with a high heat of fusion during melting and solidifying at a certain temperature. They are capable of storing and releasing large amounts of energy as per requirement.

Power The rate at which energy is consumed or produced. The unit is the Watt.

PV (photovoltaics) A technology for using semiconductors to directly convert light into electricity.

Potential energy The energy an object possesses as a result of its elevation in a gravitational field.

ppm Parts per million.

Present-value factor (PVF) The ratio of present value to future value for a given lifetime of system.

PV See **photovoltaic**.

PVT A photovoltaic thermal system used to produce electrical as well as thermal energy.

Pyranometer This is a type of actinometer used to measure broadband (total) solar irradiance on a planar surface. It is a sensor designed to measure the solar-radiation flux density (in watts per metre square) from a field of view of 180° .

Pyrheliometer An instrument for the direct measurement of normal solar irradiance.

Pyrolysis Canonization at high-process temperature.

Radiant energy (radiant exitance or radiant emittance) This is energy in the form of electromagnetic waves emerging from the surface. It has an SI unit of W/m^2 . In this case, the total amount of radiation present at all frequencies.

Radiant exitance Also known as **radiant self-exitance**: Same as **radiant energy**.

Radiant exposure Same as **irradiation**.

Radiant self-exitance Same as **Radiant energy**

Radiation **This is** electromagnetic waves that directly transport energy through space. Sunlight is a form of radiation.

Reflectivity The ratio of radiant energy reflected by a body to that falling upon it.

Relative humidity A term used to describe the amount of water vapor in a mixture of air and water vapor.

Renewable energy (sources) An energy source that renews itself without effort; fossil fuels, once consumed, are gone forever, whereas solar energy is renewable in that the sunlight we harvest today has no effect on the sunlight we can harvest tomorrow.

Reversible process This is a process that can be reversed after it has taken place without change in either the system or its surroundings. It also refers to the first law of thermodynamics.

Salvage value An estimated value that an asset will realize upon its sale at the end of its useful life.

Selective surface A special surface that has high absorptions and low emissions; a means of increasing its operation temperature and/or efficiency.

Selectivity The ratio of radiation absorption (*alpha*) to radiation emission (*epsilon*).

Sensible heat storage A heat-storage system that uses a heat storage medium and where the addition or removal of heat results in a change in temperature.

Short-circuit current (I_{sc}) Current across the terminals when a solar cell or module in strong sunlight is not connected to a load (measured with ammeter).

Short-wavelength radiation This varies from 0.26 to 2.6 μm .

Silicon A semiconductor material commonly used make PV cells

Silicon wafer Same as **wafer**.

Single-crystal structure A material having a crystalline structure such that a repeatable or periodic molecular pattern exists in all three dimensions.

Sinking-fund factor (SFF) The ratio of the annuity payment (unacost) to a specified sum at some given future time period (future value).

Solar-altitude angle The Sun's angle above the horizon as measured in a vertical plane.

Solar-azimuth angle The horizontal angle between the sun and due south in the northern hemisphere or between the Sun and due north in the southern hemisphere.

Solar cell A device that converts light energy or solar radiation (photons) directly into DC electricity.

Solar-cell module Groups of encapsulated solar cells framed in a glass or plastic units, usually the smallest unit of solar electric equipment available to the consumer.

Solar collector A device that gathers and accumulates solar radiation to produce heat.

Solar concentrator A device that uses a reflective surface in a planar, parabolic trough or parabolic-bowl configuration to concentrate solar radiation onto a smaller surface.

Solar constant This is a measure of solar-flux density. It is the amount of incoming solar electromagnetic radiation per unit area that would be incident on a plane perpendicular to the rays in the extra-terrestrial region at the mean distance from the Sun to the Earth (one astronomical unit [AU]). The accepted value is approximately 1367 W/m^2 .

Solar-declination angle The angle of the Sun north or south of the equatorial plane.

Solar distillation The process of producing drinking water or to produce pure water for lead acid batteries, laboratories, and hospitals and in producing commercial products—such as rose water—by using solar energy.

Solar distiller A device used for the purification of brackish/saline water by using solar energy.

Solar temperature An effective ambient-air temperature, which includes the effect of solar intensity and long-wavelength radiation exchange between ambient and sky.

Solar electricity Electricity that is obtained by using solar energy.

Solar energy The electromagnetic radiation generated by the Sun.

Solar fraction Same as **solar-savings fraction**.

Solar-incident angle The angle at which an incoming solar beam strikes a surface.

Solar pond This is a pool of saltwater that acts as a large-scale solar thermal-energy collector with integral heat storage for supplying thermal energy such as process heating, desalination, refrigeration, drying, and solar-power generation. It has three layers (i) UCZ: upper- **convective** zone; (ii) NCZ: **non-convective** zone, and (iii) LCZ: lower-**convective** zone.

Solar radiation The radiant energy received from the Sun from both direct and diffuse or reflected sunlight.

Solar spectrum The total distribution of electromagnetic radiation emitted from the Sun.

Solar still A device consisting of one or several stages in which brackish water is converted to potable water by successive evaporation and condensation with the aid of solar heat.

Solar-savings fraction (solar fraction) The amount of energy provided by solar technology divided by the total energy required.

Solar time This is the passage of time based on the Sun's position in the sky. The fundamental unit of solar time is the day. There are two types of solar time: apparent solar time (sundial time) and mean solar time (clock time).

Solar wall-azimuth angle The angle between normal to the wall and the projection of the Sun's rays onto a horizontal plane.

Solar water heater A water heater that depends on solar radiation as its source of power.

Specific heat The quantity of heat required to raise 1 kg of a substance by 1 °C (J/kg/°C).

Specific humidity The ratio of water vapor to dry air in a particular mass.

Spectral irradiance The total radiation for each frequency in the spectrum separately. It is expressed in SI units W/m^3 or commonly $\text{W m}^{-2} \text{nm}^{-1}$ or $\text{W m}^{-2} \mu\text{m}^{-1}$.

Standard test condition The condition having 1000 W/m^2 of solar radiation and 25°C ambient air temperature with an air mass of 1.5.

Sun An almost perfectly spherical star at the center of the solar system that consists of hot plasma interwoven with magnetic fields.

Sun-Earth angles All angles defined at Earth with respect to the Sun.

Sun's rays Rays of sunlight that appear to radiate from a single point in the sky.

Surface-azimuth angle An angle between line due south and the projection of normal to inclined plane in a horizontal plane.

Sustainable Material or energy sources that, if managed carefully, will provide at the current level indefinitely.

Temperature The degree of hotness or coldness measured on one of several arbitrary scales based on some observable phenomenon (such as expansion).

Terrestrial region An enclosure (space) between Earth and bottom of atmosphere.

Thermal-air conductance This is equivalent to the heat-transfer coefficient for an air gap.

Thermal capacity Same as **heat capacity**.

Thermal conductivity The property of a material's ability to conduct heat.

Thermal diffusivity Another physical property of material that refers to how quickly heat diffuses through material.

Thermal mass A material used to store heat, thereby slowing the temperature variation within a space. Typical thermal mass materials include concrete, brick, masonry, tile, mortar, water and rock, or other materials with high heat capacity.

Thermal storage Any of several techniques to store heat energy by using either the heat capacity of material, the latent heat of phase change, or the heat of chemical dissociation.

Thermosyphon A close-loop system in which water automatically circulates between a solar collector and a water-storage tank above it due to the natural difference in density between the warmer and cooler portions of a liquid.

Thin-film solar cell (TFSC)/thin-film photovoltaic cell (TFPV) This is a solar cell made by depositing one or more thin layers (thin film) of photovoltaic material on a substrate. The thickness range of such a layer is wide and varies from a few nanometers to tens of micrometers.

Tilt angle The angle at which a solar collector is tilted upward from the horizontal surface for maximum heat collection.

Total radiation The sum of beam and diffuse radiation.

Transfer medium A substance (air, water, or antifreeze solution) that carries heat from a solar collector to a storage area or from a storage area to in a collector.

Transmittance The ratio of solar radiation transmitted through a glazing to the total radiant energy falling on its surface.

Uniform end-of-year annual amount (uniform annual cost; unacost) An annualized sum of all relevant costs just like the amount of an installment loan payment.

Unacost (uniform annual cost) Same as **uniform end-of-year annual amount**.

U-value The amount of heat that flows in or out of a wall at steady state, in 1 hour, when there is a 1° difference in temperature between air inside and outside the building.

Ultraviolet radiation A portion of the electromagnetic radiation in the wavelength range of 4 to 400 nanometers.

Visible light (radiation) An electromagnetic radiation with a wavelength between 0.38 μm (380 nm) and 0.78 μm (760 nm) that can be detected by the human eye.

Water heating The process of generating domestic hot water by employing a flat-plate collector and using solar radiation.

Watt hour (Wh) A common energy measure arrived at by multiplying the power times the hours of use. Grid power is ordinarily sold and measured in kilowatt hours.

Watt A measure of power (or work) equivalent to 1/746 of 1 horse power.

Wavelength The distance between two similar points of a given wave.

Zenith The top of the sky dome, i.e., perpendicular to horizontal plane). It is a point directly overhead at a 90°-altitude angle above the horizon.

Zenith angle The angle between the Sun's ray and its zenith (perpendicular to horizontal plane).

References

1. H.C. Hottel, A. Whiller, *Evaluation of flat plate collector performance*. Trans of the conference on the use of solar energy, University of Arizona Press vol. 2, p. 74 (1958)
2. F. Kasten, A.T. Young, *Applied Optics* **28**, 4735 (1989)
3. R. Perez, P. Ineichen, E. Maxwell, R. Seals, A. Zelenka, *ASHRAE Trans.* **98**, 354 (1990)
4. American Society of Heating, *Refrigeration and Air-conditioning Engineers*. ASHRAE Applications Handbook (SI) (ASHRAE, Atlanta, 1999)
5. H.N. Singh, G.N. Tiwari, *Energy* **30**, 1589 (2005)
6. M.J. Ahmad, G.N. Tiwari, *CIGR E-J* **10**, 1 (2008)
7. B.Y.H. Liu, R.C. Jordan, *Solar Energy* **4**, 1–19 (1960)
8. J.F. Orgill, K.G.T. Hollands, *Solar Energy* **19**, 357 (1977)
9. D.G. Erbs, S.A. Klein, J.A. Duffie, *Solar Energy* **28**, 393 (1982)
10. J.W. Spencer, *Solar Energy* **29**, 19 (1982)
11. T. Muneer, M.M. Hawas, K. Sahili, *Energy Convers Manag* **24**, 265 (1984)
12. M.N.A. Hawldar, *Int J Ambient Energy* **5**, 31 (1984)
13. D.T. Reindl, W.A. Beckman, J.A. Duffie, *Solar Energy* **45**, 1 (1990)
14. J. Chandrasekaran, S. Kumar, *Solar Energy* **53**, 505 (1994)
15. J.C. Lam, D.H.W. Li, *Build Environ* **31**(6), 527 (1996)
16. J. Boland, L. Scott, M. Luther, *Environmetrics* **12**, 103 (2001)
17. A. Miguel, J. Bilbao, R. Aguiar, H. Kambezidis, E. Negro, *Solar Energy* **70**, 143 (2001)
18. A.P. Oliveira, J.F. Escobedo, A.J. Machado, J. Soares, *Appl Energy* **71**, 59 (2002)
19. S. Karatasou, M. Santamouris, V. Geros, *Int J Sustain Energy* **23**, 1 (2003)
20. J. Soares, A.P. Oliveira, M.Z. Boznar, P. Mlakar, J.F. Escobedo, A.J. Machado, *J Appl Energy* **79**, 201 (2004)
21. A. Whiller, *Arch Meteorol Geophys Bioclimatol* **B8**, 197 (1956)
22. M. Collares-Pereira, A. Rabl, *Solar Energy* **22**, 155 (1979)
23. T.A. Newwell, *Solar Energy* **31**, 339 (1983)
24. P.C. Jain, *Solar Wind Technol* **1**, 113 (1987)
25. C. Gueymard, *J Solar Energy Eng Trans ASME* **108**, 320 (1986)
26. H.P. Garg, S.N. Garg, *Solar Wind Technol* **4**, 113 (1987)
27. A. Baig, P. Akhter, A. Mufti, *Renew Energy* **1**, 119 (1991)
28. J.C.A. Maxwell, *Treatise on Electricity and Magnetism*, II edn. (Clarendon Press, Oxford, UK, 1981)
29. D.A.G. Bruggeman, *Ann. Phys. Leipzig* **24**, 636 (1935)
30. R.L. Hamilon, O.K. Crosser, *I& EC fundam* **1**, 182 (1962)
31. F.J. Wasp, *Solid Liquid Slurry Pipeline Transportation* (Trans. Tech, Berlin, 1977)
32. K. Khanafer, K. Vafai, *Int J Heat Mass Transf* **54**, 4410 (2011)
33. A. Einstein, *Ann Phys Leipzig* **19**, 289 (1906)
34. H.C. Brinkman, *J Chem. Phys.* **20**, 571 (1952)
35. G. Batchelor, *J Fluid Mech* **83**, 97 (1977)

36. T. Lundgren, *Journal of Fluid Mechanics* **51**, 273 (1972)
37. S. Maiga, S.J. Palm, C.T. Nguyen, G. Roy, N. Galanis, *Int J Heat Fluid Flow* **26**, 530 (2005)
38. J. Buongiorno, *ASME J Heat Transf* **128**, 240 (2006)
39. C.T. Nguyen, F. Desgranges, G. Roy, N. Galanis, T. Mare, S. Boucher, H.A. Mints, *Int J Heat Fluid Flow* **28**, 1492 (2007)
40. W.J. Tseng, K.C. Lu, *Material Science Eng. A* **355**, 186 (2003)
41. P.K. Namburu, D.P. Kulkarni, D. Misra, D.K. Das, *Exp Therm Fluid Sci* **32**, 397 (2007)
42. P.K. Namburu, D.K. Das, K.M. Tanguturi, R.S. Vajjha, *Int J Therm Sci* **48**, 290 (2009)
43. W. Duangthongsuk, S. Wongwises, *International Journal of Heat Mass Transfer* **52**, 2059 (2009)
44. D.P. Kulkarni, D.K. Das, G. Chukwa, *J Nanosci Nanotechnol* **6**, 1150 (2006)
45. D.P. Kulkarni, D.K. Das, S.L. Patil, *J Nanosci Nanotechnol* **7**, 2318 (2007)
46. C.J. Ho, W.K. Lui, Y.S. Chang, C.C. Lin, *Int J Therm Sci* **49**, 1345 (2010)
47. Y. Xuan, W. Roetzel, *Int J Heat Mass Transf* **43**, 3701 (2000)
48. R.S. Vajjha, D.K. Das, *ASME* **131** (2009)
49. K. Khanafer, K. Vafai, M. Lighthstone, *Int J Heat Mass Transf* **46**, 3639 (2003)
50. K.S. Wang, J.H. Lee, S.P. Jhang, *Int J Heat Mass Transf* **50**, 4003 (2007)
51. C.J. Ho, M.W. Chen, Z.W. Li, *Int J Heat Mass Transf* **51**, 4506 (2008)
52. E.N. Seider, G.E. Tate, *Ind. Eng. Chem.* **28**(12), 1429 (1936)
53. B.C. Pak, Y.I. Cho, *Exp Heat Transf* **11**(2), 151 (1998)
54. Y. Xuan, Q. Li, *Trans. ASME* **125** (2003)
55. S.E.B. Maiga, C.T. Nyugen, N. Galanis, G. Roy, T. Mare, M. Coqueux, *Int J Numer Meth Heat Fluid Flow* **16**(3), 275 (2006)
56. S.M. Fotukian, M.N. Esfashany, *Int. Comm. Heat Mass Transf* **37**, 214 (2010)
57. L. Qiang, X. Yimin, *Sci. China, (Series E)* **45**(5), 408 (2002)
58. V. Gnielinski, *Int. Chem. Eng.* **16**, 359 (1976)
59. W. Duangthongsuk, S. Wongwises, *Exp Therm Fluid Sci* **33**, 706 (2009)
60. B.C. Pak, Y.I. Cho, *Exp Heat Transf* **11**, 151 (1999)
61. P.K. Singh, K.B. Anoop, T. Sundararajan, K.D. Sarit, *Entropy generation due to flow and heat transfer in nanofluids. Int J Heat Mass Transf* **53**, 4757–4767 (2010)
62. O. Mahian, A. Kianifar, A.Z. Sahin, S. Wongwises, *Entropy generation during Al₂O₃/water nanofluid flow in a solar collector: effects of tube roughness, nanoparticle size, and different thermo-physical models. Int J Heat Mass Transf* **78**, 64–75 (2014)
63. F.P. Incropera, D.P. De-Witt, *Fundamentals of Heat and Mass Transfer*, 4th edn. (Wiley, New York, 1996)
64. C.F. Colebrook, *Turbulent flow in pipes, with particular reference to the transition region between the smooth and rough pipe laws. J. Inst. Civil Eng.* **11**, 133–156 (1939)
65. M.A. Khairul, R. Saidur, M.M. Rahman, M.A. Alim, A. Hossain, Z. Abidin, *Heat transfer and thermodynamic analyses of a helically coiled heat exchanger using different types of nanofluids. Int J Heat Mass Transf* **67**, 398–403 (2013)
66. R.C. Xin, M.A. Ebdian, *The effect of Prandtl numbers on local and average convective heat transfer characteristics in helical pipes. J Heat Transf* **119**, 467–473 (1997)
67. P.K. Nag, *Engineering Thermodynamics*, TMH, ISBN 0-07-460275-6 (2004)