SOLAR THERMAL SYSTEMS: THERMAL ANALYSIS AND ITS APPLICATION

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Solar Thermal Systems: Thermal Analysis and its Application

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PREFACE

Solar energy is the most abundant renewable energy that can meet all the energy requirements without getting depleted and harming the environment. A lot of research is going on to harness solar thermal energy for space heating, water distillation, and electricity generation. So, there is a need for a resource that can provide knowledge regarding solar energy and research on solar thermal systems. This will help develop more efficient solar systems that are more compact, reliable, portable, and able to eliminate the dependency on conventional energy sources for meeting the energy requirement for various daily life and industrial purposes.

This book encapsulates the solar thermal systems available to meet the need of food, fresh water, cooking food, heating water *etc*. The fundamentals of thermodynamics, heat transfer and solar energy are covered in Chapter 1 and Chapter 2. The basics of some solar thermal devices along with their thermal modeling are covered in Chapter 3. The basics of solar still, its thermal modeling, applications, development in past few years and potential of solar distillation system in India is discussed in Chapter 4-6. The design, development and applications of solar cookers along with their thermal modeling are covered in Chapter 7-8. Thermal modeling of semi-transparent PVT systems and its application is discussed in Chapter 9 and Chapter 10 covers the development in solar photovoltaic technology. Chapter 11 and Chapter 12 discusses about thermal modeling of greenhouse solar dryer and case study on hybrid active greenhouse solar dryer. Chapter 13 covers the thermal analysis of photovoltaic thermal (PVT) air heater employing thermoelectric module (TEM). The applications of various solar systems in building sectors and the development in this field are covered in Chapter 14. Chapter 15 deals with exergo and environ- economics analysis of bio-gas integrated semi-transparent photo-voltaic thermal (Bi-iSPVT) system for Indian composite climate.

The book has a broad scope and helps students and researchers in universities, industries, and national and commercial laboratories to learn the fundamentals and in-depth knowledge regarding thermal modeling and developments in solar thermal systems in the past few years. It is a research-oriented book in which different researchers have contributed in the form of different chapters. I hope that the book will provide sufficient knowledge regarding solar systems and will not discourage the readers. This book can be used as a reference tool for teaching the solar energy and thermal modeling of solar thermal systems to the students and research fellows in universities and research organizations

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Finally, I want to express my special thanks to my family, my parents Shri Shukhad Gaur and Smt. Archana Devi Gaur and my in-laws Shri P.K. Saxena and

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CHAPTER 1

Introduction

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Abstract: This chapter covers the basics of thermodynamics and heat transfer, which helps in understanding the heat transfer mechanism and thermal modeling of various solar thermal systems covered in further chapters. The laws of thermodynamics and heat transfer are also covered in the chapter. The general terms related to thermodynamics and heat transfer are also defined in this chapter, as these terms will be used frequently in upcoming chapters.

Keywords: Basics of heat transfer, Basic terminology, Laws of heat transfer, Thermodynamics.

1. THERMODYNAMICS AND HEAT TRANSFER

Thermodynamics is a branch of science that deals with heat and work interaction and its effect on the system and surroundings. The amount of heat transferred from the system or heat transferred to the system and the amount of work done on the system or work done by the system are studied in thermodynamics. However, in thermodynamics, we cannot determine the rate of heat transfer from the system or to the system. Heat transfer is interrelated to thermodynamics as it is based on the second law of thermodynamics only.

The heat supplied to various solar systems by various modes is determined using the concept of heat transfer like heat transfer by solar radiation to inside air of dryer, heating of basin of solar still by absorbing the solar radiation, heat loss from solar systems to surrounding, heat carried away by hot water supplied through solar water heater, *etc.* [1,2].

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2. GENERAL TERMS RELATED TO THERMODYNAMICS

The various terms related to thermodynamics that are frequently used are defined below [3]:

2.1. System

The system is simply the quantity of matter upon which the study is focused. In the context of solar systems, it can be a crop dried inside the dryer, water flowing inside the heat pipe, vapor inside the solar still, air or food inside the solar cooker, *etc*. The hypothetical system having an imaginary boundary is called control volume and the quantity of matter inside the control volume is called control mass.

2.2. Surrounding

Everything external to the system is called a surrounding. In other words, the point up to which the effect of the system is observed is called as surrounding, and the remaining is the environment.

2.3. Boundary

The boundary separates the system from the surroundings and it can be rigid or flexible depending upon the system. For example, the transparent cover of the dryer acts as a boundary that separates the inside air from the surrounding air. The water mass inside the heat pipe is an example of a control volume having an imaginary flexible boundary. The boundary is also classified as an adiabatic boundary and diathermic boundary. There is no transfer of heat through an adiabatic boundary, while a diathermic boundary allows the transfer of heat from the system to the surroundings or *vice versa*.

2.4. Types of System

The system is classified into three types: open, closed, and adiabatic system. In an open system, both heat and mass transfer takes place, while in a closed system, there is a transfer of heat only. In an adiabatic system, neither the heat nor the mass is transferred from or to the system.

2.5. Heat

The form of energy that transfers due to temperature differences between the two bodies is termed as heat or thermal energy. In terms of thermodynamics, it is defined as the energy in transition across the boundary between the thermodynamic system and its surroundings without any transfer of mass. Heat always flows from high temperature body to lower temperature body. It is generally measured in calories, Joules, or btu.

2.6. Temperature

Temperature is a measure of the degree of hotness or coldness of anybody. The temperature is also defined as the average kinetic energy of molecules in a body. In simple words, the temperature of any substance denotes the amount of thermal energy inside that substance. The most common instrument used to measure temperature is a thermometer. The temperature is generally measured in degree Celsius (°C), Kelvin (K), and Fahrenheit (F).

2.7. Entropy

Entropy simply denotes the molecular disorder or randomness in the system. It is a property of the system, so it depends on the state, not on the path followed to reach that particular state.

2.8. Enthalpy

Enthalpy is also a property of a thermodynamic system and it is basically the summation of the internal energy *(U)* of the system and product of pressure *(p)* and volume *(V)*. It is expressed as,

$$H = U + pV \tag{1}$$

Change in enthalpy of the system can also be defined as the total heat supplied to the system at constant pressure and temperature.

2.9. Latent Heat

At constant temperature, the amount of heat absorbed or released by the substance during a change of its phase is called latent heat. The heat required for changing the solid to liquid phase or *vice versa* is called the latent heat of fusion. When liquid changes its phase to gas or *vice versa* is called the latent heat of vaporization. Various phase change materials are used in solar systems to store the excess solar thermal energy during the sunshine period and supply that stored energy during the off sunshine period. In this way, the solar systems can be used in the off sunshine period also. The SI unit of latent heat is kJ/kg.

CHAPTER 2

Basics of Solar Energy and Various Sun-Earth Angles

Brian Norton[1*]

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Abstract: This chapter discusses the causes and effects of solar energy incidents on Earth's spectral, skyward angular, intensity, and luminous characteristics. A particular perspective is how these characteristics influence and determine how particular practical devices, systems, and applications harness available solar energy. The uses of solar energy to produce heat, generate electricity *via* photovoltaics, and provide daylight are considered. Moreover, diverse factors limiting the applicability of specific solar energy conversion devices or approaches are also discussed.

Keywords: Radiation, Solar energy, Solar instruments, Sun-Earth angle.

1. MATCHING SOLAR COLLECTORS TO PREVAILING SOLAR ENERGY CONDITIONS

Fundamentally, solar energy is the origin of nearly all energy sources used by people; it fuels life through photosynthesis, provides warmth, and heats the land and sea, creating atmospheric pressure differentials that generate wind and rain. It does the latter at various temporal scales affecting both climates and weather. The Sun is thus not only directly used by photovoltaic and solar thermal devices but is also the source for all wind, hydroelectric, and bioenergy renewable energy resources. Solar energy directly provides [1]:

(a) Heat gain and daylight directly through the windows of buildings.

(b) Heating of heat transfer fluids. This can be water for sanitation, air for crop drying, or direct use in distillation or cooking. High-temperature heat transfer fluids can drive power conversion systems to produce electricity. Thermal energy storage provides heat to solar devices during inadequate sunshine.

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(c) Electricity *via* photovoltaic cells.

A solar energy collector intercepts and converts incident solar radiation into a usable form of electricity, heat, or light. This energy can:

(a) directly reduce specific concurrent energy demand; for example, daylight displacing electric lighting.
(b) directly meet a specific concurrent energy demand; for example, photovoltaic electricity, solar heat, or solar thermal electricity production.
(c) be stored for subsequent discharge to meet a later energy demand; for example, as sensible, latent, or thermochemical heat stores and/or as electricity in batteries.
(d) be directly used in an end application; for example, solar drying, solar cooking, passive solar distillation, solar detoxification, and/or
(e) be further converted; for example, *via* photovoltaic powered electrolysis to produce hydrogen.

In flat-plate and evacuated-tube thermal solar collectors, a selective solar radiation absorber material absorbs incident solar energy, converting it to thermal energy and heating that absorber plate. Tubes or ducting in the absorber plate constitute a specialized heat exchanger that removes the heat from the plate in the form of a liquid or gas. The latter is conveyed to heat storage or directly to the load. A transparent aperture in front of a flat absorber plate and opaque insulation on the back of the absorber allows solar radiation to be collected while reducing heat losses from a collector. A contiguous glass tube enclosing an evacuated space surrounding the absorber [2] performs these functions.

Photovoltaic modules, flat plate collectors, and evacuated tube collectors absorb direct sunlight, diffuse sunlight from the sky, and reflect sunlight from the ground. They seldom track the Sun's daily path across the sky. In fixed mounting, the tilt is usually provided toward the south at an angle equal to the latitude to minimize the average angle between the Sun's rays and the surface for optimal solar energy interception.

A total of 120,000 terawatts of solar energy strike the Earth’s surface. However, this incident solar energy has a low power density with annual daily averages between 400Wm^2 and 600Wm^2, so its use to meet larger energy loads thus requires the use of available suitable unshaded outdoor space on buildings and specifically devoted areas of land. For smaller loads, additional purposing to incorporate solar energy harnessing devices enables autonomous powering of outdoor systems, such as streetlights. When maximizing the use of an area to harness solar energy, shading can arise from:

- Thermal collectors or photovoltaic modules shading each other at lower sun angles in large arrays of successive rows.
- Buildings features, such as chimneys, shade roof-mounted solar energy collection systems.
- Surrounding trees or other buildings for both roof-mounted and ground-located solar energy collection systems.

  Concentrating solar collectors are developed for high-temperature thermal applications. All higher-concentration optical concentrating collectors can only concentrate incident beam normal solar radiation. Concentrating solar energy systems must track the Sun's azimuthal motion across the sky to align at normal incidence with the changing incident angle of beam solar radiation. Concentrators generally used for higher temperature applications are [3]:

- Parabolic troughs that concentrate incident solar radiation onto the axis of the trough. A tubular receiver carrying heat transfer fluid placed along this axis absorbs the concentrated solar radiation and heats the fluid. A parabolic trough tracks the sun about one, usually east-to-west aligned, axis.
- Parabolic dishes track the azimuthal motion of the Sun about two axes to concentrate incident solar radiation to a point. An insulated cavity at that point absorbs the concentrated radiation.
- Central receiver systems consist of an extensive array of independent heliostat flat mirrors. Each heliostat separately moves differently about two axes throughout the day to reflect incident solar energy to maintain a high-intensity cumulative reflection from all the heliostats on a receiver located at the top of a "solar tower."

Full two-axis tracking collects the most direct solar radiation. However, it can be expensive to operate and maintain two-axis tracking systems. This may not be viable, particularly in climates that have a short duration of periods with high direct components of solar radiation for significant parts of the year. Full two-axis tracking requires a greater distance between each solar energy collection device than would be the case for single-axis tracking solar collectors. Shows the amount of incident solar energy received by different tracking strategies than two-axis tracking.

In large-scale solar energy installations, inter-row shading at low sun angles enables maximum utilization of the available land area. At latitudes outside the tropics, the greater electricity production at high Sun angles from a maximized photovoltaic

CHAPTER 3

Internal Characteristics of Double-base Array

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Abstract: The thermal applications of solar energy have gained momentum after the revolution in the field of PV technology in recent decades. The worldwide quest to harness the thermal component of solar energy, which constitutes the major part of the incident, solar radiation incident globally, has led to the development of numerous thermal devices and applications that harness and store or utilize the same with never before seen efficiency. A few applications and devices are discussed here in this chapter. The first part of the chapter presents a brief discussion of the solar pond and its features along with thermal modeling of the system, followed by the thermal modeling and discussions about solar cooling systems. The later part of the chapter describes solar refrigerators and solar concentrators. The application and devices discussed here are of prime importance in developing basic and advanced solar thermal devices to harness solar thermal energy efficiently for human needs.

Keywords: Application, Solar cooling, Solar devices, Solar thermal.

1. GENERAL INTRODUCTION TO THE SOLAR POND

The concept of natural heating of water reservoirs existed before humans came into existence and can be regarded as one of the key factors responsible for the creation of life on the planet we live on. An optimum water temperature across the oceans is not only essential for the sustenance of marine flora and fauna, but as per the recent century's turn of events, our very existence may also depend upon the temperature of the oceans. The temperature rise of the oceans may be worrisome, but there are numerous applications of a water reservoir with hot water. In its simplest form, a water reservoir that receives heat from the sun and stores the same for later use may be regarded as a solar hot water pond or simply a solar pond. It

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may be any water reservoir with a black bottom in order to achieve heating capability. However, the heat received in the above case will be lost to the ambient due to convective and buoyancy effects that cause the hot water to rise to the surface. To avoid convective loss, a layer of still water can be maintained above the hot water using a salt concentration gradient along with the depth, a physical partition between the convective and non-convective layers or using a viscosity gradient along with the depth. Under the current discussion, the three systems are discussed briefly, and the more widely accepted salt gradient stabilization method is discussed in detail across this chapter.

1.1. Partitioned Salt-stabilized Pond

The simplest yet most effective way to counter the heat loss due to all convective zone type ponds is to inhibit the mixing of the convective and non-convective zones using a physical barrier or partition. Here, the partition used may be a transparent cellophane sheet that separates the convective zone from a non-convective zone. This kind of arrangement eliminates the need for heat exchangers for thermal extraction and eliminates the need for brine solution as a thermal stabilizer. The large surface area, maintaining transparency by avoiding the fouling of the transparent sheet are the few critical challenges that limit the practical implementation of this type of pond.

1.2. Viscosity Stabilized Pond

This system is similar to the salt concentration stabilized system discussed in the next subsection. The key difference is using gels and thickeners instead of salts to separate convective and non-convective zones. Polymers, detergent oil, water gels, *etc.*, are the required thickeners.

1.3. Stabilization using a Salt Concentration Gradient

The convective effect obtained in the pond water due to the temperature rise near the bottom of the pond is the main cause for concern here since the hot water tends to rise to the top, hence losing the heat gained to the ambient. This is a cyclic process, and hence at the end of the day, the water can lose the heat gained during the day. This also calls for measures to impede the convective heat loss through vertical currents along the depth to maximize heat storage. One of the most effective means of achieving this is to provide a density gradient between the top and bottom layers of the pond so that the warm water may never attain a density lower than that of the top layer and hence does not tend to rise to the surface. This can be done using a salt concentration gradient between the layers of water. As shown in Fig. (**1**), the layer of water closest to the bottom has the highest salt concentration, while the layer at the top is freshwater.

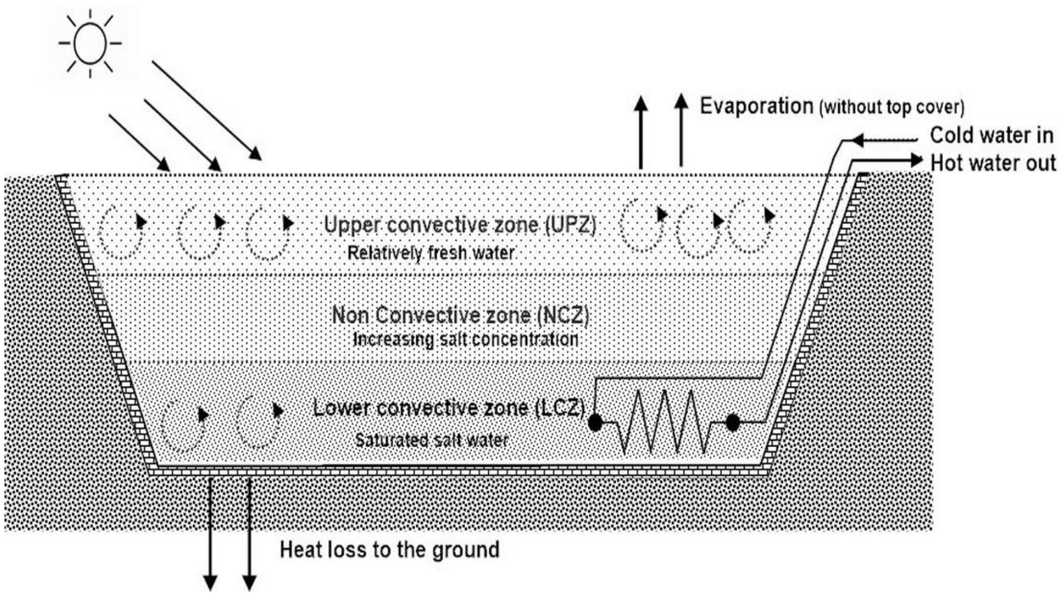

Fig. (1). Solar pond with a salt concentration gradient.

The salt concentration gradient can be achieved using pumping brine with varying salt concentrations through floating diffusers. The heat extraction from such a pond may be done using a heat exchanger in a closed or open loop. In the case of a closed-loop heat exchanger, the brine may be circulated across two heat exchangers where one of them is placed at the bottom of the pond, and the other is at the place of heat requirement. The open-loop system, on the other hand, withdraws the brine from the convective layer and pumps it back to the pond bottom after passing it through the heat exchanger.

Fig. (**2)** can be used to predict thermal energy efficiency of an ideal pond (solar). Instantaneous performance characteristics like thermal efficiency cannot be determined for such a pond since the mass of water, and resulting storage capacity are huge. The figure thus can be utilized for an average annual insolation level of

CHAPTER 4

Thermal Modeling of Solar Stills

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Abstract: The design, analysis and modeling of solar energy-based water purifiers, commonly known as a solar still, which is based on the greenhouse effect, is the requirement of time as there is a scarcity of freshwater throughout the globe. The technology of purifying dirty water using solar energy is a promising solution for simplifying contemporary water scarcity as this technology does not create any bad effect on the surroundings, unlike conventional water purification technology, which creates a lot of polluting elements and ultimately has become problematic for the environment. Most solar energy-based water purifiers are self-sustainable, and they can be installed in remote locations where sunlight and source of impure water are available in abundance. This solar energy-based technology of water purification should perform better in hilly locations as the intensity of light is higher than the intensity of light in fields. The current chapter deals with the thermal modeling of different types of passive and active solar stills, including solar stills loaded with water-based nanofluids, followed by their energy and exergy analyses.

Keywords: Solar still, Thermal modeling, Passive, Active, Nanofluid, Exergy analysis.

1. INTRODUCTION

This chapter discusses the thermal modeling of different types of solar energy-based water purifiers (SEBWP) in passive as well as active modes. Thermal modeling of SEBWP means writing the Eq. for different parts of SEBWP based on making equal input heat/energy to output energy/heat. Eqs obtained in this way are

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subsequently simplified to get a differential Eq. containing unknown parameter, which is to be expressed in terms of known parameters like solar intensity, heat transfer coefficients and some constants. The differential Eq. so obtained is solved under boundary conditions for getting the expression of an unknown parameter in terms of various known parameters like solar intensity, heat transfer coefficients and some known constants.

The first accepted research work on SEBWP was done in the sixteenth century by Arab alchemists [1]. Della Porta in 1589 made use of inverted earthen pots [2]. Further, earthen pots were exposed to the sun's radiation to heat up, due to which water got evaporated, condensed and finally got collected into containers [3]. Talbert *et al.* [4] presented a review of SEBWP on its historical background. Delyannis and Delyannis [5] studied the main SEBWP existing throughout the globe. Malik *et al.* [6] presented work reported on SEBWP in passive mode till 1982 and further, Tiwari [7] updated the work reported on SEBWP till 1992, which consisted of SEBWP operating on both passive and active modes. Delyannis [8] presented a compressive review on SEBWP. Delyannis [9] and Tiwari *et al.* [10] have investigated the various designs of SEBWP for making fresh water available. The first known work on SEBWP in active mode as per available literature was presented by Rai and Tiwari [11] and they concluded that the output (freshwater) obtained from SEBWP in active mode was 24% higher than SEBWP of the same basin area acting in passive mode. Since then, a lot of changes in SEBWP operating in passive as well as active modes have been reported. In this chapter, the development of thermal modeling for such types of SEBWP has been discussed.

2. SEBWP OF SINGLE SLOPE TYPE IN PASSIVE MODE

The schematic diagram of SEBWP of single slope type in passive mode is shown in Fig. (**1**). The work is based on the greenhouse effect. It consists of condensing cover, basin liner and water mass. So, the development of thermal modeling equations for SEBWP of single slope type in passive mode consists of writing equations for the outer surface of condensing cover, an inner surface of condensing cover, water mass and basin liner. The solar energy-based water purifier of single slope type in passive mode is oriented towards the south if the system is being studied for the place in the northern hemisphere and towards the north if the system being studied lies in the southern hemisphere for getting better annual solar energy. Assumptions [12] for writing equations based on balancing input energy to output energy are as follows:

(i) The vapor leakage in SEBWP is neglected.
(ii) Solar distiller unit's water depth is constant. The change in distilled water yield is very small when the water depth changes thus, change in depth can be neglected.
(iii) The brackish water held in the basin does not develop layers.
(iv) The heat capacity of the bottom and side insulating material, along with condensing glass cover is neglected.
(v) The condensation with film-type characteristics occurs at the inside plane of the condensing cover. Careful cleaning of the inner surface of the glass ensures film-wise condensation and providing a small angle to the condensing cover favors it. The component of gravity force along the condensing cover will allow the condensate to trickle down along the surface and finally be collected in a measuring jar.

The interaction of heat for the outer surface of the condensing cover has been shown in Fig. (**1a**). Heat reaches the surface on the outer side of the glass cover from the surface on the inner side of the glass cover. The temperature of the surface on the inner side of the glass cover is higher than the temperature of the outer surface of the condensing cover. Heat is lost by the outer surface of condensing cover to the surrounding through convection and radiation. Hence, the Eq. for the surface on outer side of glass cover based on balancing input heat to output heat can be written as [12]:

$$\frac{K_g}{L_g}\left(T_{gi} - T_{go}\right)A_g = h_{1g}\left(T_{go} - T_a\right)A_g \tag{1}$$

Here, h_{1g} stands for total heat transfer coefficient (HTC) from the surface on the outer side of the glass cover to the surrounding. Fourier's law has been used for the heat transfer by conduction mode from the inner surface to an outer surface of condensing cover (expression on the left side of Eq. 1). Newton's law of cooling has been used to write heat transfer by convection from the surface on the outer side of a glass cover to the surrounding (expression on the right side of Eq. 1). The expression for h_{1g} can be written as:

$$h_{1g} = 5.7 + 3.8V \tag{2}$$

Where V represents blowing air velocity.

CHAPTER 5

Application and Development in Solar Stills

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Abstract: One-third of the Earth is covered by seawater, yet there is a constant lack of water in many places. A total of 97% of the water is present in the sea as salt water, and only 3% of water is potable, out of which only 1% of clean water reaches the people. Therefore, a device is needed that can convert salt water into clean water. Solar still is a sustainable device through which dirty and salt water can be converted into clear water. Due to the low productivity of conventional solar still; it is not popular in the market. Increasing the productivity of conventional solar still is a major challenge for researchers. Researchers are continuously working on the performance of solar still to increase its productivity. The modifications and designs made by researchers in solar still over the last ten years are encapsulated in this chapter. Solar still with PCM, nanoparticles, reflectors, collectors, external condenser, wick materials, and different angles are studied, and applications of distilled water have also been covered in this chapter.

Keywords: Active solar still, Distilled water, Passive solar still, Solar still.

1. INTRODUCTION

Water is a necessary component of animal and human life. A total of 71% of the Earth's surface is covered with water. 97% is present in the oceans and seas, which is salty and cannot be used for drinking. Only 3% of potable water is available for drinking, of which 2% is found in glaciers in the North and South Pole, and the rest of 1% is available in rivers, lakes, ponds, and groundwater, so a device is required which converts the saline water into potable water.

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Various water purifier devices are available in the market, but all are operated through electricity, which is not environmentally friendly. Hence, a device is needed that works using renewable energy and can produce fresh water at a low cost. Solar still (SS) is a sustainable device using direct solar radiation to purify impure and saline water [1]. Due to the low production rate, solar still is not popular in the market.

As the population increases, the demand for clean water is also increasing. So solar still is the best alternative to the existing convention water purifiers, but SS is not used on a large scale due to its low productivity. Therefore, researchers constantly use several methods to enhance the yield of SSs. The classification of solar still is given in Fig. (**1**). Solar still is generally of two types; the first is passive SS, and another is active SS. When SS is operated in the natural mode, it is called passive SS, and when an external device is used to heat the water, it becomes active SS. The passive and active SSs are divided into two parts: single slope and double slope. SS with only one inclined condensing cover is called single slope SS, and in the dual-slope SS, two glass covers are installed with opposite facing.

Many researchers have intensively studied the parameters affecting the performance and heat transfer of SS to achieve maximum yield. Various modifications have been made that can increase the productivity of SSs.

A comprehensive review has been prepared by Panchal and Mohan [2]; they studied the performance of fins, heat storage material, and multi-basin. They have studied how to increase the productivity of stills through three effects. Kabeel *et al.* [3] described the various heat exchange mechanisms adopted by the researchers on different modified SSs. External and internal mirror reflectors were used by Tanaka [4] to increase the convective and evaporative heat transfer coefficient of SSs and study their heat and mass transfer. Raju and Narayan [5] performed an experimental study on a SS; they added a different number of flat plate collectors (FPC) to a simple SS. It was found that when a single flat plate collector was added to the setup, its distilled efficiency was 6.82%. When two FPC were added to the setup, the distilled efficiency was 7.29%. As the number of FPCs was added to the SS, the solar radiation receiving area increased, and water got preheated quickly before entering the basin.

Kabeel *et al.* [6] used a separate condenser chamber to increase the productivity of SS and nanoparticles were mixed in the basin water to increase its thermal conductivity and evaporation rate. Productivity increased by 53.2% when an external condenser was added to the setup, and productivity increased by 116% when the nanoparticle was added to the basin water. Refalo *et al.* [7] analyzed the effect of solar chimneys and condensers on the productivity of SS. It was found that when the chimney was added to the SS, the setup produced 5.1 liters/m^2 of distilled water in a day. When the external condenser was added to the setup, the setup productivity was 4.7 liters/m^2 in a single day. The chimney and external condenser increased the surface area of the vapor; hence the productivity increased. Rashidi *et al.* [8] placed a rectangular sponge of rubber inside the SS and did an exergy analysis. The productivity of this modified SS was 17.35% higher than the conventional SS. The sponge produced the capillary effect, broke the water molecules into small sizes, and started to evaporate in less time.

Many modifications have been made to improve the productivity and efficiency of solar still. The development in solar distillation in the past few years is discussed in this chapter. The application of distilled water produced from these SSs is also examined in this chapter.

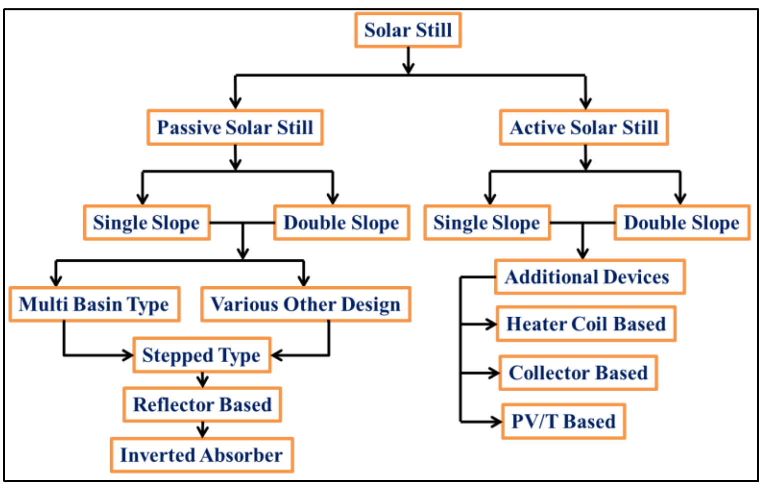

Fig. (1). Classification of solar still.

2. DEVELOPMENTS IN SOLAR STILLS IN THE LAST FEW YEARS

There have been many changes in SSs over time due to their low productivity rate. The authors have used various techniques to improve the yield of SS, which are discussed below.

CHAPTER 6

Potential of Solar Distillation Plant in India

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Abstract: With the rising population and continuous depletion of our natural resources, it has become very tough for everyone to meet their basic needs of food and water. Also, at the rate with which the water-stressed area continues to rise, we soon will be facing a huge water crisis. This chapter specifically talks about India and its potential to make a switch from conventional methods of water usage and switch to a renewable energy-based water desalination unit. This chapter presents an elaborate analysis of the Indian peninsular region and talks about the major cities' comparative performance in the basic design of the solar humidification-dehumidification desalination unit. It can be concluded that the southern-most area has a very large potential for setting up an economically feasible desalination unit. Various parameters are discussed, like humidity ratio, outgoing airstream temperature, and mass rate of evaporated water. As Chennai has the best performance for the particular unit for most of the year, with productivity reaching 44 kg/day, the least favorable site seems to be Puri in Odisha, where productivity remains less and constant at a maximum of 34 kg/day during summers.

Keywords: Desalination, Freshwater, Humidification, Solar.

1. INTRODUCTION

Freshwater is in great demand and is an increasingly vital issue in rural areas of India. Potable water is very scarce in arid areas and the establishment of a human habitat in these areas strongly depends on how much water can be made available. Water is an essential element of life. The issue of supplying potable water can hardly be overstressed. There are abundant resources on earth. The planet's three-fourths of its surface is covered by water. About 97% of the earth's water is

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saltwater in the oceans. Only 3% is freshwater contained in the poles (in the form of ice), groundwater, lakes, and rivers, which supply most human and animal needs. Nearly 70% of this tiny 3% of the world's fresh water is frozen in glaciers, permanent snow cover, ice, and permafrost. Thirty percent of all freshwater is underground, most of it in deep, hard-to-reach aquifers. Lakes and rivers together contain just a little more than 0.25% of all freshwater; lakes contain most of it.

Salman H. Hamaadi *et al.* (2018) studied the specific effect of temperature change of glass and air along the length of the distiller when it allows for the mass transfer and heat convection between glass cover and air. He stated that the maximum production of freshwater was during the month of March that is 2.2 kg/m^2.day and reached a minimum value during July, which was 0.66 kg/m^2day also, the "productivity decreases with increasing air velocity inside the distiller while the evaporation rate increases"; also this study is very much relative to the present study [1].

Ali *et al.* (1993) considered the influence of convection (forced) within the solar still upon the coefficient of mass and heat transfer. Diverse factors are considered, like fluting the surface of the water. The motion of air results in turbulent eddies, an increase of gases that are incondensable, and vapor velocity in the still. He came up with; any rise in the yield of the solar desalination unit is primarily because of the improvement in the coefficients of heat and mass transfer owing to the presence of the vapor-air blend turbulent wave interior of the still [2]. Sartori *et al.* (1996) offered a theoretical evaluation concerning the thermal performance of a basin from a solar still and that of a solar evaporator. The evaporator and the still are fabricated of glass fiber and insulated (thermally) with glass wool of 0.045 m at the sides and bottom. Both surfaces of water have $1m^2$ and 0.04 m layers. A conjoint 3 mm impenetrable glass has been engaged to cover the still and established that vaporization in stills was in a smaller amount than in open evaporation regardless of the greater temperatures of water in the previous arrangement. For higher system temperatures, the fraction of evaporation is equal to 50% or even higher than the parallel overall heat transmission [3].

Radhwan *et al.* (2004) offered a transitory study of a solar still in a unique stepped design for humidifying and heating of, particularly agriculture utilized gases. Air dispersed within still present is moistened as well as heat. So the still outcomes indicated produce was 4.92 L for a unit area every day, with a reduction in the flow rate of air having a minor impact on the method output [4]. Mofreh H. Hamed *et al.* (2015) proposed a practical system of humidification-dehumidification desalination and analyzed the operation in two periods, one of which when he calculated the working cycle between 9 am and 5 pm local time; the other begins with preheating the air going for humidification at 1 pm till 5 pm local time. So, the result showed the system ran 4 hr every day, and preheating provides greater production, which is around 22 L/daym^2, and the overall cost per liter of that unit remains close to Rs. 4 [5].

Zhou *et al.* (2010) introduced another technique relating to the withdrawal of heat and humidity present in a brine solution in the accumulator of the solar vent arrangement regarding electricity production and water treatment. Further, their study resolved that amount produced through water generators and wind turbine generators in the joint plant is lower than that of the standard system because of the discharge of latent heat of vapor following the gases escalating in the chimney [6].

Okati *et al.* (2016) considered a desalination method through solar energy of humidification–dehumidification method comprising a humidification setup with underground condenser apparatus intended to generate clean water. Brine gets heated inside the humidification device, then at that point the steam gets delivered over a fixed set of ducts concealed in the ground, the condensation mechanism then starts and freshwater is produced. The outcomes presented that the production rate of fresh H_2O per concealed duct's size is 3.8120 (kg/m.hr) [7]. Okati*et al.* (2018) offered a work of another solar-assisted desalination unit working on the above principle of humidification-dehumidification (HDH) method, combining the solar still with a concealed dehumidifier working as a condenser. The outcome specified that the water production rate could range above 265 kg/day (approx.) [8].

Abdel Dayem and Fatouh (2009) set up as well as examined a “numerous-effect HDH solar desalination unit. The system involves 2 loops, a water desalination loop and a solar loop. Three systems were analyzed by testing and numerically. It was evident that the unlocked structure with free circulation for solar energy is more effective irrespective of real awkwardness, whereas the locked structure with a supplementary heater has the maximum distilled production of water [9]. Prakash *et al.* (2010) presented a broad analysis with a futuristic “solar humidiifcation dehumidiifcation (HDH) desalination unit.” Specific consideration had been set on heaters, with limited modification parameters; also, direct water heating was matched with direct air heating for process calculations. Different methods centered on the HDH theory were also looked over and compared. It was decided that HDH machinery has pronounced potential for decentralized limited water production uses, even though further studies and advances are desirable intended for reducing capital cost and enhancing system efficiency [10]. Design, along with a study regarding various HDD developments, was examined by Ettouney *et al.* (2005).

CHAPTER 7

Design and Thermal Modeling of Solar Cookers

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Abstract: Solar energy technologies are upgrading day by day in every sunshine-rich region around the globe. These technologies provide a strong platform for humans for high-demand activities like cooking, air heating, power generation, *etc.* Among these activities, solar cooking is much popular due to daily cooking needs. Different designs of solar cookers are available in the market according to the family size. In the present work, the designs of some commonly used solar cookers and their thermal performance evaluation have been discussed. Heat transfer analysis shows that cookers with some potential heat storage materials are better than conventional solar cookers. The design of such cookers is feasible to cook efficiently for long hours, even during off sunshine hours (for a limited period).

Keywords: Design, Heat transfer, Solar cooker, Thermal performance.

1. INTRODUCTION

In recent years, the use of renewable energy sources has been increased to reduce dependence on fossil fuels, and many alternative energy technologies, including solar energy, have become a part of our daily lives. Several studies have been conducted in the last two decades, especially on solar energy, and various environmentally friendly, cost-effective, and sustainable systems related to both electricity and thermal energy generation from solar energy have been developed

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[1]. Solar cookers, one of the promising thermal applications of solar energy, have attracted researchers and people living in rural areas in developing societies due to their simple, cost-effective, environmentally friendly, and reliable features and performance characteristics [2]. Solar cookers are available in numerous designs and applications; therefore, making a general classification for them is not easy. However, it would not be wrong to evaluate solar cookers under three main headings: solar panel cookers, solar box cookers, and solar parabolic/dish cookers, as shown in Fig. (**1**) [3].

When solar cooking technology is examined closely, it is understood that the first applications started with the simplest and cheapest designs, then steady and continuous advancements took place concerning demand due to technological developments and improved income levels. The diversification of performance parameters of solar cookers from year to year has led to the widespread use of scientific studies in the relevant technical field and the introduction of a wide variety of designs on the commercial product side [4].

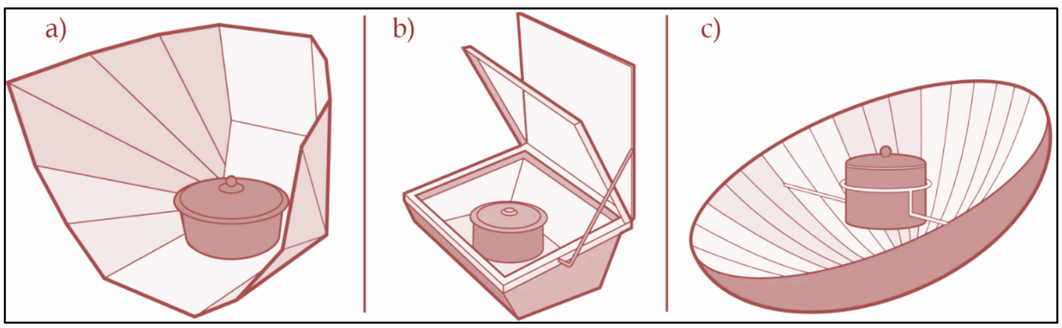

Fig. (1). Typical classification of solar cookers: **a**) solar panel cookers, **b**) solar box cookers, and c) solar parabolic/dish cookers [3].

2. CLASSIFICATION OF SOLAR COOKERS

The aforesaid performance parameters can be listed as efficiency, cooking speed, cost, durability, reliability (attention needed in operation), versatility (being adaptive to cook different foods), portability, heat storage feature (cooking after sunset), performance at cold and windy conditions, performance at low solar radiation conditions, *etc.* Each type of solar oven has many advantages and disadvantages. When the performance mentioned above criteria have been considered, it can be asserted that there is no flawless system. For example, panel-type solar cookers work to reflect the incoming solar radiation on the cooking pots. Therefore, dependence on environmental conditions is relatively high. A similar scenario applies to solar parabolic cookers. However, solar parabolic/dish cookers are driven by the solar concentration phenomenon; thus, their performance is rarely dependent on solar radiation, thermal insulation, or design due to their notably higher cooking power [5].

On the other hand, solar box cookers are highly thermally resistive in most cases. They are appropriate to design with sensible and latent heat storage media for late evening cooking. Phase change materials (PCMs) are often utilized in solar box cookers to enable their use after sunset [6] and enhance the designs' cost-effectiveness and reliability. Solar panel cookers are superior to other cooker types in terms of cost and portability, but the minimal cooking power is their most significant handicap. Solar parabolic/dish cookers are ideal for hard-to-cook foods; however, they have a perspicuous risk of burning food; therefore, someone must be present during cooking. An illustrative, precise, and useful comparison of the solar cooker types concerning the performance mentioned above criteria is given in Table **1**.

Table 1. Classification of solar cooker types by some main performance parameters.

Criteria	Solar Panel Cooker	Solar Box Cooker	Solar Parabolic/ Dish Cooker	Advanced Solar Panel Cooker	Solar Box Cooker With Booster Reflectors And Heat Storage	Advanced Solar Parabolic/Dish Cookers With Solar Tracking And Highly Reflective Coating
Efficiency	Very poor	Fair	Good	Poor	Good	Very good
Cooking Speed	Very poor	Poor	Very good	Poor	Fair	Very good
Cost	Very good	Good	Poor	Good	Fair	Very poor
Durability	Poor	Fair	Good	Fair	Good	Good
Reliability	Good	Good	Poor	Very good	Good	Poor
Versatility	Poor	Poor	Poor	Poor	Fair	Poor
Portability	Very good	Good	Very poor	Very good	Fair	Very poor
Heat Storage	Very poor	Good	Fair	Very poor	Very good	Good

CHAPTER 8

Application and Development in Solar Cooking

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Abstract: The consumption of conventional energy has increased exponentially due to the ever-increasing population of the world. Studies revealed that cooking activities contribute majorly to the overall energy consumption throughout the globe, further accounting for an increasing global warming potential. Being an enormous, virtually unlimited, and expandable source, solar energy turns out to be a favorable solution to the situation. Solar energy's widespread availability and processing technologies make the thermal energy conversion process easily accessible. Hence, solar energy has emerged as a 'natural solution' to the energy crisis and the adverse environmental impact, such as the greenhouse effect. This chapter outlines the various solar cooker fundamentals and development in different types of solar cookers, namely box type, panel, funnel type, parabolic type, and indirect type, along with the application of different solar cookers.

Keywords: Application, Box type, Development, Solar cooker, Solar thermal.

1. INTRODUCTION

After absorption and dispersion, the solar flux reaching the Earth's surface is about 1.08108 GW, equivalent to 3,400,000 EJ of energy reaching the Earth's surface each year, contributing to 7000-8000 times the world's annual primary energy consumption [1]. In general, energy management depends upon two key parameters, energy-saving and maximum use of non-conventional sources of energy. Studies revealed that the energy crisis could be reduced by moving towards non-conventional sources of energy [2]. The application of solar energy has a broad array of choices, including utilization as thermal power and photovoltaic conversions. Thermal utilization of solar energy has undergone extensive research

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compared to photovoltaic or other forms because it is not limited to a particular solar radiation region. Although medium and high-temperature utilization of solar energy dominates the energy sector, the critical importance of low-temperature necessities in human life, such as cooking, water heating, conventional air dehumidification by using desiccant, *etc*., cannot be ignored because of their potential possibilities at various scales and forms ranging from our homes, societies, and townships to industries and businesses. Of all the practiced utilities, cookers based on solar energy are the simplest, feasible and lucrative choice that offers an extremely efficient and tidy cooking method. It is widely suited to urban and rural living in all worlds, developed, developing or underdeveloped regions experiencing a scarcity of energy [3]. The expected high demand for conventional fuel for cooking is due to the fast-changing work culture, modernization and global warming. Solar energy is considered a potential way to lower the demand for a conventional energy sources.

Solar cookers are recognized as one of the most successful solar energy applications. Due to their simple design, reachability, cost-efficiency, reliability, and performance, they have become a favorite subject of both scientists and consumers in the rural areas of developing countries [4]. The general classification of solar cookers may be difficult because they are available in numerous designs with various applications. However, scientifically, we can still evaluate solar cookers under the following three major heads based on their shapes: solar box cookers, solar panel cookers, and solar parabolic/dish cookers [5]. Most NGOs around the world are encouraging the utilization of solar cookers to minimize the conventional fuel expenses (an enthusiastic step for below the poverty line people), reduce the emission of greenhouse gases and, slow down deforestation, overcome land degradation due to mining coal and chopping wood for cooking, and increase the status of women [6].

The first solar cooker was developed and tested for cooking by a Swiss Naturalist in 1767 [7]. Until the discovery of solar energy-based advanced cooking devices (*i.e*., box-type solar cookers), most of their predecessors suffered from numerous deficiencies [8]. However, another truth is that, despite their benefits, solar energy-based devices have not been broadly utilized, especially for domestic purposes, although many inexpensive designs exist [3, 9, 10]. Few studies have been carried out to make solar cookers more user-friendly and practicable for developing and developed countries [11]. In many developing countries with abundant annual solar radiation, the employment of such devices has recently increased [12]. Researchers have compared solar energy-based cookers with conventional energy-based cooking devices in India and revealed that, after the conventional gas (LPG) and naphtha-based cookers, solar box type cooking devices are in the third position, followed by solar concentrating type cookers in the order of practical adoption [13].

2. CLASSIFICATION OF SOLAR COOKERS

A variety of energy sources are used for cooking on Earth. Although, most of the rural areas of developing countries are mainly dependent on wood and coal for cooking. Conventional sources of energy are decreased with the increase in population. Therefore, around 350 NGOs worldwide are promoting a non-conventional source for cooking. Solar Cooker International (SCI, 2020) is one of the top NGOs in the world that is determined to promote pollution-free sustainable development and, more importantly, to make the end-users aware of the benefits and impact.

Solar Cooker International (SCI) has introduced many types of solar cookers, like box cookers, panel cookers, parabolic cookers, trough cookers, evacuated tube cookers, fresnel solar cooker designs, and solar wall oven designs. Currently, many types of solar cookers are available. Therefore, solar cookers can be classified under various distinctions, such as their shapes and operability. The detailed classification of solar cookers is shown in Fig. (**1**).

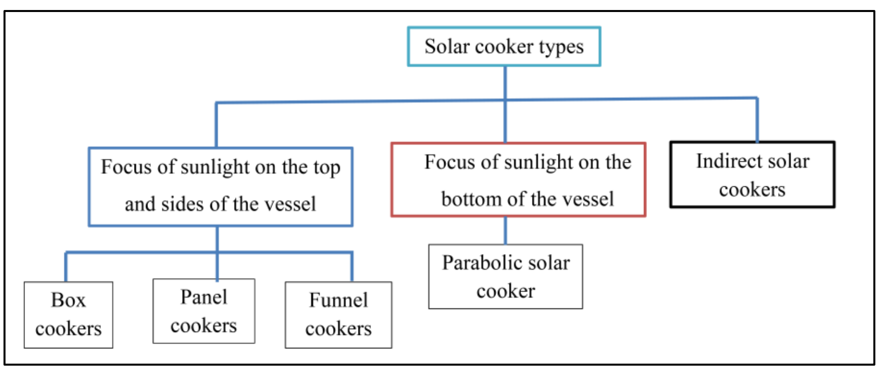

Fig. (1). Solar cooker classification.

A way to describe the performance of solar energy-based cooking devices is through attributes, such as effectiveness, cooking time, payback period, the required operational care, versatility (capable of cooking a variety of food), portability, thermal energy storage function (ability to cook after sunset), performance in severe weather conditions like cold and windy, performance when clouds are obstructing the sunlight or condition with low solar radiation, *etc*. Considering the above-mentioned performance factors, each solar cooker has its own merits and demerits

CHAPTER 9

Semi-Transparent Photovoltaic Thermal (SPVT) Modules and their Application

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Abstract: In this review, an attempt has been made for various applications of semi-transparent photovoltaic thermal (SPVT) modules used for PVT-CPC water air collector, drying, space heating/cooling of the building, greenhouse integration for agricultural production of vegetables, and power generation. It has been observed that semi-transparent photovoltaic thermal (SPVT) modules are more efficient and economical for many sectors and have more advantages than opaque photovoltaic thermal modules. The brief details of each case have been discussed. Furthermore, a greenhouse integrated semi-transparent photovoltaic thermal (GiSPVT) system has been elaborated for vegetable growth with different packing factors.

Keywords: Semi-transparent PV module, Solar energy, Thermal energy.

1. INTRODUCTION

It has now been established that solar-cell-based photovoltaic (PV) technology is best suited for the sustainability of the environment and climate [1]. A photovoltaic (PV) system produces electrical power by harnessing solar energy. Solar power generation plants come under renewable energy sources (RES) as they do not involve fossil fuels, such as coal, petroleum, and natural gas sources for power generation. Solar PV plants are classified broadly based on their location.

Furthermore, photovoltaic thermal modules are generally known as PVT, generating both DC electrical and thermal energy using solar energy. The history and development of PVT technology have been described by Tiwari and Dubey [2]. It is also important to mention that PVT technology is a self-sustained system and does not require grid power to operate solar thermal technology under the forced

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mode of operation. Furthermore, the photovoltaic module has been categorized as opaque and semi-transparent transparent PV modules. It has been found that semi-transparent PV modules are more efficient in terms of electrical efficiency [3]. There are many applications of PVT technology which include:

➢**PVT-CPC water/ air collectors:** Tiwari *et al.* [4] have developed a general expression for an analytical thermal and electrical model for outlet fluid temperatures, the rate of thermal, electrical energy, overall thermal energy and exergy, and an instantaneous thermal efficiency. The developed thermal and electrical models are valid for conventional flat plate collectors, PVT, and CPC collectors. The PVT-CPC collector can be used for active solar distillation [5], swimming pool heating [6], biogas digester heating [7], and vapor absorption refrigeration (VAR) system [8].

➢**PVT solar dryers:** Based on the literature survey, it can be observed that a mixed-mode solar dryer is the most appropriate technology for vegetables/fruit crop drying to retain its color, quality, and market value. The semi-transparent integrated dryer is self-sustaining and most suitable [9, 10].

➢**PVT building:** Basically**,** there are three types of PV integration into a building as per requirement, namely (a) on the roof to provide only electrical power and reducing solar flux into the room below it for cooling purposes, (b) rooftop installation to provide electrical power and shadow over the roof for thermal cooling, and (c) integration on the roof as a greenhouse for use as an electrical power source as well as greenhouse roof for either floriculture, dryer or sunbath during winter [11]. In the first case, opaque PV modules have been used, while in the second and third cases, opaque and semi-transparent PV modules have been used.

➢**PVT greenhouse:** There are many categories of a greenhouse concerning shape, cost, uses, technologies, *etc.* [12]. It has been found that ridge and furrow type greenhouse is most economical from the commercial point of view. Based on a review of the research work, it has been found that only semi-transparent PV modules, which generate more electrical power, can also be used as a roof of a greenhouse for the photosynthesis process needed for plant growth inside a greenhouse.

2. COMPARISON BETWEEN THE PERFORMANCE OF OPAQUE AND SEMI-TRANSPARENT PV MODULES

In this section, we will discuss the energy balance of a single opaque and semi-transparent PV module with the following assumptions:

(i) One-dimensional heat conduction.

(ii) The system is in a quasi-steady state condition.

(iii) The ohmic losses between solar cells of PV modules are negligible due to high electrical conductivity.

(iv) The heat capacity of transparent glass, tedlar, and ethyl vinyl acetate (EVA) is negligible.

2.1. Energy Balance for Opaque (Glass to Tedlar) (Fig. 1a)[13]

In this case, solar radiation, $I(t)$, after transmission from the glass cover $\tau_g I(t)$ is absorbed by a solar cell with an area A_m and packing factor, β_c is $\tau_g \alpha_c \beta_c I(t) A_m$. The remaining solar radiation, $\tau_g (1-\beta_c) I(t)$, is absorbed by Tedlar (α_T) on the non-packing area of the PV module, which is $\tau_g \alpha_T (1-\beta_c) I(t) A_m$. The temperature of solar cells increases when light is reflected on them. Therefore, there will be (a) an upward rate of overall heat loss $\left[U_{t,ca}(T_c - T_a) A_m\right]$ from the solar cell to ambient air through the top glass cover and (b) bottom rate of overall heat loss $\left[U_{b,ca}(T_c - T_a) A_m\right]$ from the solar cell to ambient air through tedlar in addition to electrical power generation as $\tau_g \eta_c \beta_c I(t) A_m$. The thermal circuit diagram corresponding to Fig. (**1a**) in terms of various heat loss and gain has been shown in Fig. (**1c**).

Following Fig. (**1a**), an energy balance equation for an opaque PV module can be expressed as follows:

$$\tau_g[\alpha_c \beta_c I(t) + (1-\beta_c)\alpha_T I(t)] \\ = \left[U_{tc,a}(T_c - T_a) + U_{bc,a}(T_c - T_a)\right] + \tau_g \eta_c \beta_c I(t) \quad \textbf{(1)}$$

The above equation can be rearranged as

$$\tau_g[\alpha_c \beta_c I(t) + (1-\beta_c)\alpha_T I(t)] = U_{Lm}(T_c - T_a) + \eta_m I(t) \quad \textbf{(2)}$$

CHAPTER 10

Developments in Solar PV Cells, PV Panels, and PVT Systems

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Abstract: With the advancement in technology and manufacturing techniques, various solar cell materials evolved, and their practical implementation led to modification in the design and installation of photovoltaic panels. Different solar cells are compared in this chapter considering their efficiency, performance, temperature coefficient, *etc.* Developments in PV panel and photovoltaic thermal (PVT) systems are outlined with their respective applications and advantages. It was found that the cost and efficiency of any solar cell are crucial parameters for deciding its implementation in PV panels. Additionally, the solar panel's temperature deflates its efficiency and lowers the thermal conversion. In order to overcome this problem, a PV system was incorporated with different thermal storage materials and cooling mediums, such as air, water, oil, fluids, *etc.*, lowering the temperature of solar panels and making them able to store the excess solar thermal energy to use it during the sun-off period. It was concluded that thin solar cells, such as perovskite and DSSC solar cells, are widely used where flexibility is important and thermal storage materials are utilized with nanoparticles for better thermal efficiency.

Keywords: Bifacial, Electricity, Power, PVT, Solar cell, Solar energy.

1. INTRODUCTION

Due to abrupt changes in the climatic condition of the world and the total consumption of conventional resources, it is high time to utilize renewable energy most effectively. Although actions have been taken globally in this field, its abundant nature and future potential are still concerning for researchers and scientists. Generally, solar energy utilization is directly linked with solar rooftops

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generating electricity, but solar panels' efficiency is inversely proportional to their temperature. In 2009, the Jawaharlal Nehru National Solar Mission (JNNSM) was launched. The goal was to initiate 20 GW of grid-connected solar projects by 2022. The government raised the target to 100 GW by 2022 in May 2015. With solar energy projects in Tamil Nadu, Rajasthan, Gujarat, and Maharashtra, solar power has become India's fastest-growing industry and continues to produce electricity.

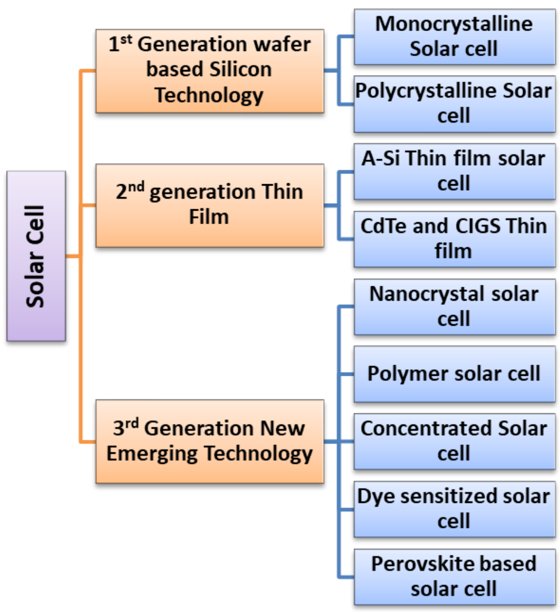

Fig. (1). PV Material Chart [2].

These states are also the top five states with India's highest wind electricity production. Solar energy prices have decreased from Rs. 17.90 per unit in 2010 to around Rs. 7 per unit in 2015. Moreover, solar power achieved grid parity in 2017-18 with technological advances and market rivalry. The Ministry of Energy Resources for Non-Convection, the Government of India, is attempting to increase its power capacity and meet the 100 GW mark by 2022 [1].

2. MATERIAL AND CLASSIFICATION OF SOLAR CELL

A description of the manufacturing materials of solar cells can be found in Fig. (**1**). Silicon is widely used to manufacture solar cells because it has high efficiency.

Owing to its high costs, however, most researchers are searching for better technologies that can reduce the cost of a solar cell.

Table 1. Advancement in photovoltaic technology with time.

Year	Development	Reference
1839	Antoine – Ceser Becquerel discovered voltage output by exposing solid electrodes to electrolytes. This impact has been called the PVE.	[2]
1876	The first development was the selenium cell invented by W.G., R.E. and Adams. Photovoltaic effects were observed in solid selenium.	[3]
1883	Charles Fritz developed the first true solar cell. He used a thin layer of gold for coating semi-conductor selenium, which had an efficiency of less than 1 %.	[4]
1904	Albert Einstein wrote the first article on the photoelectric effect	[3]
1927	A new cell is produced using copper and copper oxide type, which has less than 1 % efficiency.	[2]
1941	Russell developed the photovoltaic silicon cell	[2]
1954	In silicon photovoltaic cells, the performance of the bell labs has increased rapidly to 6% and 11%.	[4]
1958	Photovoltaic cells were used in space for the first time.	[3]

3. GENERATION OF PHOTOVOLTAIC CELL

Some roadmaps are generated from the research and development (R&D) strategies, which depend on the process and technology. In 2001, a general roadmap of photovoltaic (PV) was presented by Martin Green [5]. According to this PV roadmap, the production of crystalline silicon modules cannot be lower than 1 USD/Wp, which leads to the generation of other technologies. This roadmap categorized PV cell fabrication technologies and materials into three generations, as shown in Fig. (**2**). A wafer-based crystalline silicon cell represents the quite efficient first-generation but is not too encouraging because of higher prices.

CHAPTER 11

Thermal Modeling of Greenhouse Solar Dryers

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Abstract: In agricultural applications, the preservation of crops is essential. The most suitable method of preserving the crop is drying. The traditional methods used for drying include mechanical drying, where hydrocarbon fuel or burnable materials are used as a source of heat. The other method is open sun drying, where crops are placed in an open space. Both methods affect the quality and vital nutritious properties of the crops. The mechanical drying processes are costly, whereas the latter is dependent on the weather condition. To overcome these limitations, solar dryers are developed. Mathematical modeling is highly important for the perfect design and improvement of solar dryers. The performance of the drying system depends upon the different parameters that can be optimized using thermal modeling. This chapter covers the thermal modeling of greenhouse solar dryers for active and passive modes.

Keywords: Direct, Hybrid, Indirect, Solar dryer, Thermal modeling.

1. INTRODUCTION

The drying process used for crop preservation is one of the energy-intensive processes. Many societies and organizations are working to develop an effective and economical source of green energy to achieve optimum drying efficiency and minimum energy consumption in the drying processes [1]. Solar dryers can be grouped into direct, indirect, and mixed-mode dryers. In direct dryers, solar radiation, after transmitting through a transparent cover, strikes directly over the item to be dried. In contrast, in indirect dryers, the solar energy is utilized to heat the air externally in solar collectors, and then hot air is supplied to the opaque drying cabinet [2]. A mix of these two types is a mixed-type solar dryer [3]. The dryers operate in two modes, namely active and passive mode. In active dryers, fans or blowers are used to maintain the air circulation inside the dryer, while in passive

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dryers, the air movement takes place naturally due to the buoyancy effect. The general classification of the dryer is shown in Fig. (**1**).

Thermal modeling is done using the energy balance principle of the first law of thermodynamics. The total energy input to the system must be equal to the energy going out of the system. In other words, the energy gain is always equal to the energy lost by the system. Different researchers established the energy balance of the different parts of the dryers like room air, the floor of dryer, the surface of crop, the surface of covering material, PV module surface, *etc.* The main aim of energy balance or thermal modeling is to develop an expression that can predict the temperature of the different parts of a particular type of dryer. The steps that can be followed to carry out the thermal modeling of any developed dryer are encapsulated in this chapter.

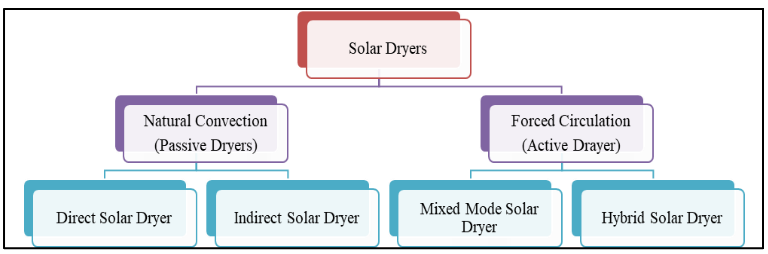

Fig. (1). General classification of solar dryers.

2. THERMAL MODELS

The thermal modeling helps in designing solar greenhouse dryers for a specific mass of crops and optimizing the design variables to maximize the performance in typical situations and for particular shapes and sizes. Using the thermal model simulation, we can investigate the effect of the design and shape of a solar dryer on the drying kinetics of the specific crop. The developed expression helps predict the required design parameters using the easily available parameters like solar radiation, ambient temperature, relative humidity of the air, the mass of crop to be dried, *etc.* This saves time as there is no need to perform the experiment to optimize the required parameter.

2.1. Moisture Ratio

The moisture ratio of a crop denotes a decrease in moisture content of the particular crop over time. The water mass inside the cops reduces with time inside the dryer. Mathematically, it is the ratio of moisture inside the crop at any instant to the initial moisture content of the crop. To predict the moisture ratio, various co-relations given by different researchers are provided in Table **1**. These expressions can predict the moisture inside the crop after a particular time interval.

Table 1. Mathematical model applied in the drying process.

S. No.	Author Model Name	Equation	Reference
1.	Henderson and Pabis	$M_r = a.\exp(-kt)$	[4]
2.	Prakash and Kumar	$M_r = at^3+bt^2+ct+d$	[5]
3.	Approximation of diffusion	$M_r = a.\exp(-kt)+(1-a)\exp(-gt)$	[6]
4.	Lewis	$M_r = \exp(-kt)$	[7]
5.	Modified Page equation-II	$M_r = \exp[-k(t/L^2)^n]$	[8]
6.	Logarithmic	$M_r = a.\exp(-kt) +c$	[9]
7.	Page	$M_r = \exp(-kt^n)$	[7]
8.	Modified Henderson and Pabis	$M_r = a.\exp(-kt) +b.\exp(-gt) +c \exp(-ht)$	[10]
9.	Verma *et al.*	$M_r =a.\exp(-kt)+b.\exp(gt)+c.\exp(-ht)$	[11]
10.	Thompson	$T = a. \ln(M_r)+b.[\ln(M_r)]^2$	[8]
11.	Two-term	$M_r = a.\exp(-k_0t)+b.\exp(-k_1t)$	[8]
12.	Wang and Singh	$M_r = 1+at+bt^2$	[5]
13.	Simplified Fick's diffusion equation	$M_r = a.\exp[-c (t/L^n)]$	[12]
14.	Midilli and Kucuk	$M_r = \exp(-k.t^n)+bt$	[5]
15.	Page's Modified	$M_r = \exp[-(kt)^n]$	[6]
16.	Two-term exponential	$M_r = a.\exp(-k.t)+(1-a) \exp(-k.a.t)$	[13]

2.2. For Natural Convection Solar Dryer

The energy balance established by Jain and Tiwari [10] for the natural convection greenhouse dryer is given as follows:

2.2.1. Crop Surface

The transmitted solar radiation received by the crop surface is equal to the summation of energy stored inside the crop and the energy lost by the crop through convection and evaporation.

CHAPTER 12

Case Study on Thermal and Drying Performance Index of Hybrid Solar Dryer with Evacuated Collector

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Abstract: Solar drying is one of the oldest and most popular food preservation methods that involve moisture removal by a complex heat and mass transfer phenomenon. The process of the drying system is dependent on a number of operating parameters. In the present chapter determination of thermal and drying performance parameters is discussed. A hybrid solar drying system with the integration of an evacuated water tube solar water heater is installed and tested for drying hygroscopic leaf crops. The drying performance of the hybrid system is evaluated in terms of mass reduction and its derived influence on moisture content and drying rate. The derived parameters are compared with the corresponding evaluations under open sun drying. The rise in greenhouse environment temperature and crop surface temperature at hourly intervals as compared to the ambient condition were used as parameters for the thermal performance of dryer. The average values of SMER were 60% lesser than that of the simple PVT-hybrid system (without ETSC), but the drying performance parameters of mass reduction, drying rate and mass shrinkage ratio provide favourable results. The drying time was reduced by 3.5 and 2.5 hours, respectively, for the present sample size of two crops as compared to the open sun drying.

Keywords: Hybrid, Solar dryer, Evacuated tube, Solar collector, Drying.

1. INTRODUCTION

Using the power of the Sun for the preservation of foodstuff and other products from agriculture has been in practice for centuries. The recent solar drying methods have good efficiency, provide hygiene and are capable of preventing the crops from undue damage. Researchers have proposed several designs of solar dryers with arrangements for favourable drying conditions. Performance evaluation of these

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modified drying systems is important in terms of comparative analysis with conventional designs. The selection of a solar dryer for a particular food product is determined by quality requirements, product characteristics and economic factors. A systematic classification of available solar food dryers, based on the design of system components and the mode of utilization of solar energy, is presented in Fig. (**1**).

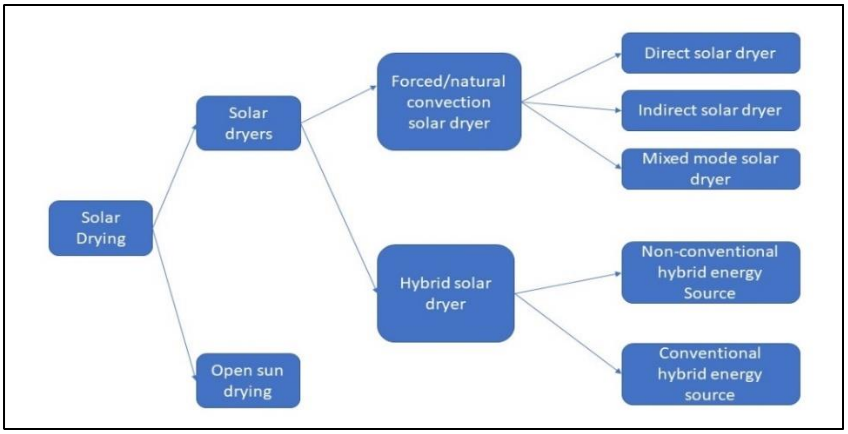

Fig. (1). Broad Classification of solar drying systems.

Flat plate collector type solar dryers are widely used for generating heated air for drying the products as compared to evacuated tube collectors. Recently some researchers have used evacuated tube heating as assistance for solar dryers and achieved favourable results.

Solar vacuum tubes were used by Mahesh *et al.* to increase the temperature of the supplied ambient air by heating. Testing of setup was carried out for drying various samples of vegetables and fruits. The result showed that conventional drying takes almost 150% more time as compared to the designed vacuum tubes type dryer [1]. Daghigh and Shaifeian used a double function heat pipe type vacuum tube drying. system and produced hot air at 45.5 °C. Outcomes of the analysis suggest that the heat provided by the evacuated tube was enough to replace the usage of auxiliary electric heating after certain hours of sunshine [2]. Ubale *et al.* tested the performance outcomes of vacuum tube solar collector for drying grape with forced convection heat transfer mode. The gross efficiency of the designed collector was found to be 24.3% as compared to 16-22% for flat plate collectors [3]. Thermal performance through experimental investigation was determined by Singh *et al.* for an evacuated tube-based solar dryer having shell and tube heat exchanger as main components integrated with drying space. The result showed 35.4 °C as the maximum rise in hot air temperature as compared to ambient air and 55% as the maximum evaluated efficiency of the setup [4]. Singh *et al.* developed a batch-type dryer using an evacuated tube for banana chips drying in a closed area. The influence of time of drying on energy, exergy, economic and other parameters were evaluated. The result showed comparatively better performance as compared to simple heat pump-based dryers [5]. Malakar *et al.* used heat pipe for development of solar dryer and performed experimentation for drying 10kg of garlic cloves 69% to 8% moisture content (wb). Using airflow velocities of 1, 2, and 3 m/s, the thermal performance was determined at no load and full load conditions. The highest temperature, drying rate and exergy efficiency achieved were 86.7°C, 1.56 kg H_2O/kg dry solid/h and 56.59% at 2 m/s airflow velocity [6].

2. MATERIAL AND METHOD

The complete assembly of hybrid greenhouse dryer (HSD) with evacuated water tube collector, as shown in Fig. (**2**) is mounted on the roof of Madhav Institute of Technology and Science, Gwalior, India (26.2183° N, 78.1828° E). The setup consists of frame type drying platform placed inside the greenhouse with two layers of floor area 200x185 cm each. Each layer of drying platform has 17 arrays of U-type copper tubes, each having length of 196cm for a series flow of heated water. Steel wire mesh with holes of 1.2x1.2 mm and wire diameter 0.3mm is placed over the copper tubes; this wire mesh gains heat by direct contact with copper tubes and transfers it to the drying product placed over it, besides this the greenhouse environment air also receives this additionally secondary heat (primary source is greenhouse heating). The fresh air enters from a 15 mm height wire mesh passage at the bottom of the greenhouse. The desired greenhouse temperature is maintained by controlling the rate of flow of heated water inside the copper tubes through a flow regulating valve [7].

Fig. (2). Actual view of installed PVT-hybrid greenhouse dryer.

CHAPTER 13

Thermal Analysis of Photovoltaic Thermal (PVT) Air Heater Employing Thermoelectric Module (TEM)

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Abstract: This chapter provides the description and analysis of a photovoltaic thermal (PVT) air heater, including a thermoelectric module (TEM). A PVT air heater offers several advantages over a PVT water heater. The problems such as corrosion and freezing do not exist when air is used as a working fluid. Also, the system design is less complex, incurs lower operation costs and can be easily integrated into buildings. Furthermore, it is not a cause of any major concern in case of air leaks from the duct. A PVT air heater poses some drawbacks as well, such as uneven cooling of PV panels and lower overall efficiency compared to a PVT water heater resulting from lower specific heat capacity of air. Nevertheless, the choice of the type of working fluid is subject to a variety of factors like efficiency, cost including capital investment, installation, operation and maintenance costs and the particular application.

Keywords: Bifacial, Electricity, Power, PVT, Solar cell, Solar energy.

1. CLASSIFICATION AND WORKING PRINCIPLE

A conventional photovoltaic thermal (PVT) air heater consists of an air duct placed underneath (or above) a photovoltaic module for the flow of air [1]. Huen and Daoud [2] reported a comprehensive literature review on thermoelectric modules coupled with solar technologies. A PVT air heater, therefore, produces both heated air at the outlet of the duct and electricity from the solar cells. The air flowing through the duct removes heat from the solar cells, which in turn reduces the solar cell temperature and improves the electrical efficiency of the PV module [3]. If a thermoelectric module (TEM) is incorporated in the design of the PVT air heater,

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it contributes to the total electrical production and the resulting new design is termed a PVT-TEM air heater. Fig. (**1**) illustrates the cross-sectional view of a PVT-TEM air heater, where the thermoelectric module (TEM) is placed below the PV module. A PV module consists of solar cells encapsulated between a top layer and a bottom layer. Typically, glass is used as the top covering layer to protect the solar cells against dirt and other environmental issues since it allows the solar radiation (*i.e.* short wavelength radiation) to transmit through to be absorbed by the solar cells. The solar cells absorb the solar radiation incident over the packing area of the PV module, transmit through the top glass cover, and produce electricity. The bottom layer of PV module could be either transparent (glass), making the design semi-transparent, or opaque (tedlar). TE module is essentially a combination of p-type and n-type semiconductors, connected thermally in parallel while electrically in series, and encapsulated between thermally conducting plates. Bismuth and antimony alloys are the most commonly used materials for TEM owing to their properties of low thermal conductivity and high electrical conductivity [4]. The working principles of semi-transparent and opaque PVT-TEM air heaters are discussed next.

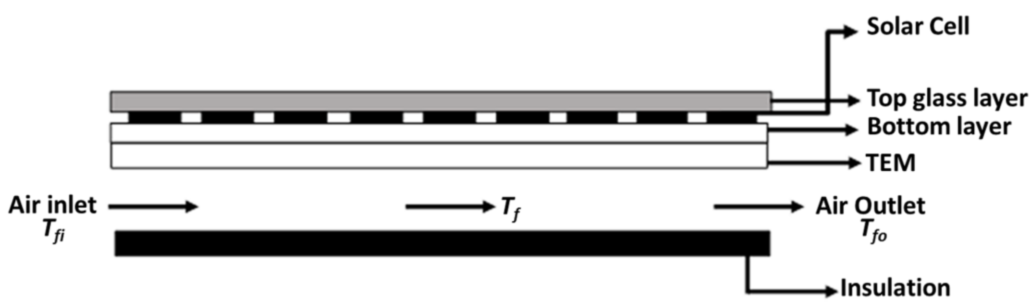

Fig. (1). A schematic representation of PVT-TEM air heater [5–7].

1.1. Semi-transparent PVT-TEM Air Heater

When glass is used as the bottom layer (Fig. **1**), the PVT-TEM air heater is known as a semi-transparent PVT-TEM air heater. Therefore, the top-side of TEM receives and absorbs the solar radiation entering through the non-packing area of the PV module ($(1-\beta_{sc})A_m$), *i.e.* direct gain. Also, the top side of TEM receives thermal energy from the bottom of the solar cells, through indirect gain, reducing the solar cell temperature. The temperature of the top-side of TEM increases as a result of both direct and indirect gain. Moreover, heat is extracted owing to the air flowing in the duct from the bottom-side of TEM. This increases the temperature of the air at the outlet of the duct, and the heated air is utilized for space heating applications. The flow of air helps to maintain a temperature gradient across the TEM and hence, the TEM produces electricity through the Seebeck effect [8].

1.2. Opaque PVT-TEM Air Heater

Opaque PVT-TEM air heater has tedlar, *i.e.* opaque in nature, as the bottom layer (Fig. **1**). Therefore, tedlar absorbs solar radiation through the non-packing area of the PV module (direct gain). Further, thermal energy flows from underneath the solar cells to tedlar (indirect gain). This causes an increase in the temperature of the top side of TEM, which obtains thermal energy from the tedlar. Furthermore, the air flowing in the duct reduces the bottom-side temperature of TEM, leading to a temperature difference and generation of electricity. The heated air at the outlet presents a thermal energy gain from the air heater. The schematic representation depicted in Fig. (**1**) can be used in forced mode, wherein the electricity produced by the PV module and TEM is used to drive the pump for the circulation of air through the duct to make the system self-sustained.

In the next section, thermal models of semi-transparent and opaque PVT-TEM air heaters based on the energy balance between different components will be presented and discussed. The assumptions considered while writing the energy balances are stated below:

a) The PVT-TEM air heater is assumed to be in quasi-steady state.

b) Absence of temperature difference across the thickness of air column, solar cell, glass cover and tedlar.

c) The heat capacity of glass cover, tedlar and solar cells is neglected.

d) Ohmic losses in solar cells are negligible.

e) One-dimensional heat flow has been assumed.

f) The temperature of the top of tedlar (in the case of an opaque PVT-TEM air heater) is the same as the solar cell temperature.

CHAPTER 14

Applications and Development of Solar Systems in Buildings

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Abstract: Many harmful effects on the environment can be observed over the past decades due to the extensive usage of non-renewable energy. Most discussed and harmful are the ever-changing global climate change scenarios and their aftermath. As a point of fact, a major part of the world's energy consumption is dependent on non-renewable energy sources, such as petroleum, oil, coal, and gas. Unquestionably, these fossil fuels contribute a great deal to greenhouse gas emissions, carbon dioxide, methane, *etc*., which further leads to global health issues, global warming, and climate change. With the emergence of sustainable development as a holistic concept since the late 1980s, the issue of global warming has been given prominent attention. It is evident that failure to curb global warming has led to slower progress in achieving sustainable development. About 30% of energy demand is from the built environment sector, which is also responsible for contributing 28% of carbon emissions and continues to add an estimated 1% every year, according to reports by UN Environment [1]. Therefore, the fossil fuel-based energy systems are antagonistic with the goals of sustainable development agendas. Hence, using renewable sources in harnessing clean energy for the built environment has not remained a choice but a fundamental need. Solar energy is one of the cleanest renewable energy sources that provide solutions to climate change and global warming. Often termed as the alternative energy source against oil and coal-based energy sources, solar energy has the potential for abundant availability and is an economical way with a lower ecological and environmental footprint, leading to a better quality of life. Thus, there is a massive amount of global interest in harnessing solar energy for its application and development in building systems.

Keywords: Application, Buildings, Development, Solar systems, Solar in buildings.

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1. SOLAR ENERGY RESOURCE IN WORLD

Solar energy has become the third most substantial renewable energy source with more than 486GW of installed capacity, with photovoltaic (PV) being the leading technology (Fig. **1**). By the end of 2021, the global concentrating solar power (CSP) installed capacity will reach about 5.5 GW, hinting at the rise of CSP technology. At present, the giant solar PV capacity is being possessed by India, China, US, Germany, Italy, and Japan in the world, whereas 42% of the global CSP capacity is dominated by Spain. During the last five years, the annual growth rate of cumulative solar energy capacity has averaged about 25%, which makes solar the fastest growing renewable power source. Of the total of 94 GW of global solar power expansions, Asia accounted for approximately 70%, while Germany, the United States, and Australia added 3.6 GW, 8.4 GW, and 3.8 GW in recent solar-powered projects during the past year. At present, the largest single-site solar power plant in the world is United Arab Emirates' 1.17GW Noor Abu Dhabi solar project.

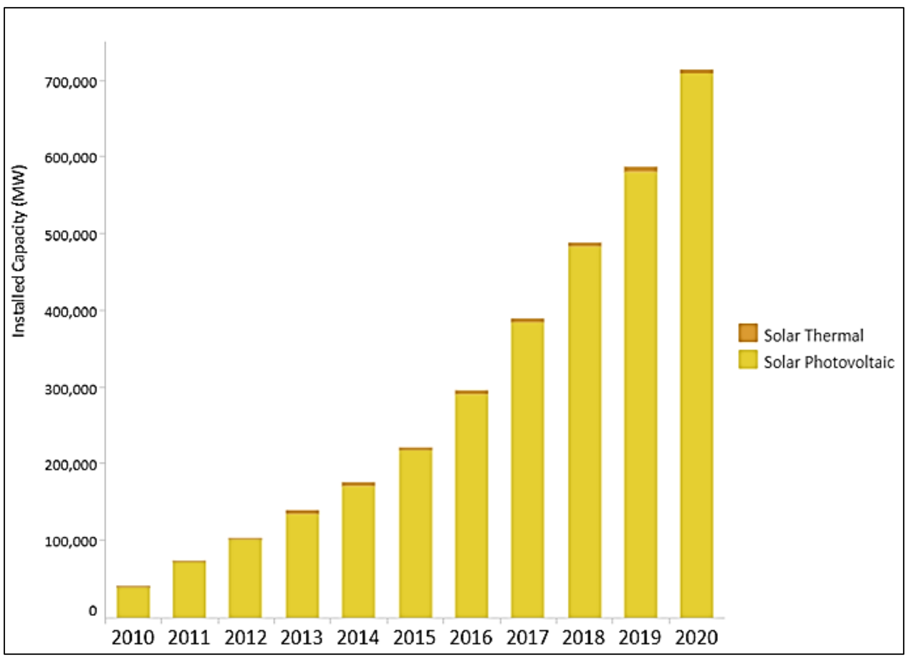

Fig. (1). Global trend of installed capacity in the past decade.

2. APPLICATIONS AND DEVELOPMENT OF SOLAR ENERGY IN THE BUILDING SECTOR

2.1. Solar Water Heating Systems

Since the early 1980s, solar energy has been utilized to arrange hot water at domestic levels and has since evolved technologically as well as at building scales. In this section, an overview of solar water heating developments in the building sector has been discussed. A solar water heating (SWH) system comprises typically of following units:

(i) Solar collectors

(ii) Thermal storagez

(iii) System controller unit

The application and development of solar water heating systems in the building sector are discussed below:

2.1.1. Passive Solar Water Heating Systems

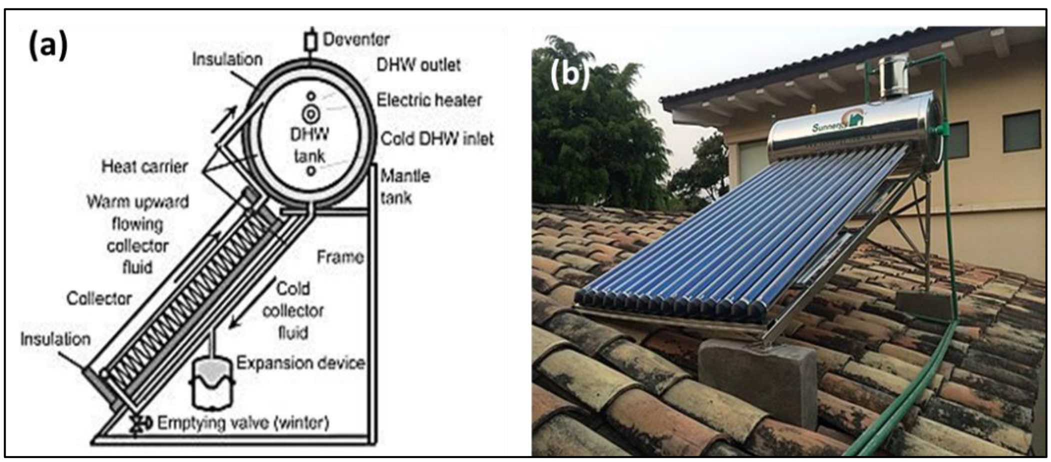

Fig. (2). (a) Schematic diagram of the passive solar water heater **(b)** Installed Thermosyphon SWH on roof.

This is also known as thermosyphon solar water heaters (Fig. **2**), and this type of system does not depend upon electricity and works on the principle of gravity (gravity-driven circulation) in a way that it uses the gravitational differences

CHAPTER 15

The CO_2 Mitigation and Exergo and Environ-Economics Analysis of Bio-gas Integrated Semi-Transparent Photo-voltaic Thermal (Bi-iSPVT) System for Indian Composite Climate

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Abstract: It is to be noted that biogas production is drastically reduced in cold climatic conditions, especially in winter, due to a drop in ambient air temperature, which is much below an optimum temperature of about 37℃ for fermentation of slurry. Many methods, such as hot charging, passive/active for slurry heating, have been tested, and it has been found that the passive heating method is neither practical nor self-sustained. In order to make bio-gas heating self-sustained, economical, and friendly to ecology and the environment, a new approach of Bi-iSPVT has been adopted. Based on the finding, we have made an attempt to analyze the system in terms of CO_2 mitigation, energy matrices, and environ- and exergo-economics to have a clean environment and sustainable climate. An analysis has been performed by using embodied energy, the annual overall thermal exergy of the system for ecological balance for the good health of human beings. It has been found that an energy payback time (EPBT) for a sustainable Bi-iSPVT system is about 1.67years, along with an exergo-economic parameter (*Rex*) of 0.1016 kWh/₹0.1016 $kWh/₹$.

Keywords: Active heating, Bi-iSPVT, CO_2 mitigation, Energy matrices, Energy payback time (EPBT).

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Manoj Kumar Gaur, Brian Norton & Gopal Tiwari (Eds.)

1. INTRODUCTION

Energy conservation is the way to conserve fossil fuel using either efficient fossil-based tools or renewable energy sources. One of the renewable energy sources is the use of wasted organic products, including cattle manure in biogas plants, by fermentation at an optimum temperature of 37°C. The product from the biogas plant is an excellent renewable fuel providing gas for clean energy applications and can be used for cooking, lighting, and water heating along with farming by using its waste [1-3]. This will help in the reduction of the use of fossil fuels. Energy conservation has become an important topic of research due to the increase in CO_2 levels in the atmosphere to 415 ppm from 270 ppm after world war-II. The main reasons behind this are the fast growth of industrialization and population density. In order to have a clean environment, energy conservation plays an important role. Normally, climatic conditions in the world are classified into six zones, namely (i) cold and humid, (ii) composite, (iii) harsh cold and sunny,(iv) moderate, (v) warm and dry, and (vi) warm humid. It is hard to design any renewable energy system for composite climatic conditions. For such climatic conditions, one needs to know the number of heating and cooling day requirements in a year. During the cold period, ambient air temperature is significantly dropped much below the optimum temperature for fermentation of slurry in the digester of biogas plants [4-6].

The following methods have been adopted in the past for slurry heating in cold climatic conditions:

(a) Passive method: In this case, marginal heating of slurry can be achieved by using a greenhouse over dome [7-13], glazed dome [14], covering of dome at night by an insulating cover, SSP water heater [15].

(b) Active method: Flat plate collector [13, 16,17],Tubular collector [18]

(c) Self-sustained active method: PVT-CPC collector [19,20]

In this paper, we have made an attempt to analyze the CO_2 mitigation, energy matrices, and environ- and exergo-economics of bio-gas integrated photovoltaic thermal (Bi-ISPVT) systems to balance between ecology and environment. The Bi-iSPVT can also be referred to as the active heating of biogas plants. It is observed that the energy payback time (EBPT) of such a system is 1.67 years with an energy production factor of 14.92, which is most economical from an ecological and environmental point of view. An exergo-economic parameter (*Rex*) of Bi-iSPVT has been found to be $0.1016\ kWh/₹$.

2. DESIGN OF BI-ISPVT SYSTEM

Fig. (**1**) shows that the digester of the biogas plant is integrated with semi-transparent photo-voltaic thermal (SPVT) collectors through heat exchangers to increase the slurry temperature during the winter period to maintain bio-gas production. In the present case, we have only considered a series connection of SPVT [20, 21]. The outlet of the SPVT collector is connected to the lower end of coil type heat copper exchanger for faster heat transfer between the fluid of the heat exchanger and the slurry of the digester. Furthermore, the outlet of the heat exchanger is connected to the inlet of the SPVT collector. The SPVT collector provides both thermal and electrical energy with an efficiency of 45% and 10%, respectively. The electrical energy is used to pump off the water of a capacity of 0.5 to circulate the fluid between the SPVT collector and digester under the forced mode of operation (6 hours/ day). Solar radiation incident of SPVT collector is partially converted into electrical power and the remaining into thermal energy to be used for slurry heating. The average annual solar radiation has been considered 450 Wm^{-2} with sunshine hours of 6 hours. The capacity of digester and production of biogas plants is 1000 kg and 35 m^3 per day [22].

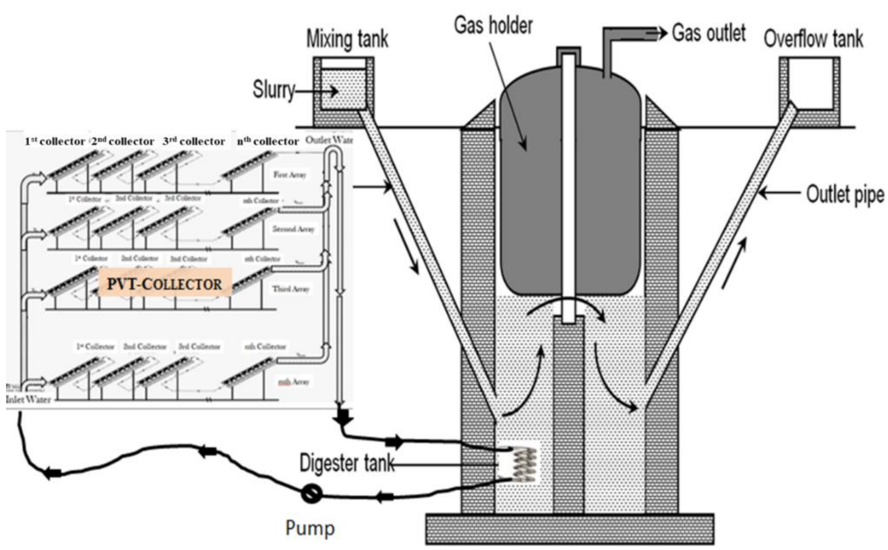

Fig. (1). Cross-sectional view of floating biogas integrated SPVT collectors connected in series and parallel.

APPENDIX

APPENDIX A

Expressions for various terms used in Eq. 50 and Eq. 66 are as follows:

$$U_{tca}=\left[\frac{1}{h_o}+\frac{L_g}{K_g}\right]^{-1} \quad ; \quad U_{tcp}=\left[\frac{1}{h_i}+\frac{L_g}{K_g}\right]^{-1} \quad ; \quad h_o=5.7+3.8V, Wm^{-2}K^{-1} \quad ; \quad h_i=5.7\, W/m^2K$$

$$U_{tpa}=\left[\frac{1}{U_{tca}}+\frac{1}{U_{tcp}}\right]^{-1}+\left[\frac{1}{h_i'}+\frac{1}{h_{pf}}+\frac{L_i}{K_i}\right]^{-1} \quad ; \quad h_i'=2.8+3V\ \ Wm^{-2}K^{-1} \quad ; \quad U_{L1}=\frac{U_{tcp}U_{tca}}{U_{tcp}+U_{tca}}$$

$$U_{L2}=U_{L1}+U_{tpa} \quad ; \quad U_{Lm}=\frac{h_{pf}U_{L2}}{F'h_{pf}+U_{L2}} \quad ; \quad U_{Lc}=\frac{h_{pf}U_{tpa}}{F'h_{pf}+U_{tpa}} \quad ; \quad PF_1=\frac{U_{tcp}}{U_{tcp}+U_{tca}}$$

$$PF_c=\frac{h_{pf}}{F'h_{pf}+U_{tpa}} \quad ; \quad PF_2=\frac{h_{pf}}{F'h_{pf}+U_{L2}} \quad ; \quad (\alpha\tau)_{1eff}=(\alpha_c-\eta_c)\tau_g\beta_c \quad ; \quad (\alpha\tau)_{ceff}=PF_c.\alpha_p\tau_g$$

$$(\alpha\tau)_{meff}=\left[(\alpha\tau)_{2eff}+PF_1(\alpha\tau)_{1eff}\right] \quad ; \quad (\alpha\tau)_{2eff}=\alpha_p\tau_g^2(1-\beta_c)' \quad ; \quad A_m=WL_m$$

$$A_cF_{Rc}=\frac{\dot{m}_fc_f}{U_{Lc}}\left[1-exp\left(\frac{-F'U_{Lc}A_c}{\dot{m}_fc_f}\right)\right] \quad ; \quad A_mF_{Rm}=\frac{\dot{m}_fc_f}{U_{Lm}}\left[1-exp\left(\frac{-F'U_{Lm}A_m}{\dot{m}_fc_f}\right)\right]$$

$$(AF_R(\alpha\tau))_1=\left[A_cF_{Rc}(\alpha\tau)_{ceff}+PF_2(\alpha\tau)_{meff}A_mF_{Rm}(1-\frac{A_cF_{Rc}U_{Lc}}{\dot{m}_fc_f})\right] \quad ; \quad A_c=WL_c$$

$$(AF_RU_L)_1=\left[A_cF_{Rc}U_{Lc}+A_mF_{Rm}U_{Lm}(1-\frac{A_cF_{Rc}U_{Lc}}{\dot{m}_fc_f})\right]$$

$$(AF_R(\alpha\tau))_{m1}=PF_2(\alpha\tau)_{meff}A_mF_{Rm} \quad ; \quad K_K=\left(1-\frac{(AF_RU_L)_1}{\dot{m}_fc_f}\right)$$

$$(\alpha\tau)_{effN}=\frac{(AF_R(\alpha\tau))_1}{(A_c+A_m)}\left[\frac{1-(K_K)^N}{N(1-K_K)}\right] \quad ; \quad K_m=\left(1-\frac{A_mF_{Rm}U_{Lm}}{\dot{m}_fc_f}\right)$$

$$U_{LN}=\frac{(AF_RU_L)_1}{(A_c+A_m)}\left[\frac{1-(K_K)^N}{N(1-K_K)}\right] \quad ; \quad (AF_RU_L)_{m1}=A_mF_{Rm}U_{Lm}$$

Expressions for a and $\underline{f}(t)$ used in Eq. 68 are as follows:

$$a=\frac{1}{M_wC_w}\left[\dot{m}_fC_f(1-K_k^N)+U_sA_b\right] \quad ; \quad \alpha'_{eff}=\alpha'_w+h_1\alpha'_b+h'_1\alpha'_g \quad ; \quad h_1=\frac{h_{bw}}{h_{bw}+h_{ba}}$$

$$\underline{f}(t)=\frac{1}{M_wC_w}\left[\alpha_{eff}{}'A_b\underline{I_s}(t)+\frac{(1-K_k{}^N)}{(1-K_k)}(A\,F_R(\alpha\tau))_1\underline{I}(t)+\left(\frac{(1-K_k{}^N)}{(1-K_k)}(A\,F_RU_L)_1+U_sA_b\right)\underline{T_a}\right]$$

$h_1' = \frac{h_{1w}A_g}{U_{c,ga}A_g + h_{1w}A_b}$; $h_{1w} = h_{rwg} + h_{cwg} + h_{ewg}$; $U_s = U_t + U_b$

$U_s = U_t + U_b$; $U_b = \frac{h_{ba}h_{bw}}{h_{bw} + h_{ba}}$; $U_t = \frac{h_{1w}U_{c,ga}A_g}{U_{c,ga}A_g + h_{1w}A_b}$; $U_{cga} = \frac{\frac{K_g}{l_g}h_{1g}}{\frac{K_g}{l_g} + h_{1g}}$

$h_{ba} = \left[\frac{L_i}{K_i} + \frac{1}{h_{cb} + h_{rb}}\right]^{-1}$; $h_{cb} + h_{rb} = 5.7\ Wm^{-2}K^{-1}$; $h_{bw} = 100\ W/m^2\mathrm{K}$

Expressions for different terms used in Eq. 73 and 82 are as follows:

$U_{tca} = \left[\frac{1}{h_o} + \frac{L_g}{K_g}\right]^{-1}$; $U_{tcp} = \left[\frac{1}{h_i} + \frac{L_g}{K_g}\right]^{-1}$; $h_o = 5.7 + 3.8V\ Wm^{-2}K^{-1}$; $h_i = 5.7\ W/m^2\mathrm{K}$

$U_{tpa} = \left[\frac{1}{U_{tca}} + \frac{1}{U_{tcp}}\right]^{-1} + \left[\frac{1}{h_i'} + \frac{1}{h_{pf}} + \frac{L_i}{K_i}\right]^{-1}$; $h_i' = 2.8 + 3V' W/m^2\mathrm{K}$; $U_{L1} = \frac{U_{tcp}U_{tca}}{U_{tcp} + U_{tca}}$

$U_{L2} = U_{L1} + U_{tpa}$; $U_{Lm} = \frac{h_{pf}U_{L2}}{F'h_{pf} + U_{L2}}$; $U_{Lc} = \frac{h_{pf}U_{tpa}}{F'h_{pf} + U_{tpa}}$; $PF_1 = \frac{U_{tcp}}{U_{tcp} + U_{tca}}$

$PF_2 = \frac{h_{pf}}{F'h_{pf} + U_{L2}}$; $PF_c = \frac{h_{pf}}{F'h_{pf} + U_{tpa}}$; $(\alpha\tau)_{1eff} = \rho(\alpha_c - \eta_c)\tau_g\beta_c\frac{A_{am}}{A_{rm}}$

$(\alpha\tau)_{2eff} = \rho\alpha_p\tau_g^2(1 - \beta_c)\frac{A_{am}}{A_{rm}}$; $(\alpha\tau)_{meff} = \left[(\alpha\tau)_{1eff} + PF_1(\alpha\tau)_{2eff}\right]$

$(\alpha\tau)_{ceff} = PF_c.\rho\alpha_p\tau_g\frac{A_{ac}}{A_{rc}}$; $A_{rm} = b_rL_{rm}$; $A_{am} = b_oL_{am}$

$A_cF_{Rc} = \frac{\dot{m}_fc_f}{U_{Lc}}\left[1 - exp(\frac{-F'U_{Lc}A_c}{\dot{m}_fc_f})\right]$; $A_mF_{Rm} = \frac{\dot{m}_fc_f}{U_{Lm}}\left[1 - exp(\frac{-F'U_{Lm}A_m}{\dot{m}_fc_f})\right]$

$(AF_R(\alpha\tau))_1 = \left[A_cF_{Rc}(\alpha\tau)_{ceff} + PF_2(\alpha\tau)_{meff}A_mF_{Rm}(1 - \frac{A_cF_{Rc}U_{Lc}}{\dot{m}_fc_f})\right]$; $K_K = \left(1 - \frac{(AF_RU_L)_1}{\dot{m}_fc_f}\right)$

$(AF_RU_L)_1 = \left[A_cF_{Rc}U_{Lc} + A_mF_{Rm}U_{Lm} + A_mF_{Rm}U_{Lm}(1 - \frac{A_cF_{Rc}U_{Lc}}{\dot{m}_fc_f})\right]$; $K_m = \left(1 - \frac{A_mF_{Rm}U_{Lm}}{\dot{m}_fc_f}\right)$

$(AF_R(\alpha\tau))_{m1} = PF_2(\alpha\tau)_{meff}A_mF_{Rm}$; $(AF_RU_L)_{m1} = A_mF_{Rm}U_{Lm}$;

$a = \frac{1}{M_wC_w}\left[\dot{m}_fC_f(1 - K_k^N) + U_sA_b\right]$

Expressions for a and $f(t)$ used in Eq. (68) are as follows:

$$f(t) = \frac{1}{M_w C_w}\left[\alpha_{eff}{}' A_b I_s(t) + \frac{(1-K_k{}^N)}{(1-K_k)}(A\,F_R(\alpha\tau))_1 I_b(t) + \left(\frac{(1-K_k{}^N)}{(1-K_k)}(A\,F_R U_L)_1 + U_s A_b\right)T_a\right]$$

$$\alpha'_{eff} = \alpha'_w + h_1\alpha'_b + h'_1\alpha'_g \quad ; \quad h_1 = \frac{h_{bw}}{h_{bw}+h_{ba}} \quad ; \quad h'_1 = \frac{h_{1w}A_g}{U_{c,ga}A_g + h_{1w}A_b}$$

$$h_{e,wg} = 16.273 \times 10^{-3} h_{c,wg}\left[\frac{P_w - P_{gi}}{T_w - T_{gi}}\right] \quad ; \quad h_{1w} = h_{rwg} + h_{cwg} + h_{ewg}$$

$$h_{c,wg} = 0.884\left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})(T_w + 273)}{268.9\times10^3 - P_w}\right] \quad ;$$

$$P_w = exp\left[25.317 - \frac{5144}{T_w + 273}\right] \quad ; \quad P_{gi} = exp\left[25.317 - \frac{5144}{T_{gi} + 273}\right]$$

$$h_{rwg} = (0.82 \times 5.67\times10^{-8})\left[(T_w+273)^2 + (T_{gi}+273)^2\right]\left[T_w + T_{gi} + 546\right]$$

$$U_s = U_t + U_b \quad ; \quad U_b = \frac{h_{ba}h_{bw}}{h_{bw}+h_{ba}} \quad ; \quad U_t = \frac{h_{1w}U_{c,ga}A_g}{U_{c,ga}A_g + h_{1w}A_b} \quad ; \quad U_{c,ga} = \frac{\frac{K_g}{l_g}h_{1g}}{\frac{K_g}{l_g} + h_{1g}}$$

$$h_{ba} = \left[\frac{L_i}{K_i} + \frac{1}{h_{cb}+h_{rb}}\right]^{-1} \quad ; \quad h_{cb} + h_{rb} = 5.7\ W/m^2\text{K} \quad ; \quad h_{bw} = 250\,W/m^2\text{K}$$

Different terms used in Eq. 89-93:

$$(AF_R(\alpha\tau))_1 = PF_1\alpha\tau^2 A_R F_R \quad ; \quad (A\,F_R U_L)_1 = (1-K_k)\dot{m}_f c_f \quad ; \quad PF_1 = \frac{h_{pf}}{F' h_{pf} + U_{tpa}}$$

$$U_L = \frac{U_{t,pa}.h_{pf}}{F' h_{pf} + U_{t,pa}} \quad ; \quad F_R = \frac{\dot{m}_f C_f}{U_L A_R}\left[1 - exp(-\frac{2\pi r' L' U_L}{\dot{m}_f c_f})\right] \quad ; \quad K_K = \left(1 - \frac{A_R F_R U_L}{\dot{m}_f c_f}\right)$$

$$h_{pf} = 100W/m^2\text{K} \quad ; \quad U_{t,pa} = \left[\frac{Ro_2}{R_{o1}h_i} + \frac{R_{o2}ln(\frac{Ri_2}{Ri_1})}{K_g} + \frac{1}{C_{ev}} + \frac{R_{o2}ln(\frac{Ro_2}{Ro_1})}{K_g} + \frac{1}{h_o}\right]^{-1}$$

Different terms used in Eq. 94 to 98 are as follows:

$$\alpha'_{eff} = \alpha'_w + h_1\alpha'_b + h'_1\alpha'_g \quad ; \quad h'_1 = \frac{h_{1w}A_g}{U_{c,ga}A_g + h_{1w}A_b} \quad ; \quad h_1 = \frac{h_{bw}}{h_{bw}+h_{ba}}$$

$$h_{1w} = h_{rwg} + h_{cwg} + h_{ewg} \quad ; \quad h_{ewg} = 16.273\times10^{-3} h_{cwg}\left[\frac{P_w - P_{gi}}{T_w - T_{gi}}\right]$$

$$h_{cwg} = 0.884\left[(T_w - T_{gi}) + \frac{(P_w - P_{gi})(T_w + 273)}{268.9\times10^3 - P_w}\right]^{\frac{1}{3}}$$

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Brian Norton

Professor Brian Norton is a Member of the Royal Irish Academy and a Fellow of the Irish Academy of Engineering. He is an Honorary Fellow of the Chartered Institute of Building Services Engineers. His awards include the CIBSE Napier Shaw Medal for the development of the "Degree-hour" building energy-use correlation. He has received the Energy Institute Roscoe Award and the Lifetime Achievement Award at the Solaris Conference in Varanasi, India in 2012. He is a co-author of the 2012 American Association of Publishers "PROSE Award" winning book "Comprehensive Renewable Energy" and recipient of "Solar Energy" Journal Best Paper Award in Photovoltaic in 2007. He is currently a Principal Investigator in MaREI, the Irish national research Centre for Energy, Climate and Marine and leads its Energy Efficiency research area. He is currently Vice-President and Treasurer of the European Sustainable Energy Innovation Alliance and serves on the board of the International Energy Research Centre. Professor Norton has supervised over fifty doctorates and authored over 200 peer-reviewed journal research papers and over 270 conference papers. His research outputs have received nearly 10,000 citations with an h-index of 51. He is trained both as a physicist and an engineer, his qualifications include Doctorates from Nottingham and Cranfield Universities in the UK.

Gopal Nath Tiwari

Professor Gopal Nath Tiwari had received postgraduate and doctoral degrees in 1972 and 1976, respectively, from Banaras Hindu University (B.H.U.). Since 1977, he has been actively involved in teaching programme at Centre for Energy Studies, IIT Delhi. His research interests are solar distillation, solar drying, greenhouse technology, Passive building design and Hybrid photovoltaic thermal systems for greenhouse. He has guided about 100 Ph.D. students and published over 600 research papers in journals of repute. He has authored twenty books associated with reputed publishers. He is a co-recipient of Hari Om Ashram Prerit S.S. Bhatnagar Award in 1982. He was also a recipient of European Fellow in 1997. He had been to the University of Ulster (U.K.) in 1993. He is responsible for development of Solar Energy Park at IIT Delhi and Energy Laboratory at University of Papua, New Guinea, Port Moresby. Professor Tiwari had visited many countries and successfully co-coordinated various research projects funded by the Govt. of India in the past. He has also been conferred "Vigyan Ratna" award by Government of Uttar Pradesh in the year 2007. Currently, he is President of Bag Energy Research Society (BERS-2007) (www.bers.in) to disseminate energy education in rural areas.