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Dr. Osama Mohammed Elmardi Suleiman Khayal was born in Atbara, Sudan in 1966. He received a bachelor degree in mechanical engineering from Sudan University of Science and Technology, College of Engineering in 1998, and a master degree in solid mechanics from Nile Valley University, Atbara, Sudan in 2003, and a PhD in structural engineering in 2017.

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LITERATURE REVIEW IN UTILIZING SOLAR ENERGY FOR THERMAL PURPOSES

SOLAR COLLECTORS

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June 2020

Dedication

In the name of Allah, the merciful, the compassionate

All praise is due to Allah and blessings and peace is upon his messenger and servant, Mohammed, and upon his family and companions and whoever follows his guidance until the day of resurrection.

To the memory of Professor Sabir Mohammed Salih, Professor Elfadil Adam Abdallah, Associate Professor Mohi-Eldin Idris Habra, Associate Professor Hashim Ahmed Ali, Associate Professor Abdel-Jaleel Yousef, Lecturer Ishraga Salih, Lecturer Intisar Abdu and Associate Professor Salah Ahmed Ali who they taught us the greatest value of hard work and encouraged me in all my endeavors.

This book is dedicated mainly to undergraduate engineering students, especially mechanical, production and chemical engineering students where most of the applications presented are focused on solar renewable energy fields especially in solar collectors.

Finally, may Allah accepts this humble work and we hope that it will be beneficial to its readers.

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The authors would like to acknowledge with deep thanks and gratitude the moral and financial support extended to them by Nile Valley University via its Faculty of Engineering and Technology despite its financial hardships.

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sequentially the various chapters of this book.

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Abstract

The aim of the present research was to review the utilization of solar energy for thermal purposes from the view point of the history of solar energy, theoretical study of solar collectors, and solar collector applications.

One of the most important sources of renewable energy is solar energy. Clearly, the sun provides a huge amount of energy for the earth that is distributed across the earth’s surface. However, the intensity of solar rays, and therefore the amount of energy, can change significantly across different regions, seasons, and time of day. The practical amount of energy that can be utilized is also significantly affected by other factors, such as the amount of cloud cover. In some regions, this energy can be more than one kilowatt hour per square meter of area (one kwh/m^2) or less than 0.1 kwh/m^2 (kilowatt hour per square meter). Solar energy can be utilized by one of the following to methods: conversion of solar radiation to electrical energy, using photovoltaic cells, and conversion of solar radiation to direct heat energy using solar collectors.

Solar collectors are the key component of active solar-heating systems. They gather the sun's energy, transform its radiation into heat, and then transfer that heat to a fluid (usually water or air). The solar thermal energy can be used in solar water-heating systems, solar pool heaters, and solar space-heating systems.

There are a large number of solar collector designs that have shown to be functional. These designs are classified into two general types of solar collectors: flat-plate collectors in which the absorbing surface is approximately as large as the overall collector area that intercepts the sun's

rays, and concentrating collectors in which large areas of mirrors or lenses focus the sunlight onto a smaller absorber.

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Preface

This book was originally prepared in 2015 and updated recently in 2020. The concept of this book was initiated as a result of the continuing and increasing demand for small scale solar thermal collector units that could be installed and operated in the vast and multiple States of The Democratic Republic of Sudan.

One of the most important sources of renewable energy, is solar energy. Compared with other sources, solar energy is characterized by the fact that it is available, almost, everywhere, in addition, it is clean and does not has any bad effects on the environment. Solar energy can be utilized by one of the following two ways: 1. Conversion of solar radiation into electrical energy, using photovoltaic cells and 2. Conversion of solar radiation into direct heat energy, using solar collectors. Conversion of solar energy to electrical energy does not require high density of solar radiation. This is why photovoltaic cells, which convert solar energy to electrical energy, are widespread in Europe and other countries of similar climates, where solar radiation density is low. Conversion of solar energy to heat energy, on the other hand, requires high density of solar radiation, and it is therefore, the method which can be used in tropical climates, where solar radiation is very high. One of the most important factors which encourages use of thermal conversion of solar energy in tropical countries, is the cost. Solar collectors and associated components, can be manufactured, installed and operated at a very low cost, compared with photovoltaic cells. Due to intermittent nature of solar radiation a lot of research work should be carried out, to reach a suitable design which ensures optimum utilization of solar energy, at low cost. One of the most suitable application of thermal conversion of solar energy, is the generation of heat using solar collectors. This is because, the power required to operate a solar thermal system, is heat energy, which is directly available from a solar collector.

The high potential solar energy in Atbara city could be used for thermal generation through flat plate solar complexes. For the purpose of experimentation, a solar complex was designed and manufactured in the premises of the Faculty of Engineering and Technology - Atbara through which the water flows naturally.

The aim of the present research was to review the utilization of solar energy for thermal purposes from the view point of the history of solar energy, theoretical study of solar collectors, and solar collector applications.

Chapter one includes literature review of solar energy. In this chapter a comprehensive introduction and historical background were presented.

In chapter two a theoretical study of solar collectors was introduced and discussed from different points of view which include introduction, types of collectors, working principles of concentrating collectors, and comparisons of the technology used.

Chapter three discusses the importance of practical applications of solar collectors in different points which includes: solar water heating systems, solar space heating and cooling, heat pump systems, solar refrigeration, solar steam generation systems, solar thermal power systems, solar furnaces, and solar chemistry applications.

Chapter One

Literature Review of Solar Energy

1.1 Introduction

Energy is one of the most serious problems which facing all the world. People in different societies used to depend on traditional sources of fuel; petroleum; cool; natural gas...etc.

In recent years, problems with traditional energy production have become difficult for the world to ignore. The problems include a limited supply of fossil fuels and uncertain effects on the environment. The rate at which fossil fuels are being consumed is growing annually, while the amount available remains finite. The environmental effects of burning fossil fuels are becoming more visible as numerous studies indicate detrimental climate effects and adverse personal health risks.

The solution to these problems comes in the form of alternative energy generation. Renewable energy seems to be a good alternative. Renewable energy is energy obtained from sources that are infinite in quantity. In other words, our supply of renewable energy will never be depleted. Technology has come a long way and it is beginning to be able to utilize renewable energy more effectively. It can help us supplement our current demands for fossil fuels. Renewable energy will not be able to fully substitute our use of fossil fuels, but it can help lower our demand for it. Renewable energy is environmentally safe and has many advantages over non-renewable energy.

Renewable energy has always played a great deal in our human existence. The earliest form of renewable energy was wood; this is because it was the easiest to manipulate to produce thermal energy. Burning wood was important in preparing food and keeping warm. Eventually, it was found that by relative combustion without the presence of oxygen charcoal could produce; which burns longer and hotter.

Methods such as wind, hydraulic, solar, and nuclear power generation continue to advance in technology and as a result have experienced increases in production efficiency. Also, technologies such as fuel cells and wind turbines are presenting themselves as viable options to traditional methods with the promise of advanced efficiency in the future.

One of most important sources of renewable energy; is solar energy. Clearly, the sun provides a huge amount of energy for the earth that is distributed across the earth's surface. However, the intensity of solar rays, and therefore the amount of energy, can change significantly across different regions, seasons, and time of day. The practical amount of energy that can be utilized is also significantly affected by other factors, such as the amount of cloud cover. In some regions, this energy can be more than one kilowatt hour per square meter of area (one kwh/m^2) or less than 0.1 kwh/m^2 (kilowatt hour per square meter). Solar energy can be utilized by one of the following to methods:

1. Conversion of solar radiation to electrical energy, using photovoltaic cells.

2. Conversion of solar radiation to direct heat energy using solar collectors.

The first method, which is the primary method of using clean solar energy, is to use photovoltaic cells, which turn solar rays directly into electrical energy. Photovoltaic cells have historically been used in applications such as calculators, watches, and satellites, but more recently have been used in photovoltaic arrays to generate power for general electrical consumption. Photovoltaic cells generate electricity when photons in the sun's rays hit the panel and excite electrons, which can flow through the material and produce electricity. While photovoltaic arrays can provide significant amounts of clean power and can be used in a variety of places like roofs of buildings, they face a number of constraints. First, the total solar flux, or the solar energy per unit area, for a given area is relatively small. Second, since the total efficiency of photovoltaic cells only reaches around 30%, huge areas are required to result in the same level or energy output as conventional sources of energy. In addition, while the upkeep is relatively low, the initial cost of production of photovoltaic arrays is significantly higher than those of conventional power plants. Finally, like all sources of solar energy, they function best when the intensity of the solar rays is greatest.

The second method is to convert solar energy into thermal energy-usually using water, air or oil. This method has applications not only in power generation, but also in cooking, water purification, and heating. Its advantages here include the fact that it can be deployed on household levels with little initial cost or maintenance. Some household designs are as simple as putting a tank of water on the roof to be used for hot water or house heating. A design that uses air may consist of a large chimney with air inside which solar energy warms, resulting in an updraft of air that can cool the structure beneath it. Both of these design concepts can be used to generate power as well with the addition of a turbine and some modification.

The study focuses on concentrating solar thermal power generation because this is by far the greatest renewable energy resource in the tropical region. Concentrating solar thermal power technologies (CSP) are based on the concept of concentrating solar radiation to be used for electricity generation within conventional power cycles using steam turbines, gas turbines or Stirling engines. For concentration, most systems use glass mirrors that continuously track the position of the sun. The concentrated sunlight is absorbed on a receiver that is specially designed to reduce heat losses. A fluid flowing through the receiver takes the heat away towards the power cycle, where e.g. high pressure, high temperature steam is generated to drive a turbine. Air, water, oil and molten salt are used as heat transfer fluids. The range relevant for this particular solar power plant was between 0.7 kwh/m^2 and 0.85 kwh/m^2 (for varying times of day based on the location of 40 degrees latitude, the month July, and angle of light).

There are three types of solar thermal power systems. All systems concentrate sunlight on to receiver (boiler) to achieve high turbine inlet temperature and pressure

1. Trough-electric uses a long parabolic mirror to focus sunlight on a cylindrical receiver.

2. Dish/Stirling systems use a parabolic dish to focus sunlight onto a receiver containing a piston based Stirling cycle.

3. Power Towers use a field of mirrors (heliostats) to focus intense heat on a large central receiver.

1.2 History of Solar Energy

The idea of using solar energy collectors to harness the sun's power is recorded from the prehistoric times when at 212 BC the Greek scientist/physician Archimedes devised a method to burn the Roman fleet.

Archimedes reputedly set the attacking Roman fleet afire by means of concave metallic mirror in the form of hundreds of polished shields; all reflecting on the same ship [1].

The Greek historian Plutarch (AD 46 –120) referred to the incident saying that the Romans, seeing that indefinite mischief overwhelmed them from no visible means, began to think they were fighting with the gods. The basic question was whether or not Archimedes knew enough about the science of optics to device a simple way to concentrate sunlight to a point where ships could be burned from a distance. Archimedes had written a book "On burning Mirrors" but no copy has survived to give evidence [2].

Eighteen hundred years after Archimedes, Athanasius Kircher (1601–1680) carried out some experiments to set fire to a woodpile at a distance in order to see whether the story of Archimedes had any scientific validity but no report of his findings survived [2] and [3].

Amazingly, the very first applications of solar energy refer to the use of concentrating collectors, which are by their nature (accurate shape construction) and the requirement to follow the sun, more 'difficult' to apply. During the 18th century, solar furnaces capable of melting iron, copper and other metals were being constructed of polished-iron, glass lenses and mirrors. The furnaces were in use throughout Europe and the Middle East. One furnace designed by the French scientist Antoine Lavoisier, attained the remarkable temperature of 1750 8C. The furnace used a 1.32 m lens plus a secondary 0.2 m lens to obtain such temperature which turned out to be the maximum achieved by man for one hundred years.

During the 19th century the attempts to convert solar energy into other forms based upon the generation of low pressure steam to operate steam engines. August Monchot pioneered this field by constructing and operating several solar powered steam engines between the years 1864 and 1878 [2] and [3]. Evaluation of one built at Tours by the French government showed that it was too expensive to be considered feasible. Another one was set up in Algeria. In 1875, Mouchot made a notable advance in solar collector design by making one in the form of a truncated cone reflector.

Mouchot's collector consisted of silver-plated metal plates and had a diameter of 5.4 m and a collecting area of 18.6 m^2. The moving parts weighed 1400 kg.

Abel Pifre was a contemporary of Mouchot who also made solar engines [4], and [5]. Pifre's solar collectors were parabolic reflectors made of very small mirrors. In shape they looked rather similar to Mouchot's truncated cones.

In 1901 A.G. Eneas installed a 10 m diameter focusing collector which powered a water pumping apparatus at a California farm. The device consisted of a large umbrella-like structure open and inverted at an angle to receive the full effect of sun's rays on the 1788 mirrors which lined the inside surface. The sun's rays were concentrated at a focal point where the boiler was located. Water within the boiler was heated to produce steam which in turn powered a conventional compound engine and centrifugal pump [5].

In 1904 a Portuguese priest, Father Himalaya, constructed a large solar furnace. This was exhibited at the St Louis World's fair. This furnace appeared quite modern in structure, being a large, off-axis, parabolic horn collector [5].

In 1912 Shuman, in collaboration with C.V. Boys, undertook to build the world's largest pumping plant in Meadi, Egypt. The system was placed in operation in 1913 and it was using long parabolic cylinders to focus sunlight onto a long absorbing tube. Each cylinder was 62 m long, and the total area of the several banks of cylinders was 1200 m^2. The solar engine developed as much as 37–45 kW continuously for a 5 h period [2], [4], and [5]. Despite the plant's success, it was completely shut down in 1915 due to the onset of World War I and cheaper fuel prices.

During the last 50 years many variations were designed and constructed using focusing collectors as a means of heating the transfer or working fluid which powered mechanical equipment. The two primary solar technologies used are the central receivers and the distributed receivers employing various point and line-focus optics to concentrate sunlight. Central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver [6]. Distributed receiver technology includes parabolic dishes, Fresnel lenses, parabolic troughs, and special bowls. Parabolic dishes track the sun in two axes and use mirrors to focus radiant energy onto a point-focus receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Receiver temperatures range from 100 C in low-temperature troughs to close 1500 C in dish and central receiver systems [6].

Another area of interest, the hot water and house heating appeared in the mid-1930s, but gained interest in the last half of the 40s. Until then millions of houses were heated by coal burn boilers. The idea was to heat water and fed it to the radiator system that was already installed. The manufacture of solar water heaters (SWH) began in the early 60s. The industry of SWH expanded very quickly in many countries of the world. Typical SWH in many cases are of the thermosiphon type and consist of two flat-plate solar collectors having an absorber area between 3 and 4 m^2, a storage tank with capacity between 0.15 and 0.18 m^3 and a cold water storage tank, all installed on a suitable frame. An auxiliary electric immersion heater and/or a heat exchanger, for central heating assisted hot water production, are used in winter during periods of low solar insolation. Another important type of SWH is the force circulation type. In this system only the solar panels are visible on the roof, the hot water storage tank is located indoors in a plant room and the system is completed with piping, pump and a differential thermostat. Obviously, this latter type is more appealing mainly due to architectural and aesthetic reasons, but also more expensive especially for small-size installations [2] and [3].

Becquerel had discovered the photovoltaic effect in selenium in 1839. The conversion efficiency of the 'new' silicon cells developed in 1958 was 11% although the cost was prohibitively high ($1000/W) [5]. The first practical application of solar cells was in space where cost was not a barrier and no other source of power is available. Research in the 1960s, resulted in the discovery of other photovoltaic materials such as gallium arsenide (GaAs). These could operate at higher temperatures than silicon but were much more expensive. The global installed capacity of photovoltaics at the end of 2002 was near 2 GWp [7]. Photovoltaic (PV) cells are made of various semiconductors, which are materials that are only moderately good conductors of electricity. The materials most commonly used are silicon (Si) and compounds of cadmium sulphates (Cds), cuprous sulphates (Cu_2S), and GaAs.

Amorphous silicon cells are composed of silicon atoms in a thin homogenous layer rather than a crystal structure. Amorphous silicon absorbs light more effectively than crystalline silicon, so the cells can be thinner. For this reason, amorphous silicon is also known as a 'thin film' PV technology. Amorphous silicon can be deposited on a wide range of substrates, both rigid and flexible, which makes it ideal for curved surfaces and 'fold-away' modules. Amorphous cells are, however, less efficient than crystalline based cells, with typical efficiencies of around 6%, but they are easier and therefore cheaper to produce. Their low cost make them ideally suited for many applications where high efficiency is not required and low cost is important.

Amorphous silicon (a-Si) is a glassy alloy of silicon and hydrogen (about 10%). Several properties make it an attractive material for thin-film solar cells:

1. Silicon is abundant and environmentally safe.

2.Amorphous silicon absorbs sunlight extremely well, so that only a very thin active solar cell layer is required (about 1 mm as compared to 100 mm or so for crystalline solar cells), thus greatly reducing solar-cell material requirements.

3. Thin films of a-Si can be deposited directly on inexpensive support materials such as glass, sheet steel, or plastic foil.

A number of other promising materials such as cadmium telluride and copper indium diselenide are now being used for PV modules. The attraction of these technologies is that they can be manufactured by relatively inexpensive industrial processes, in comparison to crystalline silicon technologies, yet they typically offer higher module efficiencies than amorphous silicon.

The PV cells are packed into modules which produce a specific voltage and current when illuminated. PV modules can be connected in series or in parallel to produce larger voltages or currents. Photovoltaic systems can be used independently or in conjunction with other electrical power sources. Applications powered by PV systems include communications (both on earth and in space), remote power, remote monitoring, lighting, water pumping and battery charging.

The two basic types of PV applications are the stand alone and the grid connected. Stand-alone PV systems are used in areas that are not easily accessible or have no access to mains electricity. A stand-alone system is independent of the electricity grid, with the energy produced normally being stored in batteries. A typical stand-alone system would consist of PV module or modules, batteries and charge controller. An inverter may also be included in the system to convert the direct current generated by the PV modules to the alternating current form (AC) required by normal appliances.

In the grid connected applications the PV system is connect to the local electricity network. This means that during the day, the electricity generated by the PV system can either be used immediately (which is normal for systems installed in offices and other commercial buildings), or can be sold to one of the electricity supply companies (which is more common for domestic systems where the occupier may be out during the day). In the evening, when the solar system is unable to provide the electricity required, power can be bought back from the network. In effect, the grid is acting as an energy storage system, which means the PV system does not need to include battery storage.

When PVs started to be used for large-scale commercial applications, about 20 years ago, their efficiency was well below 10%. Nowadays, their efficiency increased to about 15%. Laboratory or experimental units can give efficiencies S.A. Kalogirou / Progress in Energy and Combustion Science 30 (2004) 231–295 239 of more than 30%, but these have not been commercialized yet. Although 20 years ago PVs were considered as a very expensive solar system the present cost is around 5000$ per kW and there are good prospects for further reduction in the coming years. More details on photovoltaics' are beyond the scope of this research.

The lack of water was always a problem to humanity. Therefore among the first attempts to harness solar energy were the development of equipment suitable for the desalination of sea-water. Solar distillation has been in practice for a long time. According to Malik et al. [7], the earliest documented work is that of an Arab alchemist in the 15th century reported by Mouchot in 1869. Mouchot reported that the Arab alchemist had used polished Damascus mirrors for solar distillation.

The great French chemist Lavoisier (1862) used large glass lenses, mounted on elaborate supporting structures, to concentrate solar energy on the contents of distillation flasks [7]. The use of silver or Aluminium coated glass reflectors to concentrate solar energy for distillation has also been described by Mouchot.

The use of solar concentrators in solar distillation has been reported by Pasteur (1928) [8] who used a concentrator to focus solar rays onto a copper boiler containing water. The steam generated from the boiler was piped to a conventional water cooled condenser in which distilled water was accumulated.

Solar stills are one of the simplest type of desalination equipment which uses the greenhouse effect to evaporate salty water. Solar stills were the first to be used on large scale distilled water production. The first water distillation plant constructed was a system built at Las Salinas, Chile, in 1874 [5], and [1]. The still covered 4700 m^2 and produced up to 23000 L of fresh water per day (4.9 L/m^2), in clear sun. The still was operated for 40 years and was abandoned only after a fresh-water pipe was installed supplying water to the area from the mountains. The renewal of interest on solar distillation occurred after the First World War at which time several new devices had been developed such as: roof type, tilted wick, inclined tray and inflated stills.

Another application of solar energy is solar drying. Solar dryers have been used primarily by the agricultural industry. The objective in drying an agricultural product is to reduce its moisture contents to that level which prevents deterioration within a period of time regarded as the safe storage period. Drying is a dual process of heat transfer to the product from the heating source, and mass transfer of moisture from the interior of the product to its surface and from the surface to the surrounding air. The objective of a dryer is to supply the product with more heat than is available under ambient conditions, increasing sufficiently the vapor pressure of the moisture held within the crop, thus enhancing moisture migration from within the crop and decreasing significantly the relative humidity of the drying air, thus increasing its moisture carrying capability and ensuring a sufficiently low equilibrium moisture content.

In solar drying, solar energy is used as either the sole source of the required heat or as a supplemental source, and the air flow can be generated by either forced or natural convection. The heating procedure could involve the passage of the pre-heated air through the product, by directly exposing the product to solar radiation or a combination of both. The major requirement is the transfer of heat to the moist product by convection and conduction from surrounding air mass at temperatures above that of the product, or by radiation mainly from the sun and to a little extent from surrounding hot surfaces, or conduction from heated surfaces in conduct with the product. Details of solar dryers are beyond the scope of this research.

Chapter Two

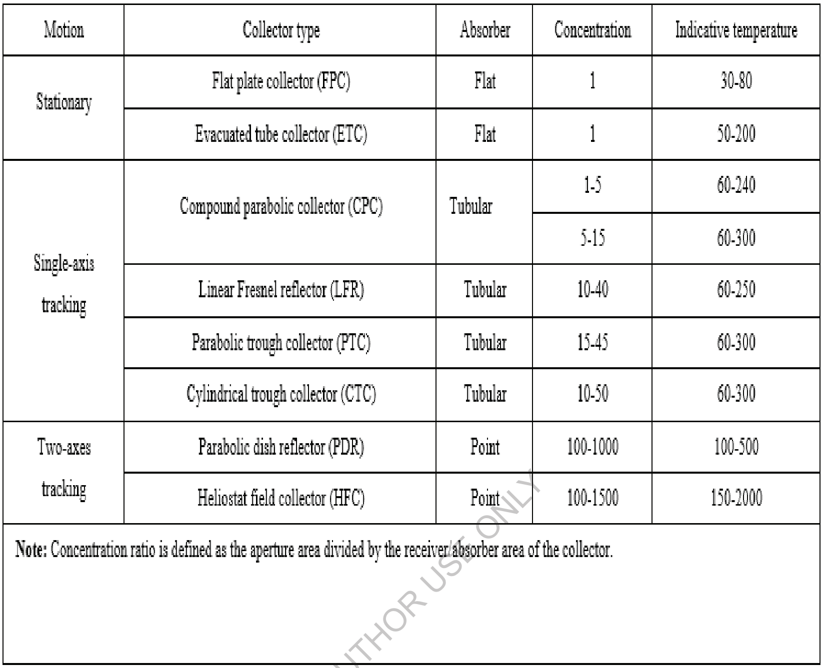
Theoretical Study of Solar Collectors

2.1 Introduction

Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. The major component of any solar system is the solar collector. This is a device which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water, or oil) flowing through the collector. The solar energy thus collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment, or to a thermal energy storage tank from which can be drawn for use at night and/or cloudy days.

There are basically two types of solar collectors: non-concentrating or stationary and concentrating. A non-concentrating collector has the same area for intercepting and for absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux. A large number of solar collectors are available in the market. A comprehensive list is shown in Table 2.1 below which shows type of motion, collector type, absorber, concentration, and indicative temperature.

Table 2.1 Types of Solar Collectors



Motion	Collector type	Absorber	Concentration	Indicative temperature
Stationary	Flat plate collector (FPC)	Flat	1	30-80
	Evacuated tube collector (ETC)	Flat	1	50-200
Single-axis tracking	Compound parabolic collector (CPC)	Tubular	1-5	60-240
			5-15	60-300
	Linear Fresnel reflector (LFR)	Tubular	10-40	60-250
	Parabolic trough collector (PTC)	Tubular	15-45	60-300
	Cylindrical trough collector (CTC)	Tubular	10-50	60-300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100-1000	100-500
	Heliostat field collector (HFC)	Point	100-1500	150-2000

Note: Concentration ratio is defined as the aperture area divided by the receiver/absorber area of the collector.

2.2 Types of Collectors

2.2.1 Stationary Collectors

Solar energy collectors are basically distinguished by their motion, i.e. stationary, single axis tracking and two axes tracking, and the operating temperature. Initially the stationary solar collectors are examined. These collectors are permanently fixed in position and do not track the sun. Three types of collectors fall in this category

1. Flat plate collectors (FPC);

2. Stationary compound parabolic collectors (CPC);

3. Evacuated tube collectors (ETC).

1. Flat Plate Collectors:

A typical flat-plate solar collector is shown in Figure 2.1. When solar radiation passes through a transparent cover and impinges on the blackened absorber surface of high absorptivity, a large portion of this energy is absorbed by the plate and transferred to the transport medium in the fluid tubes, to be carried away for storage or use. The underside of the absorber plate and the side are well insulated to reduce conduction losses. The liquid tubes can be welded to the absorbing plate or they can be an integral part of the plate. The liquid tubes are connected at both ends by large-diameter header tubes. The header and riser collector is the typical design for flat-plate collectors.

The transparent cover is used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer between the absorber plate and the glass. It also reduces radiation losses from the collector as the glass is transparent to the short wave radiation received by the sun but it is nearly opaque to long-wave thermal radiation emitted by the absorber plate (greenhouse effect).

FPC are usually permanently fixed in position and require no tracking of the sun. The collectors should be oriented directly towards the equator, facing south in the northern hemisphere and north in the southern. The optimum tilt angle of the collector is equal to the latitude of the location with angle variations of 10–15 more or less depending on the application. Flat plate collector (FPC) generally consists of the following components:

Glazing: One or more sheets of glass or other diathermanous (radiation-transmitting) material.

Tubes, fins, or passages: To conduct or direct the heat transfer fluid from the inlet to the outlet.

Absorber plates: Flat, corrugated, or grooved plates, to which the tubes, fins, or passages are attached. The plate may be integral with the tubes.

Headers or manifolds: To admit and discharge the fluid. Insulation. To minimize the heat loss from the back and sides of the collector.

Container or casing: To surround the aforementioned components and keep free from dust, moisture.

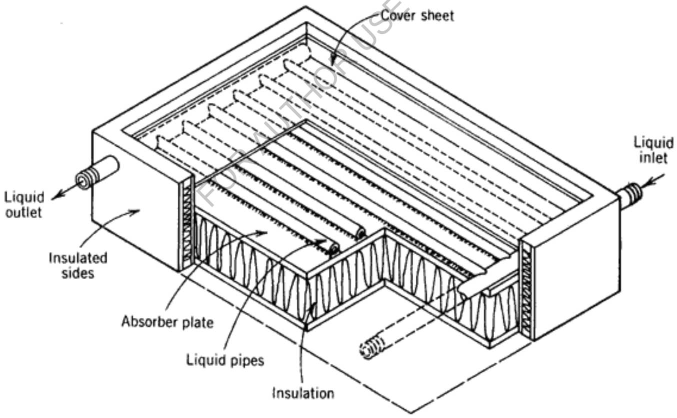


Figure 2.1 A Typical Flat Plate Collector

FPC have been built in a wide variety of designs and from many different materials. They have been used to heat fluids such as water, water plus antifreeze additive, or air. Their major purpose is to collect as much solar energy as possible at the lower possible total cost. The collector should also have a long effective life, despite the adverse effects of the sun's ultraviolet radiation, corrosion and clogging because of acidity, alkalinity or hardness of the heat transfer fluid, freezing of water, or deposition of dust or moisture on the glazing, and breakage of the glazing because of thermal expansion, hail, vandalism or other causes. These causes can be minimized by the use of tempered glass.

More details are given about the glazing and absorber plate materials in this sections. Most of these details apply also to other types of collectors.

i. Glazing Materials:

Glass has been widely used to glaze solar collectors because it can transmit as much as 90% of the incoming shortwave solar irradiation while transmitting virtually none of the long wave radiation emitted outward by the absorber plate. Glass with low iron content has a relatively high transmittance for solar radiation (approximately 0.85–0.90 at normal incidence), but its transmittance is essentially zero for the long wave thermal radiation (5.0–50 mm) emitted by sun-heated surfaces. Plastic films and sheets also possess high shortwave transmittance, but because most usable varieties also have transmission bands in the middle of the thermal radiation spectrum, they may have long wave transmittances as high as 0.40.

Plastics are also generally limited in the temperatures they can sustain without deteriorating or undergoing dimensional changes. Only a few types of plastics can withstand the sun's ultraviolet radiation for long periods. However, they are not broken by hail or stones, and, in the form of thin films, they are completely flexible and have low mass.

The commercially available grades of window and green-house glass have normal incidence transmittances of about 0.87 and 0.85, respectively. For direct radiation, the transmittance varies considerably with the angle of incidence. Refer to references [2] and [3].

Antireflective coatings and surface texture can also improve transmission significantly. The effect of dirt and dust on collector glazing may be quite small, and the cleansing effect of an occasional rainfall is usually adequate to maintain the transmittance within 2–4% of its maximum value.

The glazing should admit as much solar irradiation as possible and reduce the upward loss of heat as much as possible. Although glass is virtually opaque to the long wave radiation emitted by collector plates, absorption of that radiation causes an increase in the glass temperature and a loss of heat to the surrounding atmosphere by radiation and convection.

Various prototypes of transparently insulated FPC and CPC have been built and tested in the last decade [2]. Low cost and high temperature resistant transparent insulating (TI) materials have been developed so that the commercialization of these collectors becomes feasible. A prototype FPC covered by TI was developed by Benz et al. [2] and [3]. It was experimentally proved that the efficiency of the collector was comparable with that of ETC. However, no commercial collectors of this type are available in the market.

ii. Collector Absorbing Plates:

The collector plate absorbs as much of the irradiation as possible through the glazing, while losing as little heat as possible upward to the atmosphere and downward through the back of the casing. The collector plates transfer the retained heat to the transport fluid. The absorptance of the collector surface for shortwave solar radiation depends on the nature and color of the coating and on the incident angle. Usually black color is used, however various color coatings have been proposed in Reference [9] mainly for aesthetic reasons. By suitable electrolytic or chemical treatments, surfaces can be produced with high values of solar radiation absorptance (α) and low values of long wave emittance (ε). Essentially, typical selective surfaces consist of a thin upper layer, which is highly absorbent to shortwave solar radiation but relatively transparent to long wave thermal radiation, deposited on a surface that has a high reflectance and a low emittance for long wave radiation. Selective surfaces are particularly important when the collector surface temperature is much higher than the ambient air temperature. Lately, a low-cost mechanically manufactured selective solar absorber surface method has been proposed [2] and [3].

An energy efficient solar collector should absorb incident solar radiation, convert it to thermal energy and deliver the thermal energy to a heat transfer medium with minimum losses at each step. It is possible to use several different design principles and physical mechanisms in order to create a selective solar absorbing surface. Solar absorbers are based on two layers with different optical properties, which are referred as tandem absorbers. A semiconducting or dielectric coating with high solar absorptance and high infrared transmittance on top of a non-selective highly reflecting material such as metal constitutes one type of tandem absorber. Another alternative is to coat a nonselective highly absorbing material with a heat mirror having a high solar transmittance and high infrared reflectance [2].

Today, commercial solar absorbers are made by electroplating, anodization, evaporation, sputtering and by applying solar selective paints. Much of the progress during recent years has been based on the implementation of vacuum techniques for the production of fin type absorbers used in low temperature applications. The chemical and electrochemical processes used for their commercialization were readily taken over from the metal finishing industry. The requirements of solar absorbers used in high temperature applications, however, namely extremely low thermal emittance and high temperature stability, were difficult to fulfil with conventional wet processes. Therefore, large scale sputter deposition was developed in the late 70s. The vacuum techniques are nowadays mature, characterized by low cost and have the advantage of being less environmentally polluting than the wet processes.

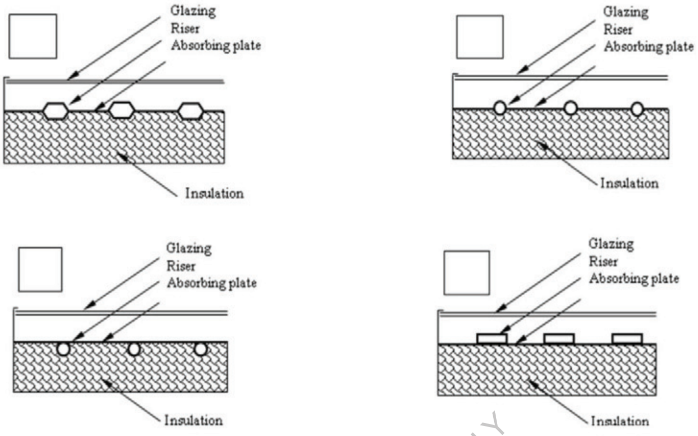
For fluid-heating collectors, passages must be integral with or firmly bonded to the absorber plate. A major problem is obtaining a good thermal bond between tubes and absorber plates without incurring excessive costs for labor or materials. Material most frequently used for collector plates are copper, aluminum, and stainless steel. UV-resistant plastic extrusions are used for low temperature applications. If the entire collector area is in contact with the heat transfer fluid, the thermal conductance of the material is not important.

Figure 2.2 shows a number of absorber plate designs for solar water and air heaters that have been used with varying degrees of success [2] and [10].

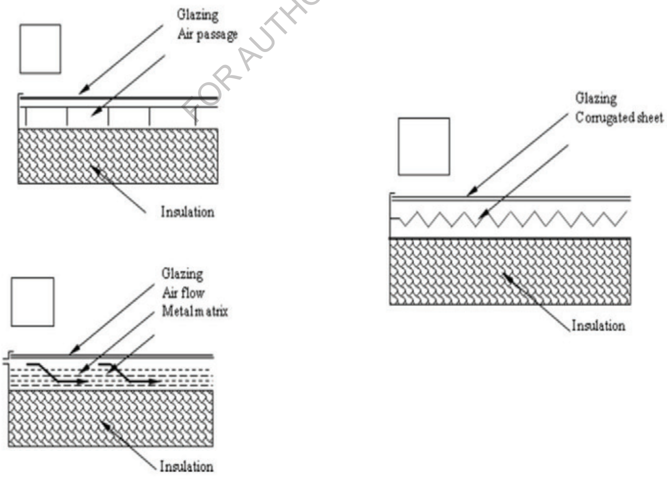
Another category of collectors which is not shown in Figure 2.2 is the uncovered or unglazed solar collector [2] and [10]. These are usually low-cost units which can offer cost effective solar thermal energy in applications such as water preheating for domestic or industrial use, heating of swimming pools, space heating and air heating for industrial or agricultural applications.

FPC are by far the most used type of collector. FPC are usually employed for low temperature applications up to 100 8C, although some new types of collectors employing vacuum insulation and/or TI can achieve slightly higher values [2] and [10]. Due to the introduction of highly selective coatings actual standard FPC can reach stagnation temperatures of more than 200 ^{0}C. With these collectors good efficiencies can be obtained up to temperatures of about 100 ^{0}C. The characteristics of a typical water FPC are shown in Table 2.2.

Lately some modern manufacturing techniques have been introduced by the industry like the use of ultrasonic welding machines, which improve both the speed and the quality of welds. This is used for the welding of fins on risers in order to improve heat conduction. The greatest advantage of this method is that the welding is performed at room temperature therefore deformation of the welded parts is avoided. These collectors with selective coating are called advance FPC and the characteristics of a typical type are also shown in Table 3.2.



Types of Flat-Plate Collectors for Water systems



Types of Flat-Plate Collectors for Air Systems

Figure 2.2 Types of Flat-Plate Collectors for Water and Air Systems

Table 2.2 Characteristics of a Typical Water FPC System

Parameter	Simple flat plate collector	Advanced flat plate collector
Fixing of risers on the absorber plate	Embedded	Ultrasonically welded
Absorber coating	Black mat paint	Chromium selective coating
Glazing	Low-iron glass	Low-iron glass
Efficiency mode	Nvs(Ti – Ta)/G	Nvs(Ti – Ta)/G
Gtest-flow rate per unit area at test conditions (kg/s m^2)	0.015	0.015
co-intercept efficiency	0.79	0.80
c1-negative of the first-order coefficient of the efficiency (W/m^2 ^{0}C)	6.67	4.78

b0-incidence angle modifier constant	0.1	0.1
Collector slope angle	Latitude 5 to 10^0	Latitude 5 to 10^0

2. Compound Parabolic Collectors:

CPC are non-imaging concentrators. These have the capability of reflecting to the absorber all of the incident radiation within wide limits. Their potential as collectors of solar energy was pointed out by Winston [11]. The necessity of moving the concentrator to accommodate the changing solar orientation can be reduced by using a trough with two sections of a parabola facing each other, as shown in Figure 2.3.

Compound parabolic concentrators can accept incoming radiation over a relatively wide range of angles. By using multiple internal reflections, any radiation that is entering the aperture, within the collector acceptance angle, finds its way to the absorber surface located at the bottom of the collector. The absorber can take a variety of configurations. It can be cylindrical as shown in Figure 2.3 or flat. In the CPC shown in Figure 2.3 the lower portion of the reflector (AB and AC) is circular, while the upper portions (BD and CE) are parabolic. As the upper part of a CPC contribute little to the radiation reaching the absorber, they are usually truncated thus forming a shorter version of the CPC, which is also cheaper. CPCs are usually covered with glass to avoid dust and other materials from entering the collector and thus reducing the reflectivity of its walls.

These collectors are more useful as linear or trough-type concentrators. The acceptance angle is defined as the angle through which a source of light can be moved and still converge at the absorber. The orientation of a CPC collector is related to its acceptance angle (θc; in Figure 2.3). Also depending on the collector acceptance angle, the collector can be stationary or tracking. A CPC concentrator can be orientated with its long axis along either the north–south or the east–west direction and its aperture is tilted directly towards the equator at an angle equal to the local latitude. When orientated along the north–south direction the collector must track the sun by turning its axis so as to face the sun continuously. As the acceptance angle of the concentrator along its long axis is wide, seasonal tilt adjustment is not necessary. It can also be stationary but radiation will only be received the hours when the sun is within the collector acceptance angle. When the concentrator is orientated with its long axis along the east–west direction, with a little seasonal adjustment in tilt angle the collector is able to catch the sun's rays effectively through its wide acceptance angle along its long axis. The minimum acceptance angle in this case should be equal to the maximum incidence angle projected in a north–south vertical plane during the times when output is needed from the collector. For stationary CPC collectors mounted in this mode the minimum acceptance angle is equal to 47^0. This angle covers the declination of the sun from summer to winter solstices ($2 * 23.5^0$). In practice bigger angles are used to enable the collector to collect diffuse radiation at the expense of a lower concentration ratio. Smaller (less than 3) concentration ratio CPCs are of greatest practical interest. These according to Pereira [12] are able to accept a large proportion of diffuse radiation incident on their apertures and concentrate it without the need of tracking the sun.

A method to estimate the optical and thermal properties of CPCs is presented in Reference [13]. In particular, a simple analytic technique was developed for the calculation of the average number of reflections for radiation passing through a CPC, which is useful for computing optical loses. Many numerical examples are presented which are helpful in designing a CPC.

Two basic types of CPC collectors have been designed; the symmetric and the asymmetric. These usually employ two main types of absorbers; fin type with pipe and tubular absorbers [14]. Practical design considerations such as the choice of the receiver type, the optimum method for introducing a gap between receiver and reflector to minimize optical and thermal loses and the effect of a glass envelope around the receiver are given in Reference [14]. Other practical design considerations for CPCs with multichannel and bifacial absorbers are given in References [13] and [14], respectively, whereas design considerations and performance evaluation of cost-effective asymmetric CPCs are given in Reference [14].

3. Evacuated Tube Collectors:

Conventional simple flat-plate solar collectors were developed for use in sunny and warm climates. Their benefits however are greatly reduced when conditions become unfavorable during cold, cloudy and windy days. Furthermore, weathering influences such as condensation and moisture will cause early deterioration of internal materials resulting in reduced performance and system failure. Evacuated heat pipe solar collectors (tubes) operate differently than the other collectors available on the market. These solar collectors consist of a heat pipe inside a vacuum-sealed tube, as shown in Figure 2.4.

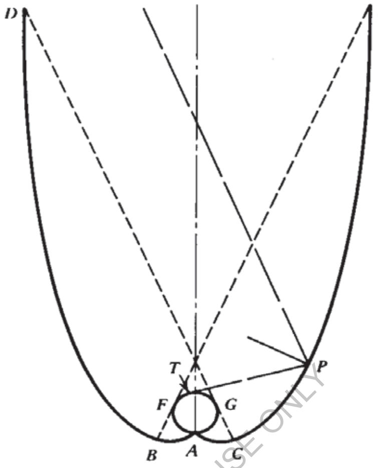


Figure 2.3 Schematic Diagram of a Compound Parabolic Collector

ETC have demonstrated that the combination of a selective surface and an effective convection suppressor can result in good performance at high temperatures [2] and [15]. The vacuum envelope reduces convection and conduction losses, so the collectors can operate at higher temperatures than FPC. Like FPC, they collect both direct and diffuse radiation. However, their efficiency is higher at low incidence angles. This effect tends to give ETC an advantage over FPC in day-long performance.

ETC use liquid–vapor phase change materials to transfer heat at high efficiency. These collectors feature a heat pipe (a highly efficient thermal conductor) placed inside a vacuum-sealed tube. The pipe, which is a sealed copper pipe, is then attached to a black copper fin that fills the tube (absorber plate). Protruding from the top of each tube is a metal tip attached to the sealed pipe (condenser). The heat pipe contains a small amount of fluid (e.g. methanol) that undergoes an evaporating-condensing cycle. In this cycle, solar heat evaporates the liquid, and the vapor travels to the heat sink region where it condenses and releases its latent heat. The condensed fluid return back to the solar collector and the process is repeated. When these tubes are mounted, the metal tips up, into a heat exchanger (manifold) as shown in Figure 2.4. Water, or glycol, flows through the manifold and picks up the heat from the tubes. The heated liquid circulates through another heat exchanger and gives off its heat to a process or to water that is stored in a solar storage tank.

Because no evaporation or condensation above the phase-change temperature is possible, the heat pipe offers inherent protection from freezing and overheating. This self-limiting temperature control is a unique feature of the evacuated heat pipe collector.

ETC basically consist of a heat pipe inside a vacuum sealed tube. A large number of variations of the absorber shape of ETC are on the market [6]. Evacuated tubes with CPC-reflectors are also commercialized by several manufacturers. One manufacturer recently presented an all-glass ETC, which may be an important step to cost reduction and increase of lifetime. Another variation of this type of collector is what is called Dewar tubes. In this two concentric glass tubes are used and the space in between the tubes is evacuated (vacuum jacket). The advantage of this design is that it is made entirely of glass and it is not necessary to penetrate the glass envelope in order to extract heat from the tube thus leakage losses are not present and it is also less expensive than the single envelope system [15].

Another type of collector developed recently is the integrated compound parabolic collector (ICPC). This is an ETC in which at the bottom part of the glass tube a reflective material is fixed [16]. The collector combines the vacuum insulation and non-imaging stationary concentration into a single unit. In another design a tracking ICPC is developed which is suitable for high temperature applications [17].

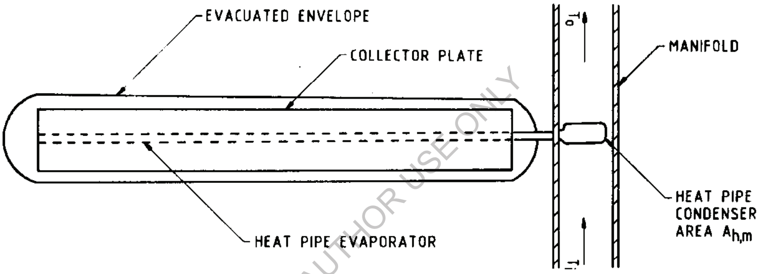


Figure 2.4 Schematic Diagram of Evacuated Tube Collectors

2.2.2 Sun Tracking Concentrating Collectors

Energy delivery temperatures can be increased by decreasing the area from which the heat losses occur. Temperatures far above those attainable by FPC can be reached if a large amount of solar radiation is concentrated on a relatively small collection area. This is done by interposing an optical device between the source of radiation and the energy absorbing surface. Concentrating collector exhibits certain advantages as compared with the conventional flat-plate type [18]. The main ones are:

1. The working fluid can achieve higher temperatures in a concentrator system when compared to a flat-plate system of the same solar energy collecting surface. This means that a higher thermodynamic efficiency can be achieved.

2. It is possible with a concentrator system, to achieve a thermodynamic match between temperature level and task. The task may be to operate thermionic, thermodynamic, or other higher temperature devices.

3. The thermal efficiency is greater because of the small heat loss area relative to the receiver area.

4. Reflecting surfaces require less material and are structurally simpler than FPC. For a concentrating collector the cost per unit area of the solar collecting surface is therefore less than that of a FPC.

5. Owing to the relatively small area of receiver per unit of collected solar energy, selective surface treatment and vacuum insulation to reduce heat losses and improve the collector efficiency are economically viable. Their disadvantages are:

1. Concentrator systems collect little diffuse radiation depending on the concentration ratio.

2. Some form of tracking system is required so as to enable the collector to follow the sun.

3. Solar reflecting surfaces may lose their reflectance with time and may require periodic cleaning and refurbishing.

Many designs have been considered for concentrating collectors. Concentrators can be reflectors or refractors, can be cylindrical or parabolic and can be continuous or segmented. Receivers can be convex, flat, cylindrical or concave and can be covered with glazing or uncovered. Concentration ratios, i.e. the ratio of aperture to absorber areas, can vary over several orders of magnitude, from as low as unity to high values of the order of 10000. Increased ratios mean increased temperatures at which energy can be delivered but consequently these collectors have increased requirements for precision in optical quality and positioning of the optical system.

Because of the apparent movement of the sun across the sky, conventional concentrating collectors must follow the sun's daily motion. There are two methods by which the sun's motion can be readily tracked. The first is the altazimuth method which requires the tracking device to turn in both altitude and azimuth, i.e. when performed properly, this method enables the concentrator to follow the sun exactly. Paraboloid solar collectors generally use this system.

The second one is the one-axis tracking in which the collector tracks the sun in only one direction either from east to west or from north to south. Parabolic trough collectors (PTC) generally use this system. These systems require continuous and accurate adjustment to compensate for the changes in the sun's orientation. The first type of a solar concentrator, shown in Figure 2.5, is effectively a FPC fitted with simple flat reflectors which can markedly increase the amount of direct radiation reaching the collector. This is a concentrator because the aperture is bigger than the absorber but the system is stationary. A comprehensive analysis of such a system is presented in Reference [19]. The model facilitates the prediction of the total energy absorbed by the collector at any hour of the day for any latitude for random tilt angles and azimuth angles of the collector and reflectors. This simple enhancement of FPC was initially suggested by Tabor in 1966 [19].

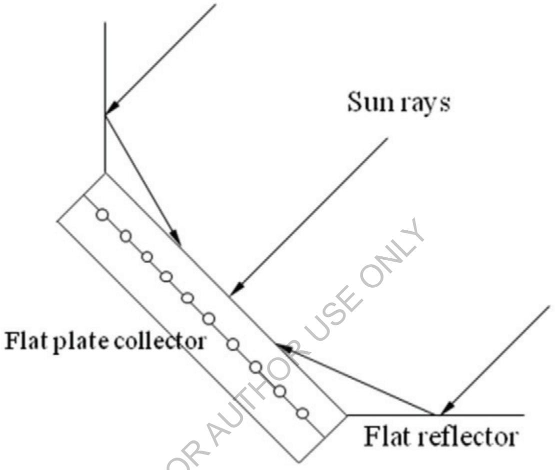


Figure 2.5 Flat Plate Collector with Flat Reflectors

Another type of collector, already covered under the stationary collectors, the CPC is also classified as concentrator. This, depending on the acceptance angle, can be stationary or tracking. When tracking is used this is very rough or intermitted as concentration ratio is usually small and radiation can be collected and concentrated by one or more reflections on the parabolic surfaces.

As was seen above one disadvantage of concentrating collectors is that, except at low concentration ratios, they can use only the direct component of solar radiation, because the diffuse component cannot be concentrated by most types. However, an additional advantage of concentrating collectors is that, in summer, when the sun rises well to the north of the east–west line, the sun-follower, with its axis oriented north–south, can begin to accept radiation directly from the sun long before a fixed, south-facing flat plate can receive anything other than diffuse radiation from the portion of the sky that it faces. Thus, in relatively cloudless areas, the concentrating collector may capture more radiation per unit of aperture area than a FPC.

In concentrating collectors solar energy is optically concentrated before being transferred into heat. Concentration can be obtained by reflection or refraction of solar radiation by the use of mirrors or lens. The reflected or refracted light is concentrated in a focal zone, thus increasing the energy flux in the receiving target. Concentrating collectors can also be classified into non-imaging and imaging depending on whether the image of the sun is focused at the receiver or not. The concentrator belonging in the first category is the CPC whereas all the other types of concentrators belong to the imaging type.

2.2.3 Concentrating Collectors

Concentrating, or focusing, collectors intercept direct radiation over a large area and focus it onto a small absorber area. These collectors can provide high temperatures more efficiently than flat-plate collectors, since the absorption surface area is much smaller. However, diffused sky radiation cannot be focused onto the absorber. Most concentrating collectors require mechanical equipment that constantly orients the collectors toward the sun and keeps the absorber at the point of focus. Therefore; there are many types of concentrating collectors [2].

Types of Concentrating Collectors:

There are four basic types of concentrating collectors:

1. Parabolic trough system.
2. A parabolic dish reflector.
3. Power tower.
4. Stationary concentrating collectors.

1. Parabolic Trough System:

In order to deliver high temperatures with good efficiency a high performance solar collector is required. Systems with light structures and low cost technology for process heat applications up to 400 C could be obtained with parabolic trough collectors (PTCs). PTCs can effectively produce heat at temperatures between 50 and 400 C.

PTCs are made by bending a sheet of reflective material into a parabolic shape. A metal black tube, covered with a glass tube to reduce heat losses, is placed along the focal line of the receiver as shown in Figure 2.6. When the parabola is pointed towards the sun, parallel rays incident on the reflector are reflected onto the receiver tube. It is sufficient to use a single axis tracking of the sun and thus long collector modules are produced. The collector can be orientated in an east–west direction, tracking the sun from north to south, or orientated in a north–south direction and tracking the sun from east to west. The advantages of the former tracking mode is that very little collector adjustment is required during the day and the full aperture always faces the sun at noon time but the collector performance during the early and late hours of the day is greatly reduced due to large incidence angles (cosine loss). North–south orientated troughs have their highest cosine loss at noon and the lowest in the mornings and evenings when the sun is due east or due west.

Over the period of one year, a horizontal north–south trough field usually collects slightly more energy than a horizontal east–west one. However, the north–south field collects a lot of energy in summer and much less in winter.

The east–west field collects more energy in the winter than a north–south field and less in summer, providing a more constant annual output. Therefore, the choice of orientation usually depends on the application and whether more energy is needed during summer or during winter [20].

Parabolic trough technology is the most advanced of the solar thermal technologies because of considerable experience with the systems and the development of a small commercial industry to produce and market these systems. PTCs are built in modules that are supported from the ground by simple pedestals at either end.

PTCs are the most mature solar technology to generate heat at temperatures up to 400 8C for solar thermal electricity generation or process heat applications. The biggest application of this type of system is the Southern California power plants, known as solar electric generating systems (SEGS), which have a total installed capacity of 354 MWe [21]. Another important application of this type of collector is installed at Plataforma Solar de Almeria (PSA) in Southern Spain mainly for experimental purposes. The total installed capacity of the PTCs is equal to 1.2 MW [22].

The receiver of a parabolic trough is linear. Usually, a tube is placed along the focal line to form an external surface receiver (Figure 2.6). The size of the tube, and therefore the concentration ratio, is determined by the size of the reflected sun image and the manufacturing tolerances of the trough. The surface of the receiver is typically plated with selective coating that has a high absorptance for solar radiation, but a low emittance for thermal radiation loss.

A glass cover tube is usually placed around the receiver tube to reduce the convective heat loss from the receiver, thereby further reducing the heat loss coefficient. A disadvantage of the glass cover tube is that the reflected light from the concentrator must pass through the glass to reach the absorber, adding a transmittance loss of about 0.9, when the glass is clean. The glass envelope usually has an antireflective coating to improve transmissivity. One way to further reduce convective heat loss from the receiver tube and thereby increase the performance of the collector, particularly for high temperature applications, is to evacuate the space between the glass cover tube and the receiver.

In order to achieve cost effectiveness in mass production, not only the collector structure must feature a high stiffness to weight ratio so as to keep the material content to a minimum, but also the collector structure must be amenable to low -labor manufacturing processes. A number of structural concepts have been proposed such as steel framework structures with central torque tubes or double V-trusses, or fiber glass [23]. A recent development in this type of collectors is the design and manufacture of Euro Trough, a new PTC, in which an advance lightweight structure is used to achieve cost efficient solar power generation [9], and [24]. Based on environmental test data to date, mirrored glass appears to be the preferred mirror material although self-adhesive reflective materials with 5–7 years life exists in the market. The design of this type of collector is given in a number of publications. The optimization of the collector aperture and rim angle is given in Reference [18]. Design of other aspects of the collector is given in References [25], and [26].

A tracking mechanism must be reliable and able to follow the sun with a certain degree of accuracy, return the collector to its original position at the end of the day or during the night, and also track during periods of intermittent cloud cover. Additionally, tracking mechanisms are used for the protection of collectors, i.e. they turn the collector out of focus to protect it from the hazardous environmental and working conditions, like wind gust, overheating and failure of the thermal fluid flow mechanism. The required accuracy of the tracking mechanism depends on the collector acceptance angle. Various forms of tracking mechanisms, varying from complex to very simple, have been proposed. They can be divided into two broad categories, namely mechanical [26] and [27] and electrical/electronic systems. The electronic systems generally exhibit improved reliability and tracking accuracy. These can be further subdivided into the following: Figure 2.7 below shows parabolic trough one axis and two axis collector tracking

1. Mechanisms employing motors controlled electronically through sensors, which detect the magnitude of the solar illumination [28].

2. Mechanisms using computer controlled motors with feedback control provided from sensors measuring the solar flux on the receiver [29] and [30].

A tracking mechanism developed by the author uses three light dependent resistors which detect the focus, sun/cloud, and day or night conditions and give instruction to a DC motor through a control system to focus the collector, to follow approximately the sun path when cloudy conditions exist and return the collector to the east during night. More details are given in Reference [31].

New developments in the field of PTC aim at cost reduction and improvements of the technology. In one system the collector can be washed automatically thus reducing drastically the maintenance cost.

After a period of research and commercial development of the PTC in the 80s a number of companies entered into the field producing this type of collectors, for the temperature range between 50 and 300 8C, all of them with one-axis tracking. One such example is the solar collector produced by the Industrial Solar Technology (IST) Corporation. IST erected several process heat installations in the United States with up to 2700 m^2 of collector aperture area [32].

The IST parabolic trough has thoroughly been tested and evaluated by Sandia [33] and the German Aerospace Centre (DLR) [34] for efficiency and durability. Improvements of the optical performance, which recently have been discussed [35], would lead to a better incident angle modifier and a higher optical efficiency. The characteristics of the IST collector system are shown in Table 2.3.

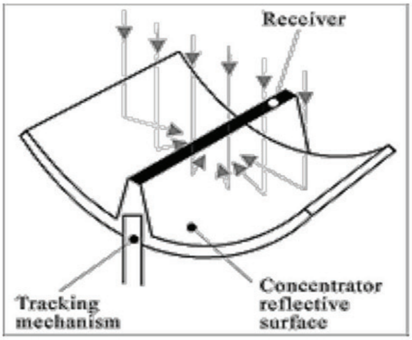


Figure 2.6 Parabolic Trough Collector

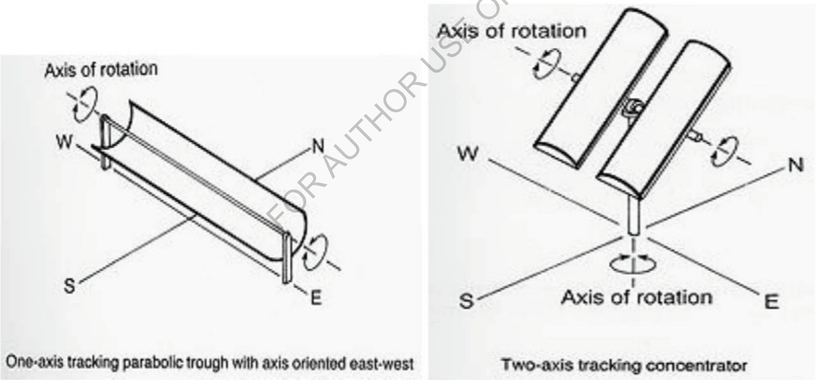


Figure 2.7 Parabolic Trough One Axis and Two Axis Collector Tracking

Table 2.3 Characteristics of the IST PTC System

Parameter	Value/type
Collector rim angle	70^0

Reflective surface	Silvered acrylic
Receiver material	Steel
Receiver surface treatment	Highly selective blackened nickel
Absorptance	0.97
Glass envelope transmittance	0.96
Absorber outside diameter	50.8 mm
Gtest : flow rate per unit area at test conditions (kg/s m^2)	0.015
k_o : intercept efficiency	0.762
k_1 : negative of the first-order coefficient of the efficiency ($W/m^2\ {}^0C$)	0.2125
k_i : negative of the second-order coefficient of the efficiency ($W/m^2\ {}^0C^2$)	0.001672
b_0 : incidence angle modifier constant	0.958
b_1 : incidence angle modifier constant	-0.298

Tracking mechanism accuracy	0.05^0
Collector orientation	Axis in N–S direction
Mode of tracking	E–W horizontal

2. Parabolic Dish Reflector (PDR):

A parabolic dish reflector, shown schematically in Figure 2.8, is a point-focus collector that tracks the sun in two axes, concentrating solar energy onto a receiver located at the focal point of the dish. The dish structure must track fully the sun to reflect the beam into the thermal receiver. For this purpose tracking mechanisms similar to the ones described in previous section are employed in double so as the collector is tracked in two axes.

The receiver absorbs the radiant solar energy, converting it into thermal energy in a circulating fluid. The thermal energy can then either be converted into electricity using an engine-generator coupled directly to the receiver, or it can be transported through pipes to a central power-conversion system. Parabolic-dish systems can achieve temperatures in excess of 1500 8C. Because the receivers are distributed throughout a collector field, like parabolic troughs, parabolic dishes are often called distributed-receiver systems.

Parabolic dishes have several important advantages:

1. Because they are always pointing the sun, they are the most efficient of all collector systems;

2. They typically have concentration ratio in the range of 600–2000, and thus are highly efficient at thermal-energy absorption and power conversion systems;

3. They have modular collector and receiver units that can either function independently or as part of a larger system of dishes.

The main use of this type of concentrator is for parabolic dish engines. A parabolic dish-engine system is an electric generator that uses sunlight instead of crude oil or coal to produce electricity. The major parts of a system are the solar dish concentrator and the power conversion unit. Parabolic-dish systems that generate electricity from a central power converter collect the absorbed sunlight from individual receivers and deliver it via a heat-transfer fluid to the power-conversion systems. The need to circulate heat transfer fluid throughout the collector field raises design issues such as piping layout, pumping requirements, and thermal losses.

Systems that employ small generators at the focal point of each dish provide energy in the form of electricity rather than as heated fluid. The power conversion unit includes the thermal receiver and the heat engine. The thermal receiver absorbs the concentrated beam of solar energy, converts it to heat, and transfers the heat to the heat engine. A thermal receiver can be a bank of tubes with a cooling fluid circulating through it. The heat transfer medium usually employed as the working fluid for an engine is hydrogen or helium. Alternate thermal receivers are heat pipes wherein the boiling and condensing of an intermediate fluid is used to transfer the heat to the engine. The heat engine system takes the heat from the thermal receiver and uses it to produce electricity. The engine-generators have several components; a receiver to absorb the concentrated sunlight to heat the working fluid of the engine, which then converts the thermal energy into mechanical work; an alternator attached to the engine to convert the work into electricity, a waste-heat exhaust system to vent excess heat to the atmosphere, and a control system to match the engine's operation to the available solar energy. This distributed parabolic dish system lacks thermal storage capabilities, but can be hybridized to run on fossil fuel during periods without sunshine. The Stirling engine is the most common type of heat engine used in dish-engine systems. Other possible power conversion unit technologies that are evaluated for future applications are micro turbines and concentrating photovoltaics [36].

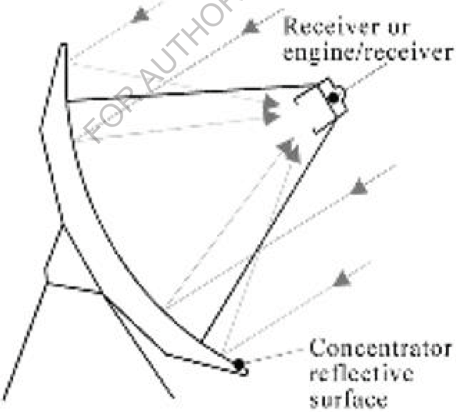


Figure 2.8 Parabolic Dish Reflector (PDR)

3. Power Tower System:

A heliostat uses a field of dual axis sun trackers that direct solar energy to a large absorber located on a tower. To date the only application for the heliostat collector is power generation in a system called the power tower [4]. A power tower has a field of large mirrors that follow the sun's path across the sky. The mirrors concentrate sunlight onto a receiver on top of a high tower. A computer keeps the mirrors aligned so the reflected rays of the sun are always aimed at the receiver, where temperatures well above 1000°C can be reached. High-pressure steam is generated to produce electricity [4]. The power tower system with heliostats is shown in the Figure 2.9 below.

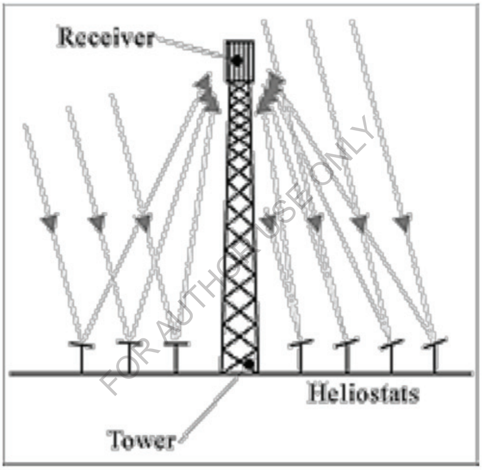


Figure 2.9 Power Tower System

4. Stationary Concentrating Solar Collectors:

Stationary concentrating collectors use compound parabolic reflectors and flat reflectors for directing solar energy to an accompanying absorber or aperture through a wide acceptance angle. The wide acceptance angle for these reflectors eliminates the need for a sun tracker. This class of collector includes parabolic trough flat plate collectors, flat plate collectors with parabolic boosting reflectors, and solar cooker.

Development of the first two collectors has been done in Sweden. Solar cookers are used throughout the world, especially in the developing countries [4].

2.3 Working Principles of Concentrating Collectors

Unlike solar (photovoltaic) cells, which use light to produce electricity, concentrating solar power systems generate electricity with heat. Concentrating solar collectors use mirrors and lenses to concentrate and focus sunlight onto a thermal receiver, similar to a boiler tube. The receiver absorbs and converts sunlight into heat. The heat is then transported to a steam generator or engine where it is converted into electricity.

2.4 Technology Comparison

Towers and troughs are best suited for large, grid-connected power projects in the 30-200 MW size, whereas, dish/engine systems are modular and can be used in single dish applications or grouped in dish farms to create larger multi-megawatt projects. Parabolic trough plants are the most mature solar power technology available today and the technology most likely to be used for near-term deployments. Power towers, with low cost and efficient thermal storage, promise to offer dispatch able, high capacity factor, solar-only power plants in the near future.

The modular nature of dishes will allow them to be used in smaller, high-value applications. Towers and dishes offer the opportunity to achieve higher solar-to-electric efficiencies and lower cost than parabolic trough plants, but uncertainty remains as to whether these technologies can achieve the necessary capital cost reductions and availability improvements. Parabolic troughs are currently a proven technology primarily waiting for an opportunity to be developed. Power towers require the operability and maintainability of the molten-salt technology to be demonstrated and the development of low cost heliostats. Dish/engine systems require the development of at least one commercial engine and the development of a low cost concentrator [5].

Chapter Three

Solar Collector Applications

Solar collectors have been used in a variety of applications. In Table 3.1 the most important technologies in use are listed together with the type of collector that can be used in each case.

3.1 Solar Water Heating Systems

The main part of a SWH is the solar collector array that absorbs solar radiation and converts it into heat. This heat is then absorbed by a heat transfer fluid (water, non-freezing liquid, or air) that passes through the collector. This heat can then be stored or used directly. Portions of the solar energy system are exposed to the weather conditions, so they must be protected from freezing and from overheating caused by high insolation levels during periods of low energy demand.

In solar water heating systems, potable water can either be heated directly in the collector (direct systems) or indirectly by a heat transfer fluid that is heated in the collector, passes through a heat exchanger to transfer its heat to the domestic or service water (indirect systems). The heat transfer fluid is transported either naturally (passive systems) or by forced circulation (active systems). Natural circulation occurs by natural convection (thermosiphoning), whereas for the forced circulation systems pumps or fans are used. Except for thermosiphon and integrated collector storage (ICS) systems, which need no control, solar domestic and service hot water systems are controlled using differential thermostats.

Five types of solar energy systems can be used to heat domestic and service hot water: thermosiphon, ICS, direct circulation, indirect, and air. The first two are called passive systems as no pump is employed, whereas the others are called active systems because a pump or fan is employed in order to circulate the fluid. For freeze protection, recirculation and drain-down are used for direct solar water heating systems and drain-back is used for indirect water heating systems.

All these systems offer significant economic benefits with payback times, depending on the type of fuel they replace, between 4 years (Electricity) and 7 years (diesel oil). Of course, these payback times depend on the economic indices, like the inflation rates and fuel price applied in a country. A wide range of collectors have been used for solar water heating systems. A review of the systems manufactured in the last 20 years is given in Reference [37].

Table 3.1 Solar Collector Applications

Application	System	Collector
Solar water heating		
Thermosiphon systems	Passive	FPC
Integrated collector storage	Passive	CPC
Direct circulation	Active	FPC, CPC ETC
Indirect water heating systems	Active	FPC, CPC
Air systems	Active	

		ETC FPC
Space heating and cooling		
Space heating and service hot water	Active	FPC, CPC ETC
Air systems	Active	FPC
Water systems	Active	FPC, CPC ETC
Heat pump systems	Active	FPC, CPC ETC
Absorption systems	Active	FPC, CPC ETC
Adsorption (desiccant) cooling	Active	FPC, CPC ETC
Mechanical systems	Active	PDR
Solar refrigeration		
Adsorption units	Active	FPC, CPC ETC
Absorption units	Active	FPC, CPC ETC

Industrial process heat		
Industrial air and water systems	Active	FPC, CPC ETC
Steam generation systems	Active	PTC, LFR
Solar desalination		
Solar stills	Passive	-
Multi-stage flash (MSF)	Active	FPC, CPC ETC
Multiple effect boiling (MEB)	Active	FPC, CPC ETC
Vapour compression (VC)	Active	FPC, CPC ETC
Solar thermal power systems		
Parabolic trough collector systems	Active	PTC
Parabolic tower systems	Active	HFC
Parabolic dish systems	Active	PDR
Solar furnaces	Active	HFC, PDR
Solar chemistry systems	Active	CPC, PTC, LFR

3.1.1 Thermosiphon Systems (Passive)

Thermosiphon systems, shown schematically in Figure 3.1, heat potable water or heat transfer fluid and use natural convection to transport it from the collector to storage. The water in the collector expands becoming less dense as the sun heats it and rises through the collector into the top of the storage tank. There it is replaced by the cooler water that has sunk to the bottom of the tank, from which it flows down the collector. The circulation continuous as long as there is sunshine. Since the driving force is only a small density difference larger than normal pipe sizes must be used to minimize pipe friction. Connecting lines must be well insulated to prevent heat losses and sloped to prevent formation of air pockets which would stop circulation. At night, or whenever the collector is cooler than the water in the tank the direction of the thermosiphon flow will reverse, thus cooling the stored water. One way to prevent this is to place the top of the collector well below (about 30 cm) the bottom of the storage tank.

The main disadvantage of thermosiphon systems is the fact that they are comparatively tall units, which makes them not very attractive aesthetically. Usually, a cold water storage tank is installed on top of the solar collector, supplying both the hot water cylinder and the cold water needs of the house, thus making the collector unit taller and even less attractive. Additionally, extremely hard or acidic water can cause scale deposits that clog or corrode the absorber fluid passages. For direct systems, pressure reducing valves are required when the city water is used directly (no cold water storage tank) and pressure is greater than the working pressure of the collectors.

There have been extensive analyses of the performance of thermosiphon SWH, both experimentally and analytically by numerous researchers. Some of the most important are shown here. Gupta and Garg [38] developed one of the first models for thermal performance of a natural circulation SWH with no load. They represented solar radiation and ambient temperature by Fourier series, and were able to predict a day's performance in a manner that agreed substantially with experiments.

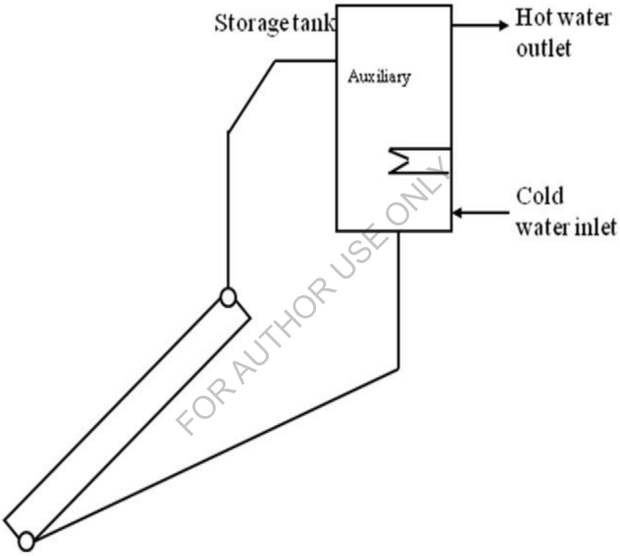


Figure 3.1 Schematic Diagram of a Thermosiphon Solar Water Heater

Ong performed two studies [39], and [40] to evaluate the thermal performance of a SWH. He instrumented a relatively small system with five thermocouples on the bottom surface of the water tubes and six thermocouples on the bottom surface of the collector plate. A total of six thermocouples were inserted into the storage tank and a dye tracer mass flow meter was employed. Ong’s studies appear to be the first detailed ones on a thermosiphonic system.

Kudish et al. [41] in their study measured the thermosiphon flow rate directly by adapting a simple and well-known laboratory technique, a constant level device, to a solar collector in the thermosiphon mode. The thermosiphon flow data gathered were utilized to construct a standard efficiency test curve, thus showing that this technique can be applied for testing collectors in the thermosiphon mode. Also, they determined the instantaneous collector efficiency as a function of time of day.

Morrison and Braun [42] have studied system modeling and operation characteristics of thermosiphon SWH with vertical or horizontal storage tank. They found that the system performance is maximized when the daily collector volume flow is approximately equal to the daily load flow, and the system with horizontal tank did not perform as well as a vertical one.

Hobson and Norton [43] in their study developed a characteristic curve for an individual directly heated thermosiphon solar energy water heater obtained from data of a 30 days tests. Using such a curve, the calculated annual solar fraction agreed well with the corresponding value computed from the numerical simulation. Furthermore, the analysis was extended, and they produced a simple but relatively accurate design method for direct thermosiphon solar energy water heaters.

Shariah and Shalabi [44] have studied optimization of design parameters for a thermosiphon SWH for two regions in Jordan represented by two cities, namely Amman and Aqaba through the use of TRNSYS simulation program. Their results indicate that the solar fraction of the system can be improved by 10–25% when each studied parameter is chosen properly. It was also found that the solar fraction of a system installed in Aqaba (hot climate) is less sensitive to some parameters than the solar fraction of a similar system installed in Amman (mild climate).

3.1.2 Integrated Collector Storage Systems (Passive)

Integrated collector storage (ICS) systems use hot water storage as part of the collector, i.e., the surface of the storage tank is used also as an absorber. The main disadvantage of the ICS systems is the high thermal losses from the storage tank to the surroundings since most of the surface area of the storage tank cannot be thermally insulated as it is intentionally exposed for the absorption of solar radiation. Thermal losses are greatest during the night and overcast days with low ambient temperature. Due to these losses the water temperature drops substantially during the night especially during the winter.

3.1.3 Direct Circulation Systems (Active)

In direct circulation systems, shown schematically in Figure 3.2, a pump is used to circulate potable water from storage to the collectors when there is enough available solar energy to increase its temperature and then return the heated water to the storage tank until it is needed. As a pump circulates the water, the collectors can be mounted either above or below the storage tank. The optimum flow rate for such units is about 0.015 L/m^2 of collector area. Direct circulation systems can be used in areas where freezing is not frequent. For extreme weather conditions, freeze protection is usually provided by recirculating warm water from the storage tank.

Direct circulation systems often use a single storage tank equipped with an auxiliary water heater, but two-tank storage systems can also be used.

Direct circulation systems can be used with water supplied from a cold water storage tank or connected directly to city water mains. Pressure-reducing valves and pressure relief valves are required however when the city water pressure is greater than the working pressure of the collectors. Direct water heating systems should not be used in areas where the water is extremely hard or acidic because scale deposits may clog or corrode the collectors.

A variation of the direct circulation system is the drain down systems shown in Figure 3.3. In this case also potable water is pumped from storage to the collector array where it is heated. When a freezing condition or a power failure occurs, the system drains automatically by isolating the collector array and exterior piping from the make-up water supply and draining it using the two normally open (NO) valves, shown in Figure 3.3. It should be noted that the solar collectors and associated piping must be carefully sloped to drain the collector's exterior piping when circulation stops. The same comments about pressure and scale deposits apply here as for the direct circulation systems.

3.1.4 Indirect Water Heating Systems (Active)

Indirect water heating systems, shown schematically in Figure 3.4, circulate a heat transfer fluid through the closed collector loop to a heat exchanger, where its heat is transferred to the potable water. The most commonly used heat transfer fluids are water/ethylene glycol solutions, although other heat transfer fluids such as silicone oils and refrigerants can also be used. When fluids that are non-potable or toxic are used double-wall heat exchangers should be employed. The heat exchanger can be located inside the storage tank, around the storage tank (tank mantle) or can be external. It should be noted that the collector loop is closed and therefore an expansion tank and a pressure relief valve are required. Additional over temperature protection may be needed to prevent the collector heat transfer fluid from decomposing or becoming corrosive.

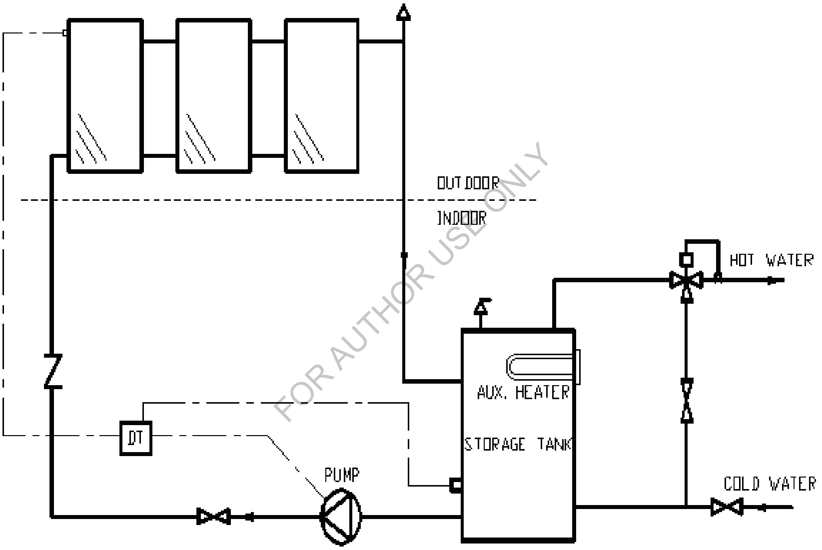


Figure 3.2 Direct Circulation System

A variation of indirect water heating systems is the drain back system. Drain-back systems are generally indirect water heating systems that circulate water through the closed collector loop to a heat exchanger, where its heat is transferred to the potable water. Circulation continues as long as usable energy is available. When the circulation pump stops the collector fluid drains by gravity to a drain back tank. If the system is pressurized the tank serves also as an expansion tank when the system is operating and in this case it must be protected with a temperature and pressure relief valves. In the case of an unpressurised system Figure 3.5, the tank is open and vented to the atmosphere. As the collector loop is isolated from the potable water, no valves are needed to actuate draining, and scaling is not a problem, however, the collector array and exterior piping must be adequately sloped to drain completely.

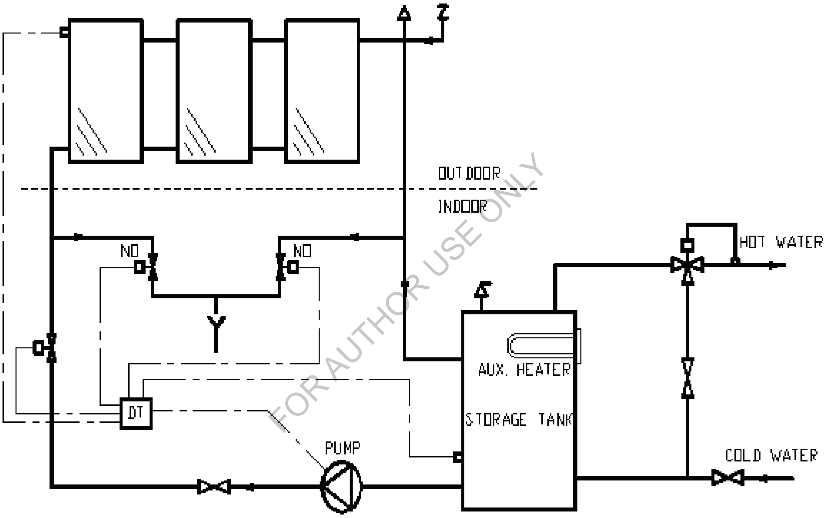


Figure 3.3 Drain-down system

3.1.5 Air Systems

Air systems are indirect water heating systems that circulate air via ductwork through the collectors to an air-to liquid heat exchanger. In the heat exchanger, heat is transferred to the potable water, which is also circulated through the heat exchanger and returned to the storage tank. Figure 3.6 shows a double storage tank system.

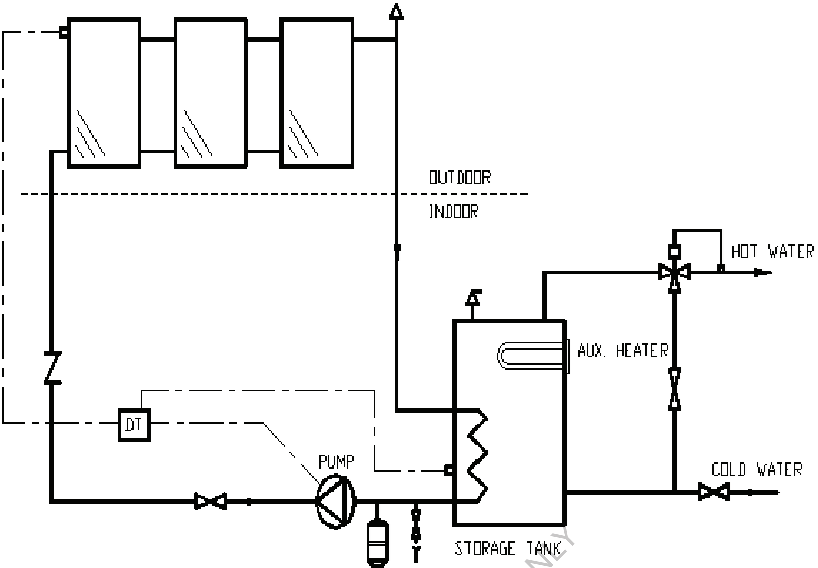


Figure 3.4 Indirect Water Heating System

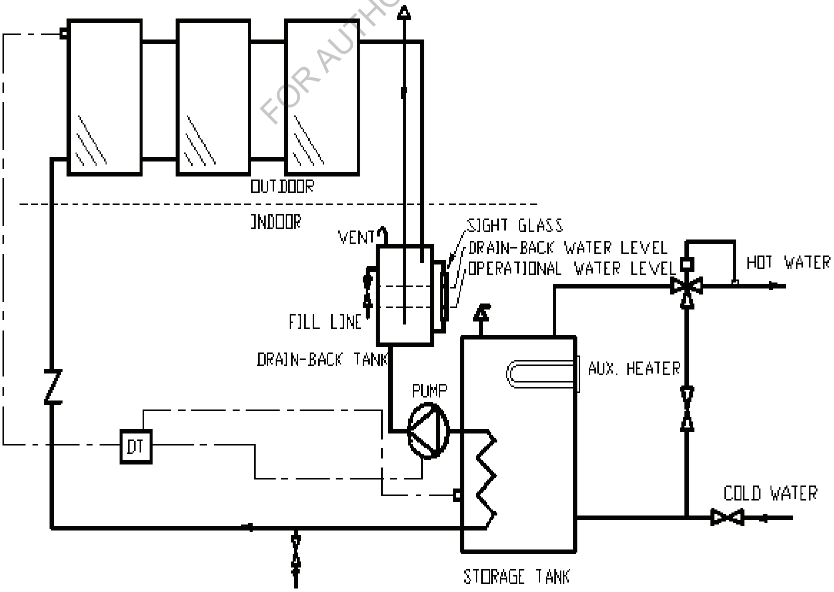


Figure 3.5 Drain-Back System

This type of system is used most often, because air systems are generally used for preheating domestic hot water and thus auxiliary is used only in one tank as shown. The main advantage of the system is that air does not need to be protected from freezing or boiling, is noncorrosive, and is free. The disadvantages are that air handling equipment (ducts and fans) need more space than piping and pumps, air leaks are difficult to detect, and parasitic power consumption is generally higher than that of liquid systems.

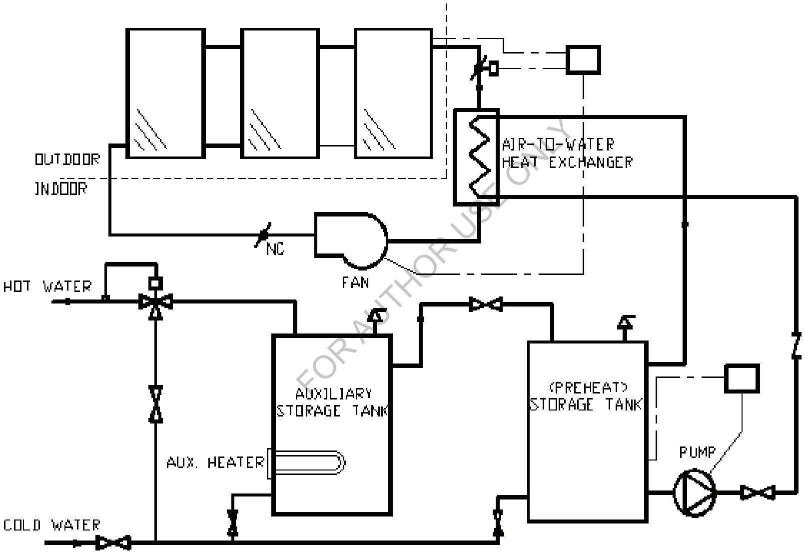


Figure 3.6 Air System

3.2 Solar Space Heating and Cooling

The components and subsystems discussed in Section 3.1 may be combined to create a wide variety of building solar heating and cooling systems. There are again two principal categories of such systems, passive and active. The term passive system is applied to buildings that include as integral part of the building elements, that admit, absorb, store and release solar energy and thus reduce the needs for auxiliary energy for comfort heating. As no solar collectors are employed in the passive systems in this paper, only active systems are considered.

Systems for space heating are very similar to those for water heating, described in Section 3.1, and as the same considerations for combination with an auxiliary source, boiling and freezing, controls, etc., apply to both these may not be repeated again. The most common heat transfer fluids are water, water and antifreeze mixtures and air. The load is the building to be heated. Although it is technically possible to construct a solar heating or cooling system which can satisfy 100% the design load, such a system would be nonviable since it would be oversized for most of the time. The size of the solar system may be determined by a life-cycle cost analysis.

Active solar space systems use collectors to heat a fluid, storage units to store solar energy until needed, and distribution equipment to provide the solar energy to the heated spaces in a controlled manner. A complete system includes additionally pumps or fans for transferring the energy to storage or to the load which require a continuous availability of non-renewable energy, generally in the form of electricity.

The load can be space cooling, heating, or a combination of these two with hot water supply. In combination with conventional heating equipment solar heating provides the same levels of comfort, temperature stability, and reliability as conventional systems.

Active solar energy systems can also be combined with heat pumps for water heating and/or space heating. In residential heating the solar system can be used in parallel with a heat pump, which supplies auxiliary energy when the sun is not available. Additionally, for domestic water systems requiring high water temperatures, a heat pump can be placed in series with the solar storage tank.

During daytime the solar system absorbs solar radiation with collectors and conveys it to storage using a suitable fluid. As the building requires heat it is obtained from storage. Control of the solar system is exercised by differential temperature controllers, i.e. the controller compares the temperature of the collectors and storage and whenever the temperature difference is more than a certain value (7–10 ^{0}C) then the solar pump is switched ON. In locations where freezing conditions are possible to occur, a low-temperature sensor is installed on the collector which controls the solar pump when a pre-set temperature is reached. This process wastes some stored heat, but it prevents costly damages to the solar collectors.

Solar cooling of buildings is an attractive idea as the cooling loads and availability of solar radiation are in phase. Additionally, the combination of solar cooling and heating greatly improves the use factors of collectors compared to heating alone. Solar air conditioning can be accomplished by three types of systems: absorption cycles, adsorption (desiccant) cycles and solar mechanical processes. Some of these cycles are also used in solar refrigeration systems and are described in the upcoming section 3.3. The rest of this section deals with solar heating and service hot water production. It should be noted that the same solar collectors are used for both space heating and cooling systems when both are present. A review of the various solar heating and cooling systems is presented in Reference [45]. A review of solar and low energy cooling technologies is presented in Reference [46].

3.2.1 Space Heating and Service Hot Water

It is useful to consider solar systems as having five basic modes of operation, depending on the conditions that exist in the system at a particular time [47]:

1. If solar energy is available and heat is not needed in the building, energy gain from the collector is added to storage.

2. If solar energy is available and heat is needed in the building, energy gain from the collector is used to supply the building need.

3. If solar energy is not available, heat is needed in the building, and the storage unit has stored energy in it, the stored energy is used to supply the building need.

4. If solar energy is not available, heat is needed in the building, and the storage unit has been depleted, auxiliary energy is used to supply the building need.

5. The storage unit is fully heated, there are no loads to meet, and the collector is absorbing heat.

When the last mode occurs, there is no way to use or store the collected energy, and this energy must be discarded. This can be achieved through the operation of pressure relief valves or if the stagnant temperature will not be detrimental to the collector materials, the flow of fluids is turned off, thus the collector temperature will rise until the absorbed energy is dissipated by thermal losses. This is more suitable to solar air collectors.

Additional operational modes can also be employed such as to provide service hot water. It is also possible to combine modes, i.e. to operate in more than one mode at a time. Moreover, many systems do not allow direct heating from solar collector to building, but always transfer heat from collector to storage whenever this is available and from storage to load whenever needed. In Europe solar heating systems for combined space and water heating are known as combisystems. The following sections describe the design of residential-scale installations.

3.2.2 Air Systems

A schematic of a basic solar heating system using air as the heat transfer fluid, with pebble bed storage unit and auxiliary heating source is shown in Figure 3.7. The various modes of operations are achieved by appropriate positioning of the dampers. In most air systems it is not practical to combine the modes of adding energy to and removing energy from storage at the same time. Auxiliary energy can be combined with energy supplied from collector or storage to top-up the air temperature in order to cover the building load. As shown in Figure 3.7, it is possible to bypass the collector and storage unit when auxiliary alone is being used to provide heat. Figure 3.8 shows a more detailed schematic of an air system. Blowers, controls, means of obtaining service hot water, and more details of ducting are shown.

The advantages of using air as a heat transfer fluid include the high degree of stratification possible in the pebble bed which leads to lower collector inlet temperatures. The working fluid is air, and warm air heating systems are in common use. Control equipment that can be applied to those systems is also readily available.

The disadvantages of water heating air systems include the difficulty of adding solar air conditioning to the systems. Finally, air collectors are operated at lower fluid capacitance rates and thus with lower values of F_R than the liquid heating collectors. Usually, air heating collectors in space heating systems are operated at fixed air flow rates, thus the outlet temperature varies through the day. It is also possible to operate them at a fixed outlet temperature by varying the flow rate. This however results in reduced F_R and thus reduced collector performance when flow rates are low.

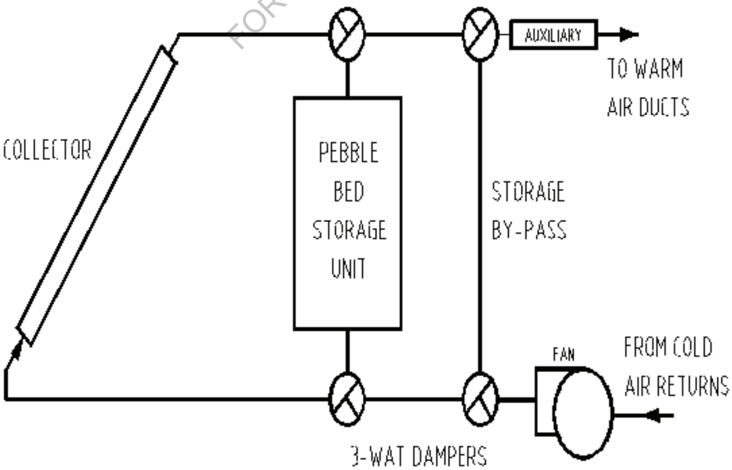


Figure 3.7 Schematic Representation of Basic Hot Air System

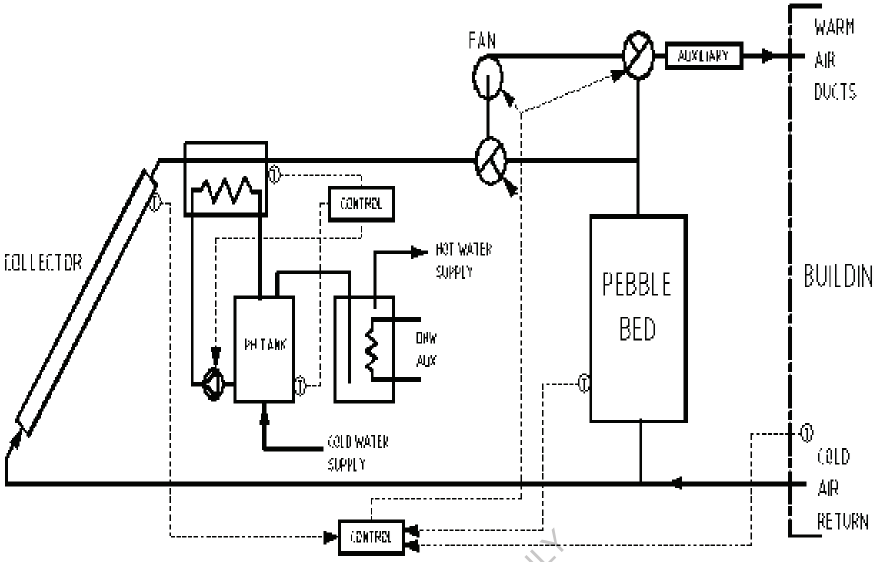


Figure 3.8 Detailed Schematic Representation of a Solar Air Heating System

3.2.3 Water Systems

There are many variations of systems used for both solar space heating and service hot water production. The basic configuration is similar to the solar water heating systems. When used for both space and hot water production this system allows independent control of the solar collector-storage and storage-auxiliary-load loops as solar heated water can be added to storage at the same time that hot water is removed from storage to meet building loads. Usually, a bypass is provided around the storage tank to avoid heating the storage tank, which can be of considerable size, with auxiliary energy.

A detailed schematic of a liquid-based system is shown in reference [47]. In this case a collector heat exchanger is shown between the collector and the storage tank, which allows the use of antifreeze solutions to the collector circuit. Relief valves are also required for dumping excess energy if the collector temperature reaches saturation. Means of extracting energy for service hot water are indicated. Auxiliary energy for heating is added so as to 'top off' that available from solar energy system.

A load heat exchanger is shown in Figure 3.9 to transfer energy from the tank to the air in the heated spaces. The load heat exchanger must be adequately designed to avoid excessive temperature drop and corresponding increase in the tank and collector temperatures.

Advantages of liquid heating systems include high collector FR; smaller storage volume, and relatively easy adaptation to supply energy to absorption air conditioners.

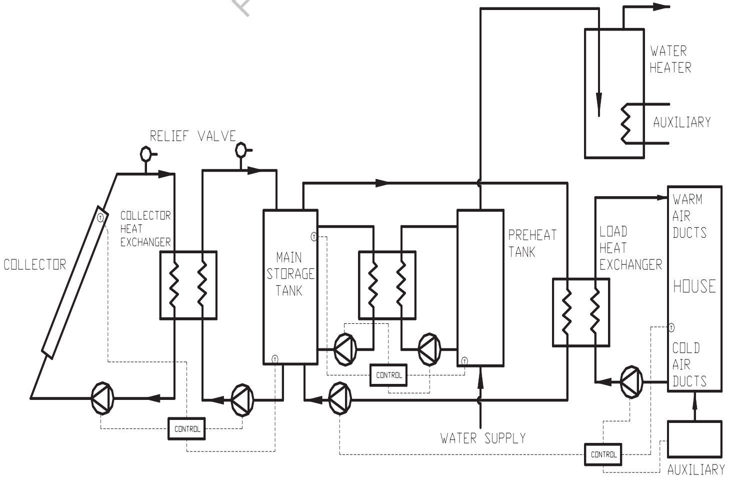


Figure 3.9 Detail Schematic of a Solar Water Heating System

3.3 Heat Pump Systems

Heat pumps use mechanical energy to transfer thermal energy from a source at a lower temperature to a sink at a higher temperature. Electrically driven heat pump heating systems have two advantages compared to electric resistance heating or expensive fuels. The heat pump's COP is high enough to yield 11 to 15 MJ of heat for each kW h of energy supplied to the compressor [6], which saves on purchase of energy, and usefulness for air conditioning in the summer. Water-to-air heat pumps, which use solar heated water from the storage tank as the evaporator energy source, are an alternative auxiliary heat source. Use of water involves freezing problems which need to be taken into consideration. Solar heating systems using liquids will operate at lower temperatures than conventional hydronic systems and will require more baseboard heater area to transfer heat into the building.

3.4 Solar Refrigeration

Solar cooling can be considered for two related processes: to provide refrigeration for food and medicine preservation and to provide comfort cooling. Solar refrigeration systems usually operate at intermitted cycles and produce much lower temperatures (ice) than in air conditioning. When the same cycles are used in space cooling they operate on continuous cycles. The cycles employed for solar refrigeration are the absorption and adsorption. During the cooling portion of the cycles, the refrigerant is evaporated and reabsorbed. In these systems the absorber and generator are separate vessels. The generator can be integral part of the collector, with refrigerant absorbent solution in the tubes of the collector circulated by a combination of a thermosiphon and a vapor lift pump.

There are many options available which enable the integration of solar energy into the process of 'cold' production. Solar refrigeration can be accomplished by using either a thermal energy source supplied from a solar collector or electricity supplied from photovoltaics. This can be achieved by using either thermal adsorption or absorption units or conventional refrigeration equipment powered from photo voltaic. Solar refrigeration is employed mainly to cool vaccine stores in areas with no mains electricity and for solar space cooling.

Photovoltaic refrigeration, although uses standard refrigeration equipment which is an advantage, has not achieved widespread use because of the low efficiency and high cost of the photovoltaic cells. As photovoltaics are not covered in this paper details are given only on the solar adsorption and absorption units with more emphasis on the latter.

3.4.1 Adsorption Units

Porous solids, called adsorbents, can physically and reversibly adsorb large volumes of a vapor, called the adsorbate. Though this phenomenon, called solar adsorption, was recognized in the 19th century its practical application in the field of refrigeration is relatively recent. The concentration of adsorbate vapors in a solid adsorbent is a function of the temperature of the pair, i.e. the mixture of adsorbent and adsorbate, and the vapor pressure of the latter. The dependence of adsorbate concentration on temperature, under constant pressure conditions, makes it possible to adsorb or desorb the adsorbate by varying the temperature of the mixture.

This forms the basis of the application of this phenomenon in the solar-powered intermittent vapor sorption refrigeration cycle.

An adsorbent–refrigerant working pair for a solar refrigerator requires the following characteristics:

1. A refrigerant with a large latent heat of evaporation.

2. A working pair with high thermodynamic efficiency.

3. A small heat of desorption under the envisaged operating pressure and temperature conditions.

4. A low thermal capacity.

Water–ammonia has been the most widely used sorption–refrigeration pair and research has been undertaken to utilize the pair for solar-operated refrigerators. The efficiency of such systems is limited by the condensing temperature, which cannot be lowered without introduction of advanced and expensive technology. For example, cooling towers or desiccant beds have to be used to produce cold water to condensate ammonia at lower pressure. Amongst the other disadvantages inherent in using water and ammonia as the working pair are the heavy gauge pipe and vessel walls required to withstand the high pressure, the corrosiveness of ammonia, and the problem of rectification, i.e. removing water vapor from ammonia during generation. A number of different solid adsorption working pairs such as zeolite–water, zeolite– methanol, and activated carbon–methanol, have been studied in order to find the one that performed better. The activated carbon–methanol working pair was found to perform the best [5].

Because complete physical property data are available for only a few potential working pairs, the optimum performance remains unknown at the moment. In addition, the operating conditions of a solar-powered refrigerator, i.e. generator and condenser temperature, vary with its geographical location [5].

The development of three solar/biomass adsorption air conditioning refrigeration systems is presented by Critoph [48]. All systems use active carbon–ammonia adsorption cycles and the principle of operation and performance prediction of the systems are given.

Thorpe presented an adsorption heat pump system which uses ammonia with granular active adsorbate. A high COP is achieved and the cycle is suitable for the use of heat from high temperature (150–200 8C) solar collectors for air conditioning.

3.4.2 Absorption Units

Absorption is the process of attracting and holding moisture by substances called desiccants. Desiccants are sorbents, i.e. materials that have an ability to attract and hold other gases or liquids, which have a particular affinity for water. During absorption the desiccant undergoes a chemical change as it takes on moisture; for example, the table salt, which changes from a solid to a liquid as it absorbs moisture. The characteristic of the binding of desiccants to moisture, makes the desiccants very useful in chemical separation processes [49].

Absorption systems are similar to vapor-compression air conditioning systems but differ in the pressurization stage. In general an absorbent, on the low-pressure side, absorbs an evaporating refrigerant. The most usual combinations of fluids include lithium bromide-water (LiBr–H_2O) where water vapor is the refrigerant and ammonia–water (NH_3–H_2O) systems where ammonia is the refrigerant.

The pressurization is achieved by dissolving the refrigerant in the absorbent, in the absorber section Figure 3.10. Subsequently, the solution is pumped to a high pressure with an ordinary liquid pump. The addition of heat in the generator is used to separate the low-boiling refrigerant from the solution. In this way the refrigerant vapor is compressed without the need of large amounts of mechanical energy that the vapor-compression air conditioning systems demand.

The remainder of the system consists of a condenser, expansion valve and evaporator, which function in a similar way as in a vapor-compression air conditioning system. The NH_3–H_2O system is more complicated than the

LiBr–H_2O system, since it needs a rectifying column that assures that no water vapor enters the evaporator where it could freeze. The NH_3–H_2O system requires generator temperatures in the range of 125–170 ^oC with air-cooled absorber and condenser and 95–120 ^oC when water-cooling is used. These temperatures cannot be obtained with FPCs. The coefficient of performance (COP), which is defined as the ratio of the cooling effect to the heat input, is between 0.6 and 0.7.

The LiBr–H_2O system operates at a generator temperature in the range of 70–95 ^oC with water used as a coolant in the absorber and condenser and has COP higher than the NH_3–H_2O systems. The COP of this system is between 0.6 and 0.8 [47]. A disadvantage of the LiBr–H_2O systems is that their evaporator cannot operate at temperatures much below 5°C since the refrigerant is water vapor. Commercially available absorption chillers for air conditioning applications usually operate with a solution of lithium bromide in water and use steam or hot water as the heat source. In the market two types of chillers are available, the single and the double effect.

The single effect absorption chiller is mainly used for building cooling loads, where chilled water is required at 6–7°C. The COP will vary to a small extent with the heat source and the cooling water temperatures. Single effect chillers can operate with hot water temperature ranging from about 80 to 150 °C when water is pressurized [50].

The double effect absorption chiller has two stages of generation to separate the refrigerant from the absorbent. Thus the temperature of the heat source needed to drive the high-stage generator is essentially higher than that needed for the single-effect machine and is in the range of 155–205°C. Double effect chillers have a higher COP of about 0.9–1.2 [51]. Although double effect chillers are more efficient than the single-effect machines they are obviously more expensive to purchase. However, every individual application must be considered on its merits since the resulting savings in capital cost of the single-effect units can largely offset the extra capital cost of the double effect chiller.

The Carrier Corporation pioneered lithium–bromide absorption chiller technology in the United States, with early single-effect machines introduced around 1945. Due to the success of the product soon other companies joined the production. The absorption business thrived until

1975. Then the generally held belief that natural gas supplies were lessening, let to US government regulations prohibiting the use of gas in new constructions and together with the low cost of electricity led to the declination of the absorption refrigeration market [50]. Today the major factor on the decision on the type of system to install for a particular application is the economic trade-off between the different cooling technologies. Absorption chillers typically cost less to operate, but they cost more to purchase than vapor compression units. The payback period depends strongly on the relative cost of fuel and electricity assuming that the operating cost for the needed heat is less than the operating cost for electricity.

The technology was exported to Japan from the US early in the 1960s, and the Japanese manufacturers set a research and development program to improve further the absorption systems. The program led to the introduction of the direct fired double-effect machines with improved thermal performance.

Today gas-fired absorption chillers deliver 50% of commercial space cooling load worldwide, but less than 5% in the US, where electricity-driven vapor compression machines carry the majority of the load [51].

Many researchers have developed solar assisted absorption refrigeration systems. Most of them have been produced as experimental units and computer codes were written to simulate the systems. Some of these designs are presented here.

Hammad and Audi [52] described the performance of a non-storage, continuous, solar operated absorption refrigeration cycle. The maximum ideal COP of the system was determined to be equal to 1.6, while the peak actual COP was determined to be equal to 0.55.

Haim et al. [53] performed a simulation and analysis of two open-cycle absorption systems. Both systems comprise a closed absorber and evaporator as in conventional single stage chillers. The open part of the cycle is the regenerator, used to reconcentrate the absorber solution by means of solar energy. The analysis was performed with a computer code developed for modular simulation of absorption systems under varying cycle configurations (open- and closed-cycle systems) and with different working fluids. Based on the specified design features, the code calculates the operating parameters in each system. Results indicate a definite performance advantage of the direct-regeneration system over the indirect one.

Hawlader et al. [54] developed a lithium bromide absorption cooling system employing an 11 £, 11 m^2 collector/regenerator unit. They also have developed a computer model, which they validated against real experimental values with good agreement. The experimental results showed a regeneration efficiency varying between 38 and 67% and the corresponding cooling capacities ranged from 31 to 72 kW.

Ameel et al. [55] give performance predictions of alternative low-cost absorbents for open cycle absorption using a number of absorbents. The most promising of the absorbents considered, was a mixture of two elements, lithium chloride and zinc chloride. The estimated capacities per unit absorber area were 50–70% less than those of lithium bromide systems.

Ghaddar et al. [56] presented modelling and simulation of a solar absorption system for Beirut. The results showed that, for each ton of refrigeration, it is required to have a minimum collector area of 23.3 m^2 with an optimum water storage capacity ranging from 1000 to 1500 l, for the system to operate solely on solar energy for about 7 h per day. The monthly solar fraction of total energy use in cooling is determined as a function of solar collector area and storage tank capacity. The economic analysis performed showed that the solar cooling system is marginally competitive only when it is combined with domestic water heating.

Erhard and Hahne [57] simulated and tested a solar powered absorption cooling machine. The main part of the device is an absorber/desorber unit, which is mounted inside a concentrating solar collector. Results obtained from field tests are discussed and compared with the results obtained from a simulation program developed for this purpose.

Hammad and Zurigat [58] described the performance of a 1.5 ton solar cooling unit. The unit comprises a 14 m^2 flat plate solar collector system and five shell and tube heat exchangers. The unit was tested in April and May in Jordan. The maximum value obtained for actual COP was 0.85.

Zinian and Ning [59] describe a solar absorption air conditioning system which uses an array of 2160 evacuated tubular collectors of total aperture area of 540 m^2 and a LiBr absorption chiller. Thermal efficiencies of the collector array are 40% for space cooling, 35% for space heating and 50% for domestic water heating. It was found that the cooling efficiency of the entire system is around 20%.

A new family of ICPC designs was developed by Winston et al. [60] which allows a simple manufacturing approach to be used and solves many of the operational problems of previous ICPC designs. A low concentration ratio is used that requires no tracking together with an off the- shelf 20 ton double effect LiBr direct fired absorption chiller, modified to work with hot water. The new ICPC design and double effect chiller was able to produce cooling energy for the building using a collector field that was about half the size of that required for a more conventional collector and chiller.

A method to design, construct and evaluate the performance of a single stage lithium bromide–water absorption machine is presented in Reference [61]. In this the necessary heat and mass transfer relations and appropriate equations describing the properties of the working fluids are specified. Information on designing the heat exchangers of the LiBr–water absorption unit is also presented. Single pass vertical-tube heat exchangers have been used for the absorber and for the evaporator. The solution heat exchanger was designed as a single-pass annulus heat exchanger. The condenser and the generator were designed using horizontal tube heat exchangers. Figure 3.10 below shows the basic principle of the absorption air conditioning system.

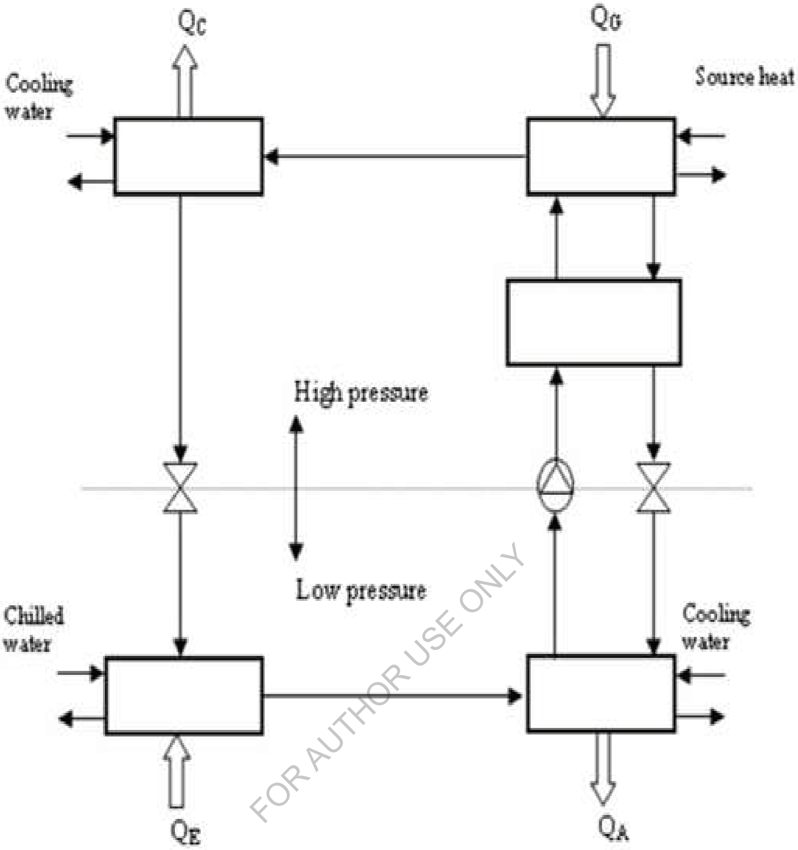


Figure 3.10 Basic Principle of the Absorption Air Conditioning System

3.5 Solar Steam Generation Systems

PTC are frequently employed for solar steam generation, because relatively high temperatures can be obtained without any serious degradation in the collector efficiency. Low temperature steam can be used in industrial applications, sterilization, and for powering desalination evaporators.

Three methods have been employed to generate steam using PTC [62]:

1. The steam-flash concept, in which pressurized water is heated in the collector and then flashed to steam in a separate vessel.

2. The direct or in situ concept, in which two phase flow is allowed in the collector receiver so that steam is generated directly.

3. The unfired-boiler concept, in which a heat-transfer fluid is circulated through the collector and steam is generated via heat-exchange in an unfired boiler.

All these systems have certain advantages and disadvantages. In a steam-flash system, shown schematically in Figure 3.11, water, pressurized to prevent boiling, is circulated through the collector and then flashed across a throttling valve into a flash vessel. Treated feed water input maintains the level in the flash vessel and the sub cooled liquid is re circulated through the collector. The in situ boiling concept, shown in Figure 3.12., uses a similar system configuration without a flash valve. Sub cooled water is heated to boiling and steam forms directly in the receiver tube. Capital costs associated with a direct-steam and a flash-steam system would be approximately the same [63].

Although both systems use water, a superior heat transport fluid, the in situ boiling system is more advantageous. The flash system uses a sensible heat change in the working fluid, which makes the temperature differential across the collector relatively high. The rapid increase in water vapor pressure with temperature requires corresponding increase in system operating pressure to prevent boiling. Increased operating temperatures reduce the thermal efficiency of the solar collector. Increased pressures within the system require a more robust design of collector components, such as receivers and piping. The differential pressure over the delivered steam pressure required to prevent boiling is supplied by the circulation pump and is irreversibly dissipated across the flash valve. When boiling occurs in the collectors, as in an in situ boiler, the system pressure drop and consequently, electrical power consumption is greatly reduced. In addition, the latent heat transfer process minimizes the temperature rise across the solar collector. Disadvantages of in situ boiling are the possibility of a number of stability problems [64] and the fact that even with a very good feed water treatment system, scaling in the receiver is unavoidable. In multiple row collector arrays, the occurrence of flow instabilities could result in loss of flow in the affected row. This in turn could result in tube dry out with consequent damage of the selective receiver coating. No significant instabilities were reported by Hurtado and Kast [63] 66when experimentally testing a single row 36 m system. Recently, once through systems are developed on a pilot scale for direct steam generation in which PTC are used inclined at 2–4^0 [65].

A diagram of an unfired boiler system is shown in Figure 3.13. In this system, the heat-transfer fluid should be non-freezing and non-corrosive, system pressures are low and control is straightforward. These factors largely overcome the disadvantages of water systems, and are the main reasons for the predominant use of heat-transfer oil systems in current industrial steam-generating solar systems.

The major disadvantage of the system result from the characteristics of the heat-transfer fluid. These fluids are hard to contain, and most heat-transfer fluids are flammable. Decomposition, when the fluids are exposed to air, can greatly reduce ignition-point temperatures, and leaks into certain types of insulation can cause combustion at temperatures that are considerably lower than measured self-ignition temperatures. Heat-transfer fluids are also relatively expensive and present a potential pollution problem that makes them unsuitable for food industry applications [66]. Heat-transfer fluids have much poorer heat-transfer characteristics than water. They are more viscous at ambient temperatures, are less dense, and have lower specific heats and thermal conductivities than water. These characteristics mean that higher flow rates, higher collector differential temperatures, and greater pumping power are required to obtain the equivalent quantity of energy transport when compared to a system using water. In addition, heat-transfer coefficients are lower, so there is a larger temperature differential between the receiver tube and the collector fluid. Higher temperatures are also necessary to achieve cost effective heat exchange. These effects result in reduced collector efficiency.

For every application the suitable system has to be selected by taking into consideration all the above factors and constrains.

3.5.1 The Steam-Flash Steam Generation Concept

In steam-flash concept, a pressurized water is heated in the collector and then flashed to steam in a separate vessel. Figure 3.11 below shows the steam-flash generation concept.

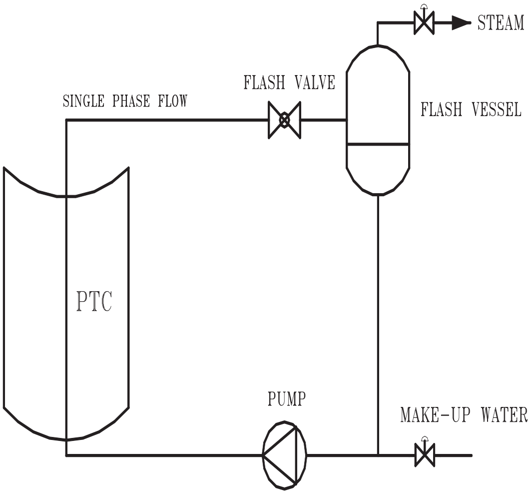


Figure 3.11 The Steam-Flash Steam Generation Concept

3.5.2 The Direct Steam Generation Concept

In direct or in-situ concept, a two phase flow is allowed in the collector receiver so that steam is generated directly. Figure 3.12 shows the direct steam generation concept.

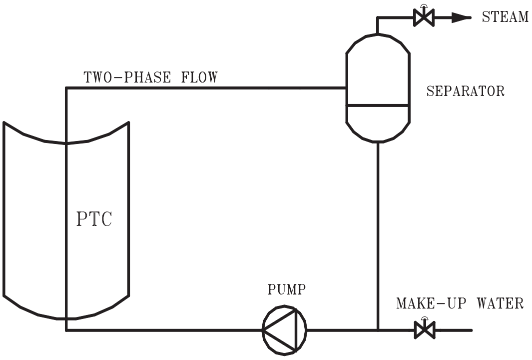


Figure 3.12 The Direct Steam Generation Concept

3.5.3 The Unfired-Boiler Steam Generation Concept

In unfired-boiler concept, a heat-transfer fluid is circulated through the collector and steam is generated via heat-exchange in an unfired boiler. Figure 3.13 shows the unfired-boiler steam generation concept.

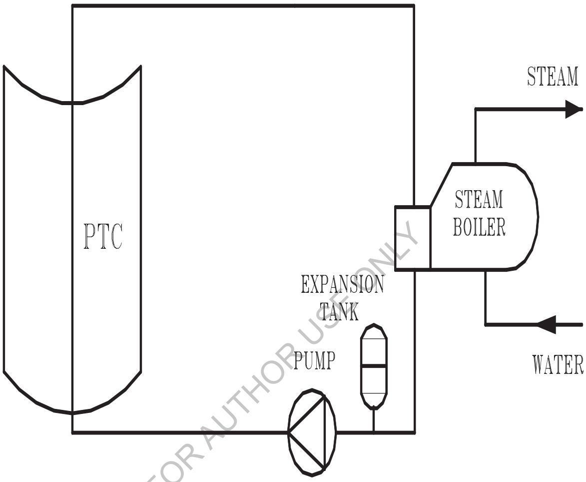


Figure 3.13 The Unfired-Boiler Steam Generation Concept

3.6 Solar Thermal Power Systems

Conversion of solar to mechanical and electrical energy has been the objective of experiments for more than a century, starting from 1872 when Mouchot exhibited a steam-powered printing press at the Paris Exposition. The idea is to use concentrating collectors to produce and supply steam to heat engines. Much of the early attention to solar thermal–mechanical systems was for small scale applications (up to 100 kW) and most of them were designed for water pumping. Since 1975 there have been several large-scale power systems constructed and operated. Commercial plants of 30 and 80 MW electric (peak) generating capacity are nowadays in operation for more than a decade.

The process of conversion of solar to mechanical and electrical energy by thermal means is fundamentally similar to the traditional thermal processes. These systems differ from the ones considered so far as these operate at much higher temperatures. Table 3.2 highlights the key features of the three solar technologies namely parabolic trough, dish/engine, and power tower.

This section is concerned with generation of mechanical and electrical energy from solar energy by processes based mainly on concentrating collectors and heat engines. There are also another three kinds of power systems, which are not covered in this paper. These are the photovoltaic cells for the direct conversion of solar to electrical energy by solid state devices, solar-biological processes that produce fuels for operation of conventional engines or power plants and solar ponds.

The basic process for conversion of solar to mechanical energy is shown schematically in Figure 3.14. Energy is collected by concentrating collectors, stored (if appropriate), and used to operate a heat engine. The main problem of these systems is that the efficiency of the collector is reduced as its operating temperature increases, whereas the efficiency of the heat engine increases as its operating temperature increases. The maximum operating temperature of stationary collectors is low relative to desirable input temperatures of heat engines, therefore concentrating collectors are used exclusively for such applications.

Identifying the best available sites for the erection of solar thermal power plants is a basic issue of project development. Recently the planning tool STEPS was developed by the German Aerospace Centre (DLR), which uses satellite and Geographic Information System (GIS) data in order to select a suitable site. The factors taken into account are the slope of the terrain, land use (forest, desert, etc.), geomorphological features, hydrographical features, the proximity to infrastructure (power lines, roads, etc.) and of course solar irradiation of the area. Three system architectures have been used for such applications, the PTC system, the power tower system, and the dish system. These are described in this section.

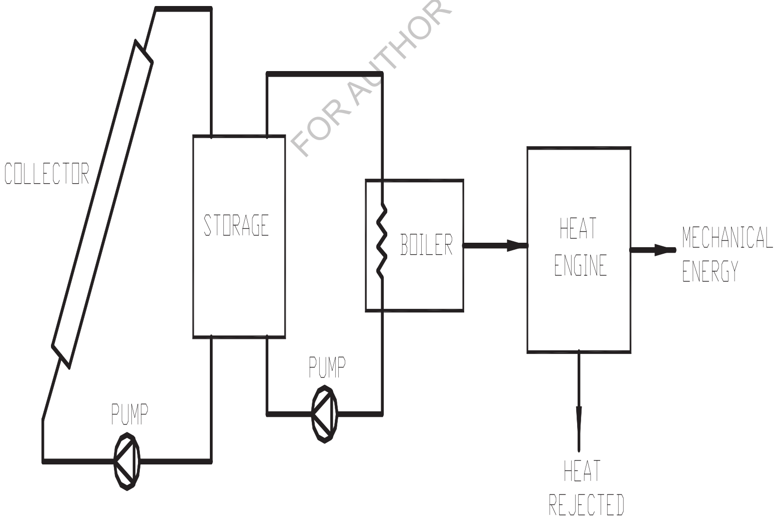


Figure 3.14 Schematic of a Solar-Thermal Conversion System

Table 3.2 Highlights the Key Features of the Three Solar Technologies

	Parabolic Trough	**Dish/Engine**	**Power Tower**
Size	**30-320 MW**	**5-25 kW**	**10-200 MW**
Operating Temperature°C	**400**	**750**	**600**
Annual Capacity Factor	**23-50 %**	**25 %**	**20-77 %**
Peak Efficiency	**20%(d)**	**29.4%(d)**	**23%(p)**
Net Annual Efficiency	**11(d)-16%**	**12-25%(p)**	**7(d)-20%**
Commercial Status	**Commercially Scale-up Prototype**	**Demonstration**	**Available Demonstration**

Technology Development Risk	**Low**	**High**	**Medium**
Storage Available	**Limited**	**Battery**	**Yes**
Hybrid Designs	**Yes**	**Yes**	**Yes**
Cost USD/W	**2,7-4,0**	**1,3-12,6**	**2,5-4,4**

3.6.1 Parabolic Trough Collector Systems

Several parabolic trough solar thermal systems have been build and operated throughout the world. Most of these systems provide process steam to industry. They displace fossil fuels such as oil or natural gas as the energy source for producing steam. These systems incorporate fields of PTC having aperture areas from 500 to 5000 m^2. Most of these systems however supply industrial process steam from 150 to 200 ^oC.

The most current example of power production using parabolic trough is the nine commercial solar energy generating systems (SEGS). The total installed capacity of SEGS is 354 MW and are designed, installed and operated in the Mojave Desert of Southern California. These plants are based on large parabolic trough concentrators providing steam to

Rankine power plants. The first of these plants is a 14 MW electric (MWe) plant, the next six are 30 MWe plants, and the two latest are 80 MWe [21].

The plants can supply peaking power, using solely solar energy, solely natural gas, or a combination of the two, regardless of time or weather, within the constraint of the annual limit on gas use. The most critical time for power generation and delivery, and the time in which the selling price of the power per kW h is highest. This is between noon and 6 p.m. in the months from June to September. Operating strategy is designed to maximize solar energy use. Natural gas is used to provide power during cloudy periods. The turbine-generator efficiency is best at full load, therefore the use of natural gas supplement to allow full-load operation maximizes plant output.

A schematic of a typical plant is shown in Figure 3.15. As it can be seen the solar and natural gas loops are in parallel to allow operation with either or both of the energy resources. The plants do not have energy storage facilities. The major components in the systems are the collectors, the fluid transfer pumps, the power generation system, the natural gas auxiliary subsystem, and the controls.

A synthetic heat transfer fluid is heated in the collectors and is piped to the solar steam generator and super heater where it generates the steam which drives the turbine. Reliable high-temperature circulating pumps are critical to the success of the plants, and significant engineering effort has gone into assuring that pumps will stand the high fluid temperatures and temperature cycling. The normal temperature of the fluid returned to the collector field is 304 °C and that leaving the field is 390 °C. Experience indicates that availability of the collector fields is about 99% [3].

The power generation system consists of a conventional Rankine cycle reheat steam turbine with feed water heaters deaerators, etc. The condenser cooling water is cooled in forced draft cooling towers.

The reflectors are made of black-silvered, low-iron float glass panels which are shaped over parabolic forms. Metallic and lacquer protective coatings are applied to the back of the silvered surface, and no measurable degradation of the reflective material has been observed [3]. The glass is mounted on truss structures, with the position of large arrays of modules adjusted by hydraulic drive motors. The reflectance of the mirrors is 0.94 when clean. Maintenance of high reflectance is critical to plant operation. With a total of 2.32 E 10^6 m^2 of mirror area, mechanized equipment has been developed for cleaning the reflectors, which is done regularly at intervals of about 2 weeks.

The receivers are 70 mm diameter steel tubes with cement selective surfaces surrounded by a vacuum glass jacket in order to minimize heat losses. The selective surfaces have an absorptance of 0.96 and an emittance of 0.19 at 350 °C.

The collectors rotate about horizontal north–south axes, an arrangement which results in slightly less energy incident on them over the year but favors summertime operation when peak power is needed and its sale brings the greatest revenue. Tracking of the collectors is controlled by a system that utilize an optical system to focus radiation on two light sensitive sensors. Any imbalance of radiation falling on the sensors causes corrections in the positioning of the collectors. There is a sensor and controller on each collector assembly, the resolution of the sensor is 0.5°.

A promising new configuration that combined SEGS parabolic-trough technology with a gas-turbine combined cycle power plant is conceived to meet utility needs for continuous operation and peaking power with minimal environmental damage. Such a hybrid combined-cycle plant uses the solar field as the evaporation stage of an integrated system, with the gas-turbine exhaust being recycled for superheating and preheating, thus, the solar field serves as the boiler in an otherwise conventional combined-cycle plant. This approach has several advantages:

1. The direct steam generation system can take advantage of the steam turbine, generator, and other facilities of the combined-cycle plant at a modest increase in capital cost.

2. Adding the direct steam generation facility requires no additional operators or electrical interconnection equipment.

3. Thermodynamic efficiencies are maximized because steam is evaporated outside the waste-heat recovery system; only the remaining thermal-heat exchange processes take place in the recovery heat exchanger. Thus, higher working-steam conditions can be achieved for the same degree of heat use which increases overall cycle efficiency.

This new configuration is preferable from the perspective of the second law of thermodynamics because the solar field reduces the production of entropy in the system.

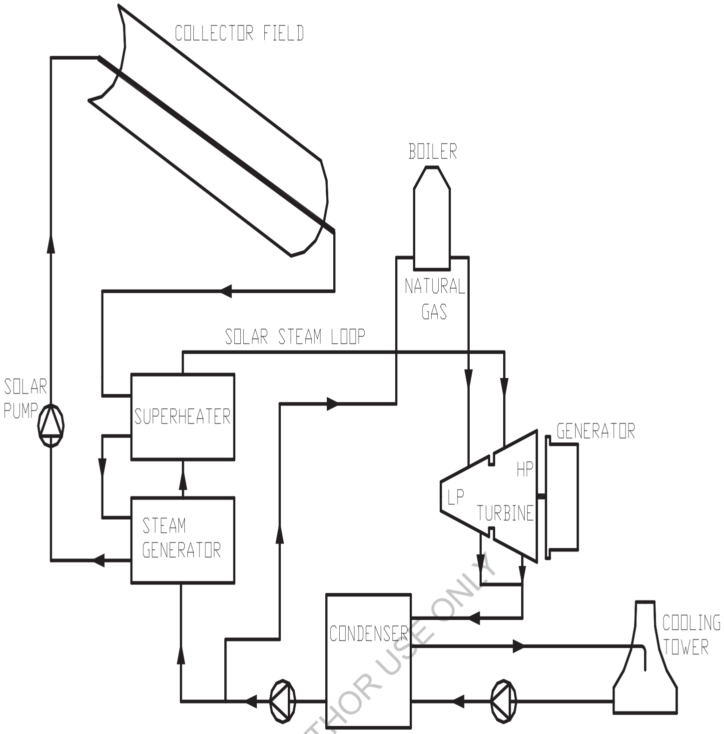


Figure 3.15. Typical Schematic Representation of SEGS Plants

3.6.2 Power Tower Systems

In power tower systems, heliostats reflect and concentrate sunlight onto a central tower-mounted receiver where the energy is transferred to a heat transfer fluid. This energy is then passed either to storage or to power-conversion systems which convert the thermal energy into electricity and supply it to the grid.

The major components of the system are the heliostat field, the heliostat controls, the receiver, the storage system, and the heat engine which drives the generator. The heliostat design must ensure that radiation is delivered to the receiver at the desired flux density at minimum cost.

Various receiver shapes have been considered, including cavity receivers and cylindrical receivers. The optimum shape is a function of the radiation intercepted and absorbed, thermal losses, receiver cost and design of the heliostat field. For a large heliostat field a cylindrical receiver has advantages when used with Rankine cycle engines, particularly for radiation from heliostats at the far edges of the field. Cavity receivers with larger tower height to heliostat field area ratios are used for higher temperatures required for the operation of Brayton cycle turbines.

As the collector represents the largest cost in the system an efficient engine is justified to obtain maximum useful conversion of the collected energy. Several possible thermodynamic cycles can be considered. Brayton or Stirling gas cycle engines operated at inlet temperatures of 800–1000 ^{0}C provide high engine efficiencies, but are limited by low gas heat transfer coefficients and by practical constrains on collector design (i.e. the need for cavity receivers) imposed by the requirements of very high temperatures. Rankine cycle engines employing turbines driven from steam generated in the receiver at 500–550 ^{0}C and have several advantages over the Brayton cycle. Heat transfer coefficients in the steam generator are high, allowing the use of high energy densities and smaller receivers. Cavity receivers are not needed and cylindrical receivers that are usually employed permit larger heliostat fields to be used. The use of reheat cycles improves steam turbine performance, but entail mechanical design problems. Additionally, it is also possible to use steam turbines with steam generated from an intermediate heat transfer fluid circulated through the collector or boiler. With such systems the fluids could be molten salts or liquid metals, and cylindrical receivers could be operated at around 600

^{0}C. In fact, these indirect systems are the only ones that can be combined with thermal storage. Power tower plants are defined by the options chosen for a heat transfer fluid, for the thermal storage medium and for the power-conversion cycle. The heat transfer fluid may be water/steam, molten nitrate salt, liquid metals or air. Thermal storage may be provided by phase change materials or ceramic bricks. Power tower systems usually achieve concentration ratios of 300–1500, can operate at temperatures up to 1500 ^{0}C, and are quite large, generally 10 MWe or more.

Power tower systems currently under development use either nitrate salt or air as the heat transfer medium. In the USA, the Solar One plant in Barstow, CA was originally a water/steam plant and is now converted to Solar Two, a nitrate salt system. The use of nitrate salt for storage allow the plant to avoid tripping off line during cloudy periods and also allow the delivery of power after sunset. The heliostat system consists of 1818 individually oriented reflectors, each consisting of 12 concave panels with a total area of 39.13 m^2, for a total array of 71 100 m^2. The reflective material is back-silvered glass. The receiver is a single pass superheated boiler, generally cylindrical in shape, 13.7 m high, 7 m in diameter, with the top 90 m above the ground. It is an assembly of 24 panels, each 0.9 m wide and 13.7 m long. Six of the panels on the south side, which receives the least radiation, are used as feed water pre heaters and the balance are used as boilers. The panels are coated with a non-selective flat black paint which was heat cured in place with solar radiation. The receiver was designed to produce 50 900 kg/h of steam at 516 8C with absorbing surface operating at a maximum temperature of 620 ^{0}C [22].

Meanwhile the PHOEBUS consortium, a European industry group, is leading the way with air-based systems. Gaseous heat transfer media allow for significantly higher receiver outlet temperatures, but require higher operating pressures. Pressure-tolerant gas-cooled ceramic-tube receivers have, however, relatively high heat losses compared to water/steam or advance receivers. The PHOEBUS consortium is developing a novel Technology Solar Air (TSA) receiver, a volumetric air receiver which distributes the heat-exchanging surface over a three dimensional volume and operates at ambient pressures. Because of its relative simplicity and safety, these plants can be used for applications in developing countries [67]. Future work will concentrate on the scaling up of the nitrate salt and TSA/PHOEBUS systems. The target size for nitrate salt plants in south–west USA is 100–200 MWe, while a 30 MWe plant is the aim for the PHOEBUS consortium. In addition to these two systems, a 20 MW Sol gas plant, using a combined cycle plant with a solar power tower back-up, is planned for southern Spain [22].

Recent research and development efforts have focused on polymer reflectors and stretched-membrane heliostats. A stretched-membrane heliostat consists of a metal ring, across which two thin metal membranes are stretched. A focus control system adjusts the curvature of the front membrane, which is laminated with a silvered-polymer reflector, usually by adjusting the pressure (a very slight vacuum) in the plenum between the two membranes. Stretched-membrane heliostats are potentially much cheaper than glass/metal heliostats because they weigh less and have fewer parts.

3.6.3 Parabolic Dish Systems

A parabolic dish concentrates solar energy onto a receiver at its focal point. The receiver absorbs the energy and converts it into thermal energy. This can be used directly as heat or supply for power generation. The thermal energy can either be transported to a central generator for conversion, or it can be converted directly into electricity at a local generator coupled to the receiver.

Dishes track the sun on two axes, and thus they are the most efficient collector systems because they are always focused. Concentration ratios usually range from 600 to 2000, and they can achieve temperatures in excess of 1500 ^{0}C. Rankine-cycle engines, Brayton-cycle engines, and sodium-heat engines have been considered for systems using dish-mounted engines the greatest attention though was given to Stirling-engine systems.

Current developments in the USA and Europe are focused on 7.5 kWe systems for remote applications. In Europe, three dish/Stirling systems are demonstrated at PSA in Spain, whereas in the USA a program has been set to demonstrate water pumping and village power applications. Stretched-membrane concentrators are currently the focus of considerable attention because they are most likely to achieve the goals of low production cost and adequate performance. Both multifaceted and single-facet designs are being pursued. Recently, a 7-meter single-facet dish was developed, which demonstrated excellent performance in tests.

The greatest challenge facing distributed-dish systems is developing a power-conversion unit, which would have low capital and maintenance costs, long life, high conversion efficiency, and the ability to operate automatically. Several different engines, such as gas turbines, reciprocating steam engines, and organic Rankine engines, have been explored, but in recent years, most attention has been focused on Stirling-cycle engines. These are externally heated piston engines in which heat is continuously added to a gas (normally hydrogen or helium at high pressure) that is contained in a closed system. The gas cycles between hot and cold spaces in the engine stores and releases the heat that is added during expansion and rejected during compression.

3.7 Solar Furnaces

Solar furnaces are made of high concentration and thus high temperature collectors of the parabolic dish and heliostat type. They are primarily used for material processing. Solar material processing involves affecting the chemical conversion of materials by their direct exposure to concentrated solar energy. A diverse range of approaches are being researched for applications related to high added-value products such as fullerenes, large carbon molecules with major potential commercial applications in semiconductors and superconductors, to commodity products such as cement [68]. None of these processes however, have achieved large-scale commercial adoption. Some pilot systems are shortly described here.

A solar thermo chemical process has been developed by Steinfeld et al. [69] which combines the reduction of zinc oxide with reforming of natural gas leading to the co-production of zinc, hydrogen and carbon monoxide. At the equilibrium chemical composition in a black-body solar reactor operated at a temperature of 1250 K at atmospheric pressure with solar concentration of 2000, efficiencies between 0.4 and 0.65 have been found, depending on product heat recovery. A 5 kW solar chemical reactor has been employed to demonstrate this technology in a high-flux solar furnace. Particles of zinc oxide were introduced continuously in a vortex flow natural gas contained within a solar cavity receiver exposed to concentrated insolation from a heliostat field. The zinc oxide particles are exposed directly to the high radiative flux avoiding the inefficiencies and cost of heat exchangers.

A 2 kW concentrating solar furnace has been used to study the thermal decomposition of titanium dioxide at temperatures of 2300–2800 K in an argon atmosphere [70]. The decomposition rate was limited by the rate at which oxygen diffuses from the liquid–gas interface. It was shown that this rate is accurately predicted by a numerical model which couples the equations of chemical equilibrium and steady-state mass transfer [70].

3.8 Solar Chemistry Applications

Solar energy is essentially unlimited and its utilization is ecologically benign. However, solar radiation reaching the earth is intermittent and not distributed evenly. There is thus a need to store solar energy and transport it from the sunny uninhabited regions to the industrialized populated regions where energy is needed. The way to achieve this is by the thermo chemical conversion of solar energy into chemical fuels. This method provides a thermo chemically efficient path for storage and transportation. For this purpose high concentration ratio collectors similar to the ones used for power generation are employed. Thus by concentrating solar radiation in receivers and reactors, energy can be supplied to high-temperature processes to drive endothermic reactions. Solar energy can also assist in the processing of energy intensive and high-temperature materials.

Applications include the solar reforming of low hydrocarbon fuels such as LPG and natural gas and upgrade it into a synthesis gas that can be used in gas turbines. Thus weak gas resources diluted with carbon dioxide can be used directly as feed components for the conversion process. Therefore, natural gas fields currently not exploited due to high CO_2 content might be opened to the market. Furthermore, gasification products of non-conventional fuels like biomass, oil shale and waste asphaltenes can also be fed into the solar upgrade process [34].

Other applications include the solar gasification of biomass and the production of solar Aluminium the manufacture of which is one of the most energy intensive processes. Another interesting application is the solar zinc and syngas production which are both very valuable commodities. Zinc finds application in Zn/air fuel cells and batteries. Zinc can also react with water to form hydrogen which can be further processed for heat and electricity generation. Syn-gas can be used to fuel highly efficient combined cycles or can be used as the building block of a wide variety of synthetic fuels, including methanol, which is a very promising substitute of gasoline for fueling cars [34].

A model for solar volumetric reactors for hydrocarbons reforming operation at high temperature and pressure is presented by Yehesket et al. [71]. The system is based on two achievements: the development of a volumetric receiver tested at 5000–10 000 suns, gas outlet temperature of

1200 ^{0}C and pressure at 20 atmosphere and a laboratory scale chemical kinetics study of hydrocarbons reforming. Other related applications are a solar driven ammonia based thermo chemical energy storage system [72] and an ammonia synthesis reactor for a solar thermo chemical energy storage system [73].

Another field of solar chemistry applications is the solar photochemistry. Solar photochemical processes make use of the spectral characteristics of the incoming solar radiation to effect selective catalytic transformations which find application in the detoxification of air and water and in the processing of fine chemical commodities.

In solar detoxification photo catalytic treatment of non-biodegradable persistent chlorinated water contaminants typically found in chemical production processes is achieved. For this purpose PTC with glass absorbers are employed and the high intensity of solar radiation is used for the photo catalytic decomposition of organic contaminants. The process uses ultraviolet (UV) energy, available in sunlight, in conjunction with the photo catalyst, titanium dioxide, to decompose organic chemicals into non-toxic compounds [74]. Another application concerns the development of a prototype employing lower concentration CPC [34]. Recent developments in photocatalytic detoxification and disinfection of water and air are presented by Goswami [75].

The development of a compound parabolic concentrator technology for commercial solar detoxification applications is given in Reference [76]. The objective is to develop a simple, efficient and commercially competitive water treatment technology. A demonstration facility is planned to be erected by the project partners at PSA in Southern Spain.

Chapter Four

Conclusions

Energy is a requirement in our everyday life as a way of improving human development leading to economic growth and productivity. The return-to-renewables will help mitigate climate change is an excellent way but needs to be sustainable in order to ensure a sustainable future for generations to meet their energy needs. Knowledge regarding the interrelations between sustainable development and renewable energy in particular is still limited. The aim of the book was to ascertain the sustainability of renewable energy sources and how a shift from fossil fuel-based energy sources to renewable energy sources would help reduce climate change and its impact.

Even though the review is unable to cover a wide area of the solar thermal system, the few discovered research reports on solar thermal systems revealed that, there is a significant research work on the utilization of solar thermal energy since past three decades. Much of the work focuses on the system efficiency improvement whiles little on system suitability for process heating. Almost all the reports reviewed focused on system integration for power generation. The low and medium temperature heat demand for industrial processes is much higher than the higher temperature for electricity generation. Less attention is given to the area of low and medium temperature heat process applications. Therefore, this book recommends that current research must focus on the integration of solar thermal for low and medium heat applications.

The high potential solar energy in Atbara city could be used for thermal generation through concentrating and non – concentrating solar complexes. For the purpose of experimentation, a solar complex was designed and manufactured in the premises of the Faculty of Engineering and Technology - Atbara through which the water flows naturally.

The aim of the present research was to review the utilization of solar energy for thermal purposes from the view point of the history of solar energy, theoretical study of solar collectors, and solar collector applications.

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