LOW TEMPERATURE SOLAR COLLECTORS

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Contents

Summary

In this chapter, a survey of the various types of low temperature solar thermal collectors and their various applications is presented. Initially an analysis of the environmental problems related to the use of conventional sources of energy and the benefits offered by renewable energy systems are outlined. A description of the various types of low temperature collectors is presented including flat-plate, compound parabolic and evacuated tube collectors. This is followed by the thermal analysis of the collectors and description of the methods used to evaluate their performance. Typical applications of the various types of collectors are presented in order to show to the reader the extent of their applicability. These include solar water heating, which comprise thermosiphon, integrated collector storage, direct and indirect systems and air systems; space heating and cooling, which comprise, space heating and service hot water, air and water systems and heat pumps; refrigeration; industrial process heat, which comprise air and water systems; desalination and drying applications. As can be seen low temperature solar energy systems can be used for a wide range of applications and provide significant benefits, therefore, they should be used whenever possible.

1. Introduction

The sun is a continuous fusion reactor in which hydrogen is turned into helium. The solar energy thus generated radiates outwards in all directions. Only a tiny fraction of the total radiation emitted is intercepted by the earth. However, even this small fraction of solar radiation falling on the earth for 46 minutes is equivalent to the world energy demand for the year 2006 (490 EJ). This is estimated by considering a mean value of solar radiation equal to 700 W/m^2 and earth area equal to $2.53x10^{14}$ m^2 (earth diameter=$1.27x10^7$ m), i.e. time=$490x10^{18}/(2.53x10^{14}x700)$=2767 sec ≈46 min.
Since prehistory, man has recognized the sun as a motive power behind every natural phenomenon. Thus, many of the pre-historic tribes considered Sun as "God". Many scripts of ancient Egypt say that the Great Pyramid, perhaps the man's greatest engineering achievement, was built as a stairway to the sun. Man realized that a proper use of solar energy is beneficial, from the prehistoric times. The Greek historian Xenophon in "memorabilia" recorded the teachings of the Greek Philosopher Socrates (470 - 399 BC) concerning the correct orientation of houses in order to be cool in summer and warm in winter.

In addition to the numerous ways in which solar energy has been used by nature, it has also been deliberately harnessed by man to perform a number of useful jobs. Solar energy is used today to heat and cool buildings (both active and passive), to heat water for domestic and industrial uses, to heat swimming pools, to power refrigerators, to operate engines and pumps, to desalinate water for drinking purposes, to generate electricity and many more. This chapter is focused on the low temperature collectors and applications.

The first recorded application of solar energy collectors to harness the sun's power was by the Greek scientist, physician and inventor Archimedes who in 212 BC used solar energy to burn the Roman fleet invading Syracuse. Archimedes reputedly set fire to the attacking Roman fleet by using a concave metallic mirror in the form of hundreds of polished soldiers' shields all reflecting on the same ship. The Greek historian Plutarch (AD 46-120) recorded the incident and wrote, "The Romans, seeing that indefinite mischief overwhelmed them from no visible means, began to think they were fighting with the gods".

Remarkably, the very first attempts to use solar energy employed concentrating collectors, which are more complex as they require accurate construction and sun tracking. During the eighteenth century, solar furnaces capable of melting iron, copper and other metals were constructed using polished-iron, glass lenses and mirrors. The furnaces were used throughout Europe and the Middle East. One such furnace designed by the French scientist Antoine Lavoisier, attained the remarkable temperature of 1750°C, which turned out to be the maximum achieved by man for one hundred years.

During the nineteenth century, the attention was focused into the use of solar energy to generate low-pressure steam in order to operate steam engines. August Mouchot pioneered this field by constructing and operating several solar-powered steam engines between the years 1864 and 1878. A number of other applications for water pumping and solar furnaces were also developed early in the twentieth century.

Scientists realized that solar energy could be used for low temperature applications quite recently. The hot water and house heating appeared in the mid 1930s but gained interest in the last half of the 1940s. Until then millions of houses were heated by coal-fired boilers. The idea was to heat water by solar energy and fed it to the radiator system that was already installed. The manufacture of Solar Water Heaters (SWH) as mass production units began in the early 1960s and as the real benefits of the systems were proven, the industry expanded very quickly in many countries of the world. Typical solar water heaters in many cases are of the thermosiphon type although the force circulation type has also been used extensively.

The most important advantage of solar energy compared to other forms of energy is that it is clean. Until now, fossil fuels are used to provide most of our energy needs because they are cheaper and more convenient than solar energy and until recently environmental pollution has been of little concern. The next section gives a brief outline of the environmental problems associated with energy production and use.

1.1. Energy Related Environmental Problems

Energy is the most significant factor in economic development. This is recognized universally and historical data verify that energy availability and economic activity are strongly related. After the oil crisis at the early 1970s, the concern was on the cost of energy, recently however the environmental degradation is considered more important. The environmental problems related to energy are attributed to a combination of several factors such as the increase of the world population, energy consumption and industrial activities. Solving the environmental problems that humanity faces today requires long-term activities for sustainable development. One of the most efficient and effective solutions seems to be the use of renewable energy resources.

One of the definitions of sustainable development, which is widely accepted, is "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". For sustainable development it is required that a sustainable supply of energy and effective and efficient utilization of energy resources are secured. Such resources in the long term should be readily available at the lowest possible cost, be sustainable and be able to be utilized for all the required tasks without causing environmental pollution. Most of these can be achieved with renewable sources of energy.

Pollution depends mostly on the amount of energy consumption. Currently the world daily oil consumption is 76 million barrels and despite the well-known environmental problems related to the use of fossil fuel combustion, this is expected to increase to 123 million barrels per day by the year 2025. The factors on which the future level of energy consumption and production depends include population growth, economic performance, consumer tastes and technological developments.

Perhaps the most important parameter contributing to the increase of energy consumption is the world population. This is expected to double by the middle of the 21st century, and as economic development continues, the global demand for energy is expected to increase. It is evident today that the future of our planet will have negative impacts if humans keep degrading the environment at the current rate. The three environmental problems that are well known internationally are the acid precipitation, the stratospheric ozone depletion, and the global climate change.

It is estimated that if atmospheric concentrations of greenhouse gasses continue to increase at the present rates, the earth's temperature may increase by 2-4°C in the 21st century. If this prediction is realized, the sea level could rise approximately 30 to 60 cm. The impacts of this effect include flooding of coastal settlements, displacement of fertile agricultural zones toward higher altitudes, and decrease of the availability of fresh water. As can be easily understood, such consequences could put in danger the survival of entire populations.

1.2. Renewable Energy Systems

Renewable energy systems produce marketable energy by converting natural phenomena (solar radiation, wind, falling water, tides, etc.) into useful forms of energy. These systems harness the sun's energy and its direct and indirect effects on the earth, gravitational forces (tides), the heat of the earth's core (geothermal) and various plants (biomass) to produce energy. These resources have massive energy potential, however, they are generally diffused; most of them are intermittent and have distinct regional variabilities. These characteristics result to difficult, but solvable, technical problems.

Nowadays renewable energy systems have improved collection and conversion efficiencies, better reliability and lower initial and maintenance costs. Additionally, renewable energy systems appear to be cost effective compared to the projected high cost of oil.

The most important benefits arising from the use of renewable energy systems are the energy savings and the decrease of environmental pollution. The energy saving benefit derives from the reduction in consumption of conventional sources of energy. The magnitude of this benefit depends on the corresponding production of the renewable energy system and the saving of capital expenditure for the purchase of fossil fuels, which for many countries is imported. The decrease in environmental pollution is achieved by the reduction of air emissions due to the substitution of conventional fossil fuels.

There are many alternative energy sources, which can be used instead of fossil fuels. The decision as to what type of energy source should be utilized in each case must be made on the basis of economic, environmental and safety considerations. Because of the desirable environmental and safety aspects, it is widely believed that solar energy should be utilized instead of other alternative forms of energy.

In this chapter, emphasis is on solar thermal systems; particularly on low temperature collectors and their applications. The next section gives a brief description of several of the most common low temperature collectors available in the market.

2. Low Temperature Solar Collectors

The major component of any solar system is the solar collector. Solar energy collectors are heat exchangers that transform solar radiation into internal energy of a medium transported through them. The function of the collector is to absorb the incoming solar radiation, convert it into heat, and transfer this heat to a fluid (usually air, water, or heat transfer oil) flowing through the collector. The energy thus collected is carried from the circulating fluid and can be used either directly (for hot water or space thermal load) or stored in a thermal energy storage tank from which it can be drawn whenever required, i.e., during night and/or cloudy days.
There are two types of solar collectors; stationary or non-concentrating and concentrating. A non-concentrating collector has the same area for intercepting and absorbing solar radiation and is stationary, i.e., it is permanently fixed in position and do not track the sun. Sun-tracking concentrating solar collector usually has concave reflecting surfaces, which focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux. Concentrating collectors are suitable for high temperature applications. Solar collectors can also distinguished by the type of heat transfer liquid used (water, non-freezing liquid, air or heat transfer oil) and whether they are covered or uncovered.

In this section, a review of the various types of low temperature collectors currently available is presented. Low temperature is defined as a temperature of up to 100°C. Only collectors, which are industrially matured, are presented excluding research prototypes or types not adopted by the industry.

2.1. Flat Plate Collectors (FPC)

A detail of a typical flat-plate solar collector is shown in Figure 1. The collector consists of an absorbing plate mounted in a casing with thermal insulation at the back and one or more transparent (glass) covers on top. The absorbing plate may be flat, corrugated, or grooved, to which the riser tubes or fluid passages are attached. The plate may also be integral with the tubes. The tubes or passages are used to conduct or direct the heat transfer fluid from the inlet to the outlet. The liquid tubes are connected at both ends by large diameter header tubes. The thermal insulation is used to minimize the conduction heat loss from the back and sides of the collector and the casing is used to keep the collector components free from dust and moisture.

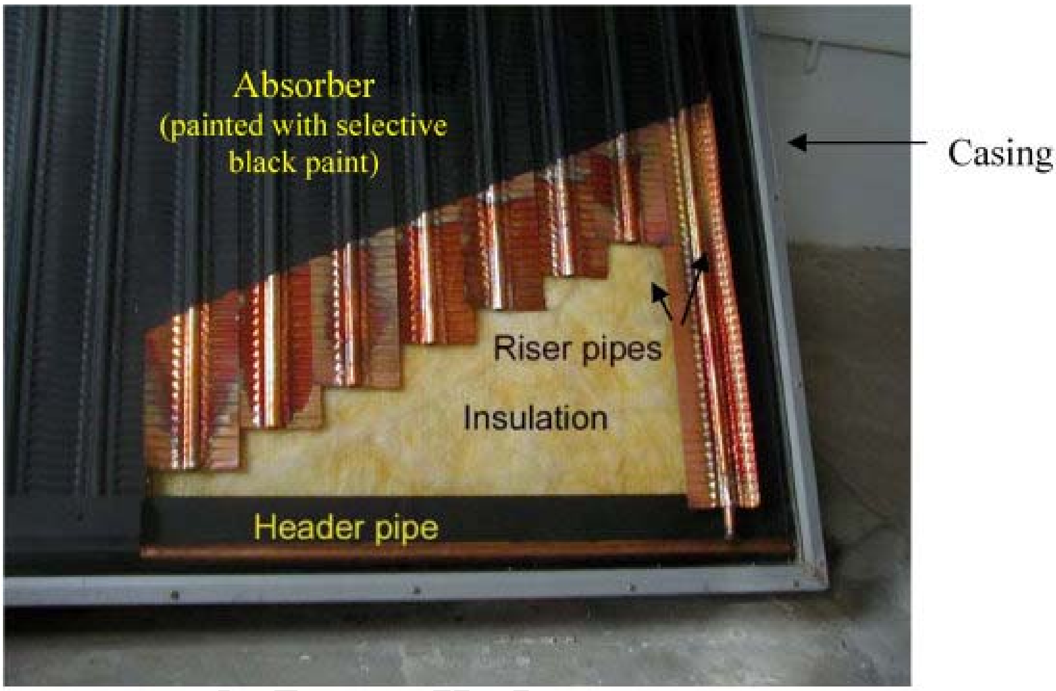

Figure 1: Detail of a flat-plate collector

When solar radiation passes through the glass, it impinges on the blackened absorber surface, which is of high absorptivity. A large portion of this energy is absorbed by the plate and transferred by conduction to the transport medium in the fluid tubes to be carried away for storage or use. It is very important that the liquid tubes are well fixed on the absorbing plate. These can be welded or they can be an integral part of the plate.

The transparent cover is used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer trapped 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 from the sun but it is nearly opaque to long-wave thermal radiation emitted by the absorber plate (greenhouse effect).

Flat plate collectors are permanently fixed in position and require no tracking of the sun. For maximum performance, the collectors must be oriented straight 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° to ±15° depending on the application. The primary advantage of flat plate collectors is that they are cheap to manufacture and that they collect both the direct and diffuse components of solar radiation.

Flat-plate collectors have been constructed from many different materials and in a wide variety of designs. They are used to heat fluids such as water, water plus antifreeze solution or air. The purpose of the system is to collect as much solar energy as possible at the lowest possible cost. It is also required that the collector should have a long effective life, despite the undesirable effects of the sun's ultraviolet radiation and problems related to corrosion and clogging because of acidity, alkalinity and hardness of the heat transfer fluid or freezing of water. Additionally problems may occur because of deposition of dust or moisture on the glazing and breakage of the glazing because of thermal expansion, hail or vandalism. Most of these problems can be minimized by the use of tempered glass.

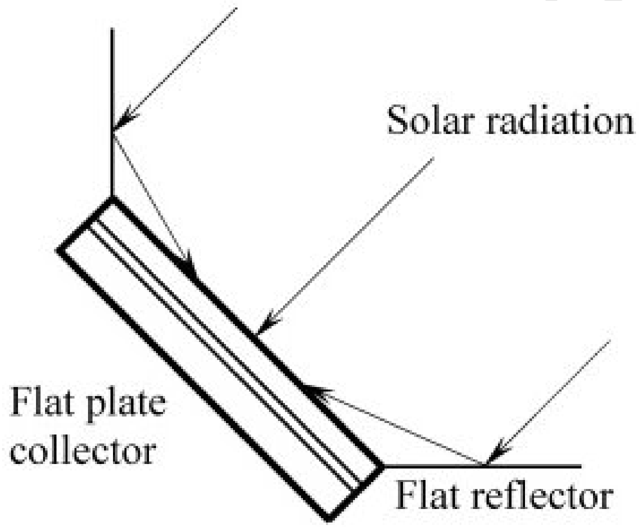

Figure 2: Flat plate collector with flat reflectors

Another variation of flat plat collectors is the use of flat reflectors either in the way shown in Figure 2 or in a saw-tooth arrangement shown in Figure 3. In both cases, the simple flat reflectors can markedly increase the amount of direct radiation reaching the collector. This is in fact a concentrator because the aperture is bigger than the absorber but the system is stationary.

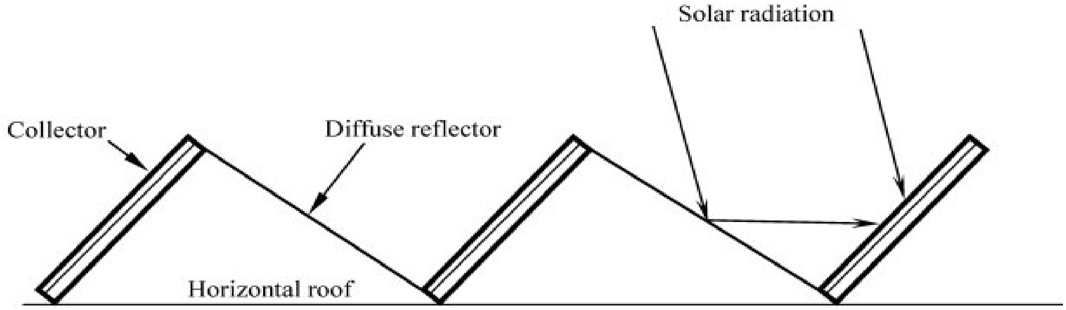

Figure 3: Flat plate collectors with saw-tooth reflectors

In the following two sections, more details are given about the glazing and absorber plate materials, which are the most crucial parts on which the performance of the collector depends. Most of these details apply also to other types of collectors.

2.1.1. Glazing Materials

Glass has been widely used to glaze flat plate solar collectors because it has a high transmittance of the incoming shortwave solar irradiation while transmitting virtually none of the longwave radiation emitted by the absorber plate.

Window glass usually has high iron content and thus it is not suitable for use in solar collectors. Toughened low-iron glass is usually used as it significantly increases the optical efficiency of the collector.

The commercially available grades of low-iron glass have transmittances of about 0.9 at normal incidence, but its transmittance is essentially zero for the longwave thermal radiation (5.0 to 50 μm) emitted by sun-heated surfaces.

For direct radiation, the transmittance varies considerably with the angle of incidence. Antireflective coatings and surface texture can also improve transmission significantly. The effect of dust on collector glazing may be quite small, and the cleaning resulting from occasional rainfall is usually adequate to maintain the transmittance to within 2 - 4% of its maximum value.

Plastic films and sheets also exhibit high shortwave transmittance, however most usable varieties also have transmission bands in the middle of the thermal radiation spectrum, thus they may have high longwave transmittance of the order of 0.40. Plastic films are generally limited in the temperatures they can sustain without deterioration and suffer from dimensional changes.

In fact only a few types of plastics can withstand the sun's ultraviolet radiation for long periods, however, they are not broken easily, have low mass and in the form of thin films, they are completely flexible.

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

These are analyzed in more detail in Section 3.Various prototypes of transparently insulated collectors (flat plate and compound parabolic) have been built and tested in the 1990s. Nowadays, low-cost and high-temperature resistant transparent insulating (TI) materials are developed so that the commercialization of these collectors becomes feasible.Experimental testing of a prototype flat-plate collector covered by transparent insulation showed that the efficiency of the collector was comparable with that of evacuated tube collectors. However, no commercial collectors of this type are available in the market yet.

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Biographical Sketch

Soteris Kalogirou, Eur Ing (CEng, MCIBSE, MASHRAE, MISES), is an Instructor of Mechanical Engineering at the Higher Technical Institute in Nicosia, Cyprus. He received his Degree in Mechanical Engineering in 1982, his M.Phil. in Mechanical Engineering from the Polytechnic of Wales in 1991, and his Ph.D. in Mechanical Engineering from the University of Glamorgan in 1995. Since 1985 he is involved in research dealing with solar energy systems. In particular his research is involved with the development of low temperature solar collectors and parabolic trough collectors, solar water heating, domestic heating and cooling systems, industrial process heat, solar absorption refrigeration and solar desalination. As part of the various research projects in which he was involved, he used extensively modeling and simulation tools and he developed predictive tools based on the use of artificial intelligence methods, like artificial neural networks and genetic algorithms, for the modeling and performance prediction of solar energy systems. He has published 157 papers, 68 in international scientific journals and 89 in refereed conference proceedings.