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Flat Plate Solar Collectors for Process Heat: A Review

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ABSTRACT

This paper presents a review of various forms of the flat plate solar thermal collectors that have been developed and evaluated for various applications.The environmental challenge associated with the use of conventional energy sources for heating applications are outlined and the benefit derived from the use of renewable energy sources clearly stated. The flat plate solar collector is then fully described with major forms of heat losses associated with it including the main components of the system. Description of the various forms of flat plate solar collectors developed for water and space heating applications, solar cooking, solar distillation, solar waste treatment among others by the researchers were discussed in details ranging from their design theories approach, materials used, construction techniques and performance evaluation. The study shows that modeling and simulation as a design tool is an effective way for optimizing flat plate solar system including appropriate selection of materials for the construction of various system components. The use of double glazing minimizes convection heat transfer losses, optimize collector tilt angle for better annual performance, enhance geometric absorber configuration and selective coating gives high absorptive of solar radiationand thus, increases fluid turbulence achieving a better thermal efficiency and system cost reduction. The addition of nano-particles to base working fluid also demonstrated some potential for increasing the overall thermal performance of the flat plate collector. The study indicated that the flat plate collectors are more profitableand environmentally friendly than the conventional energy sources.

Keywords: Flat Plate Solar Collector, Simulation, Profitability, Process Heat

1.0 Introduction

The ever-increasing world energy demand coupled with the environmental degradation from the use of conventional fossil fuels is twin challenges currently facing the world. Improvement in the social economic life style is a key factor responsible for increase in the energy demand. The world solar energy potential is high for countries within the tropical zone, beside the environmentally friendly and inexhaustible nature of it. Solar energy is harness in various promising forms notably that of solar collectors with thermal conversion. The use of solar heat for heating of water and air for domestic and industrial applications has gave popularity due to its numerous advantages over the conventional form of water and air heating. Concerted efforts have been ongoing since 1900 in the development of solar collectors for space and water heating application which have shown promising potentials. These collectors are generally divided into two classes namely flat plate collectors and concentrating collectors. Flat plate collectorsabsorbing surface is normally equal to the overall collector area intercepting the sun's rays, while large areas of mirrors or lenses concentrate or focus the solar radiation onto a small absorber area for concentrating collectors, thus giving rise to higher temperature elevation of the system. Solar energy has received special consideration. The amount of energy generated is a function of time and seams to provide a steady power desire for a secondary energy source (Gond *et al.*, 2012; Gond, *et al.*, 2016).

2.0 Materials and Methods

2.1 Materials

2.1.1 Flat Plate Collector

Flat plate solar collectors are integral part of a solar thermal system. A typical flat-plate collector is a metal box with a glass or plastic cover called the glazingat the top for transmissivity of solar radiation and a dark-colored absorber plate on the bottom for heat absorptivity. The sides and bottom of the collector are usually insulated to minimize heat loss.Flat plate collectors collect and convert the sun’s solar radiation into heat using greenhouse impact which is then transfer to a base working fluid (usually water or air). The collected solar heat is put into various applications such as space heating for crop drying, herbs, district heating; water heating for domestic and industrial use, solar pool heaters, and steam generation for electricity production (Cooper &Dunkle, 1981).

A flat plate solar collector can be an active or passive system. Active systems incorporate a pump or blower for the working fluid, while buoyancy forces are the prime factor determining fluid movement. Flat-plate collectors use both beam and diffuse solar radiation, do not require tracking of the sun, and require low-maintenance, are inexpensive and mechanically simple to construct.Solar radiation which falls on the collector is reflected, absorbed, while the remaining is transmitted through the transparent cover (glazing) reaching the absorber. The transmitted solar radiation reaching the absorber plate is lost by convection, reflection, radiation and conduction, and the remaining is then utilized as useful thermal heat (Wagner, 1995).To improve the performance of flat-plate collectors, some of the main heat losses need to be reduced.

Figure 1: Typical Solar Water Thermal System (Duffie and Beckman, 2006)

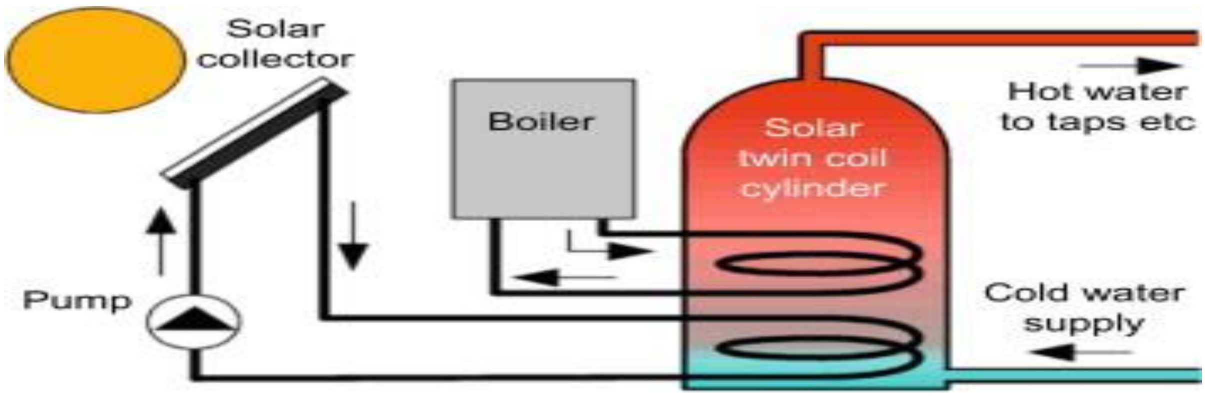

Figure 2. Principles of heating water for a household using solar thermal energy(Joardder and Masud, 2017).

2.1.2 Heat Losses in Flat Plate Solar Collectors

There are two main classes of heat loss in a flat plate solar collector. These losses can be classified as optical and thermal losses. The thermal losses rapidly increase with higher temperatures, while the optical losses are constant.

2.1.2.1 Optical losses

High quality covers of low-iron solar glass have a transmission of 90% for solar radiation (normal irradiation). If an anti-reflective coating is used the transmission can be increased to 93 - 96%. Usually about 1 - 2% is absorbed in the glass plane and the rest is lost due to reflection. The coating of the absorber can reach absorption coefficients of 95%. The optical losses grow with increasing angles of the incident solar radiation (Wagner, 1995; Rommel, 2005).

2.1.2.2 Thermal losses

Main thermal losses of a flat plate solar collector at the front are caused by convection. The working base fluid (air) circulating air between the absorber plate and cover transports the absorbed heat to the glazing. After heat conduction through the cover there is again convective loss because of the air that flows around the collector. The heated absorber also radiates infrared radiation to the cover (glazing material), from where the heat is transferred to the surrounding. The IR-emittance of a selective absorber can reach down to 5%. At the backside, thermal losses occur at the insulation. The heat conduction there depends on the used material and can be kept low by using thermal insulation of adequate thickness. For a single glazed flat-plate collector with a selective coated absorber only about one-seventh (1/7) of the total heat losses occur at the rear side (Wagner, 1995; Rommel, 2005).

2.1.3 Components of a Flat Plate Solar Collector

The construction of solar collectors is a simple process and involves some basic components. These components are fundamental to the functionality of the system. Advanced flat plate collectors differ little from standard (normal) flat plate collectors. These collectors have the following as main elements:

2.1.3.1 Transparent cover

To assure high transmittance of solar radiation and high durability for economic benefit, covers of low iron, tempered solar glass with anti-reflective coating are used. For a multi glazing cover usage, it is recommended that they are made of anti-reflective coated glass or Teflon films. Key factors of engineering consideration for glazing materials are high transmissivity, strength, non-degradable, minimum emittance, high temperature stability, and low thermal expansion(Medugu, 2010).

2.1.3.2 Absorber

Desired properties for the absorber plate material are high thermal conductivity, good tensile and compressive strength, and resistance to corrosion. The most common material for sheet and absorber pipes is copper, however sheets of aluminium are also used due to their lower costs. For corrosive applications, stainless steel is a possible material. The state-of-the-art is a selective coating on the sheet to reduce the thermal losses due to infrared radiation. The absorber pipe work should be designed to ensure high heat transfer. With regard to stagnation, the hydraulic absorber should be designed to allow a fluid emptying behavior when steam occurs under stagnation conditions (Rommel, 2005).

2.1.3.3 Insulation

The features of a good thermal insulator are; low thermal conductivity, stability at high temperatures and ease of application.Due to the high temperatures mineral wool or rock wool is often used as insulation material to reduce the thermal losses on the backside of the absorber. In some configurations additional polyurethane plates are used between the insulation mat and the rear panel of the collector. Materials like plywood and saw dust are use of recent for low temperature applications for their relative low cost (Okonkwo and okoye, 2005).

2.1.3.4 Casing

The casing ensures stability and protects the absorber and the insulation against environmental impacts. It often consists of aluminium, steel, wood or synthetic material. The frame parts can be brazed, riveted or glued. Some frames are formed as a tray so that a connection is not needed between the side plates and rear panel. Metal sheets and seasoned wood can also be use where the needed temperature is low.

2.1.4 Methods

2.2.1 Review on Flat Plate Collectors for Space and Water Heating Applications

Solar thermal heating has a long history of use throughout the globe with varying penetration across regions. Design parameters of flat plate collectors are fairly well established. However, research and development to improve the efficiency and reduce the costs of the collectors is being pursued with vigor. Some recent developments of this technology is considered here for review.

Grigorios (2009) improved the thermal performance of a passive flat plate solar collector using a novel cost-effective enhanced heat transfer technique. This was accomplished by employing an aluminium grid placed in the channels of the collector to induce a gradient of heat capacitance. This novel technique is tested theoretically by means of simplistic designs using Computational Fluid Dynamics (CFD) and experimentally using two unglazed collectors. The results of theoretical and experimentation demonstrate an enhancement in the heat transfer coefficient by 9 % resulting to an increase in the output temperature of the working fluid in the collector with the metallic insertion. The obtained CFD data and the experimental findings show a good agreement.

Rabbani, and Hooshyar (2011) applied flat plate solar collector technology for wastewater treatment to minimize negative effects and costs. A pilot-scale plant on effluent (sludge wastewater) treatment system in Kashan, Iran was used for the studies. Thermal disinfection was achieved and measured treated effluent meant WHO guideline.

Bukola and Israel (2012) analyzed the heat transfer in a flat-plate solar collector with water tubes spread across its width. The theoretical results obtained agreed well with the experimental results, except that a slightly higher deviation of heat loss was obtained in the experimental analysis and low solar radiation. The results also reveal that the performance of the solar collector depends much on the heat rate.

Ahmad (2012) described a one-dimensional mathematical model for simulating transient processes which occur in liquid flat plate solar collectors. The model considers time-dependent thermo-physical properties of heat transfer coefficients, energy conservation for glass cover, air gap, absorber, working fluid, insulation, and the storage tank. Design experimental results for the transient fluid temperature at the collector outlet showed satisfactory convergence.

Mintsa*et al.*, (2013) presented numerical simulation aimed at optimizing system design parameters (air gap thickness, collector's length) and of the operating conditions (mass flow rate, incident solar radiation, inlet temperature) on efficiency of a polymer flat plate solar collector rather than absorbers usually made of copper or aluminum offering good performance at an expensive cost.

Sunil (2013) analytically studied the exegetic performance of a flat plate solar collector. Mathematical modelling of thermal performance is simulated using MATLAB Simulink, optimal geometrical and thermodynamic parameters are predicted for optimum performance of the system. The optimization procedure was applied to a typical collector and the optimum design values of collector inlet temperature, mass flow rate, absorber plate area, and fluid outlet temperature for maximum exergy inflow from the system were obtained.

Gambo and Gerry (2014) evaluated the thermal performance of solar flat plate water heater (Model TE 39) in Bauchi, Nigeria weather conditions. Fluid was circulated through the imbedded copper tubes in the flat plate collector; inlet and outlet temperatures of the fluid were measured at intervals of five minutes. The experimental was carried out between the hours of 11:00-13:00 daily for a period of 28 days. The result shows that the outlet water temperatures were dependent on the weather condition (solar radiation intensity, wind speed, cloud cover). Maximum outlet water temperature and collector optimum efficiency were obtained at 12:05pm.

Prakash *et al*., (2015) conducted the performance of a newly developed two flat plate solar collectors of similar design for solar heating plants. The absorber plate is selectively coated for high absorptive of solar radiation. One collector is equipped with an ETFE foil between the absorber and the cover glass and the other is without ETFE foil. The efficiencies for the collectors were tested at different flow rates. On the basis of the calculated and experimentation, both efficiencies were in good agreement.

Jamal (2015) practically carried out a study on a flat plate solar collector covered by transparent layer. The collector is low cost and simple design with 170 liters volume capacity. The collector works according to the natural circulation phoneme where the flow occurs due to the differences in water density. The practical data were collected for Baghdad for three months in 2007. The performance of the solar collector was evaluated for various conditions and water demands. The obtained data show confident results, reliable and applicable to supply domestic hot water in conjugation with auxiliary heater.

Jafar*et al*., (2015) illustrated experimentally the effect of series and parallel connection of flat plate water solar collectors arrayed on the thermal performance of closed loop solar heating system. The study includes the effect of changing the water flow rate on the thermal efficiency. The results show that, the collector's efficiency in series connection is higher than the parallel connection within flow rate level less than (100) ℓ/hr.

Saioa*et al*., (2015) presented two different dynamic models of a flat-plate solar collector in the Modelica language using Dymola software. The models describe in detail each of the development process. It has been demonstrated that both provide a suitable representation of solar collector dynamic behavior and suitable for different applications.Jamal (2015) carry out a practical study on a flat plate solar collector covered by transparent layer faced toward the south and tilted 30° from the horizon. The collector is a low cost and simple design with 170 liters volume capacity and works on natural convection circulation. The performance of solar collector evaluated at various conditions and water demands show maximum fluid water temperature reaching 43°C where the inlet temperature was 18°C in a month characterize by low solar radiation.

Kuhe *et al.*, (2016) discussed a method for improving the performance of flat plate collector by integrating a phase change material (bee wax) to a thermosyphon water heater. The developed solar water heater was tested in Makurdi, Nigeria weather condition using copper pipes in header and riser with different dimensions. The mean collector efficiency of about 70 % and maximum outlet temperature of about 70 $^{\circ}$C were obtained representing an appreciable improvement in performance over the conventional flat plate collector water heating systems previously reported for Makurdi under similar periods of the year.

Turhan and Fuat (2016) stated the technical and economic features of flat plate collectors widely used for supplying hot water or air for domestic and industrial applications. Their study shows that these collectors are approximately 2.0, 3.5, 4.0, 6.0, 7.0 and 12.0 times more profitable than wood, coal, natural gas, oil, LPG, and electricity respectively for heating water.They also found thermal efficiencies for air collector; a natural circulation corrugated 304 chromium water collector and a vertical hot water tankto be 46%, 88% and 95% respectively.

Gond et al., (2016) performed the performance of a flat plate collector (FPC) with different geometric absorber configurations with the aim of achieving better thermal efficiency and cost reduction. Anexperimental laboratory set up revealed maximum collector efficiency of 40 % to 47 % for all the materials tested, while maximum outlet water temperature is below 70^{0}C. Materials tested were in order of priority for better efficiency is copper, aluminium, than stainless steel.

Deniz *et al*., (2017) work addresses a flat plate solar collector with transparent insulation material (TIM) and high temperature protection system. The design and optimization of the collector have been numerically carried out by means of a parallel object-oriented simulation tool which is capable of simulating all the entities constituting the system as a whole, using efficient coupling between the elements. Three variants of the design are chosen to first test them under laboratory conditions. These collectors then are mounted in the roof of a hospital building, where their performances are comparatively tested along with a conventional flat plate solar collector, under real meteorological conditions. It has been demonstrated that different variants of the designed prototypes are capable of delivering higher amounts of heat to the domestic hot water and space heating system of a specific hospital building when compared with the conventional flat plate solar collector.

Boubacar *et al.,* (2017) made an experimental evaluation study of the solar collector installed in the Renewable Energy Agency of Mali (REA). The objective of the study was to improve the performance of a thermosiphon effect on a solar collector (solar water heater). The simulation model was used to evaluate the solar collector effectiveness according to the variation of the thickness and the nature of its internal elements (absorber, glass and insulating material). The obtained results indicate that the proposed simulation model was accurate with experimental results. In addition, it proves that the solar collector performance was strongly linked to the thermo-physical properties of the elements.

Himangshu and Ruhul (2017) introduced a reflector in solar collector as means of improving the performance of solar thermal collectors. The reflector concentrates both direct and diffuse radiation of the sun toward the collector. To maximize the intensity of incident radiation, the reflector was allowed to change its angle with day time. The radiations coming from the sun's energy were converted into heat, and then transferred to the collector base fluid (water). A prototype of a solar water heating system was constructed and obtained about 10% improvement in the collector efficiency.

Tabet*et al.,* (2017) investigated theoretically and experimentally a flat plate solar water collector with reflectors in Algeria. A mathematical model based on energy balance equations of the thermal behavior of the collector was fully described. The experimental test was made and found that an increase of 23% for solar radiation incident on the collector surface produces corresponding collector fluid temperature increases of 5%, while the thermal efficiency of the collector ranges from 1% to 63% during the day with average value of 36%.

Himangshu and Ruhul (2017) improved the thermal performance of a flat plate solar water collector up to 10% by using solar thermal reflector to concentrate both direct and diffuse radiation of the sun toward the collector. Gungor et al., (2017) in an attempt to increase the efficiency of flat plate solar collectors to utilize solar energy, studied the effect of insertion of planar solar collectors into a pipe. Depending on collector size, a temperature increase of 8-9°C compared to conventional collector systems was achieved. This temperature increase is not enough to increase the efficiency. However, they concluded that since solar energy is the most important source of renewable energy resources, this efficiency increase will be a guide for future work.

Roghayeh*et al*., (2018) added nano-particles to base working fluid in order to improve the overall thermal performance of flat plate collector. The collector efficiency was evaluated for different shapes of cross-section of the riser pipe. It is observed that increase in nano-particle volume fraction, enhances the efficiency with maximum obtained value as 80%. Reversely, particle size increase from 20 nm to 80 nm, causes more than 3% reduction in efficiency. In addition, for different shapes of the pipe cross section, including circle, square, and triangle; circular cross sections leads to the highest efficiency in the flat plate solar collector.

Vikas *et al.,* (2018) numerically developed a model of flat plate solar collector with the objective of building a thermally efficient solar water heater. The receiver plate was constructed from an air conditioner radiator and consisted of an array of serpentine tubes through which water was circulated. The presence of high-density corrugated fins attached to the tubes was to increase the absorption of incident solar radiation. The flat plate collector was enclosed by double glazing which admitted solar radiation and minimized convection heat transfer losses, while the shell of the collector was insulated to reduce conduction losses. The model predicted the useful heat transfer to the water using an energy balance approach. An experimental program devised to verify the accuracy of the thermal performance model gave close agreement between model predictions and experimental measurements.

Shubham *et al*., (2019) focuses on the role of CeO2/water nanofluid for estimating the performance of flat plate solar collector in respect of energetic and exegetic performance. The analysis focus on a wide range of concentrations to find optimum volume concentration for which thermal performance is maximum. Performance evaluation of flat plate collector is based on first law analysis and qualitative nature of energy flow based on second law analysis. Experiments indicate that for 1.0% particle volume concentration at a mass flow rate of 0.03 kg/s, maximum collector efficiency of up to 57.1% was obtained instead of water as the base fluid. Exegetic efficiency observed 84.6% at optimum concentration (1.0% particle volume) of nanofluid at 0.01 kg/s flow rate.

Altin*et al.,* (2019) exploited the energy performance of a flat-plate collector and a heat pipe evacuated tube collector for domestic hot water production in the Mediterranean climate for comparison using yearly data obtained from two field-trial solar water heating systems. The selected systems are forced circulation, installed near each other and on the roof with same slope angle and surface azimuthal angle. The installed surface area of the flat-plate solar collector is 4.41 m^2, whereas for the heat pipe evacuated tube collector is 1.5 m^2. The annual irradiation on solar collector plane was 1,456 kWh/m^2year. Obtained results showed that the annual solar yield for the flat-plate collector was 664 kWh/ m^2year, whereas for the heat pipe evacuated tube collector was 885 kWh/ m^2year. The annual average collector efficiencies were 0.494 and 0.62 respectively.

Iyd and Ayad (2019) evaluated a flat plate collector by coding design equations in MATLAB programs language with focused objective of determining efficiency of solar plate collector. Variables of time of the day, plate collector mean temperature, solar intensity and external air temperature were measured during experimentation. It was established that the efficiency was strongly a function of solar radiation as well the temperature of the external air with maximum solar collector efficiency of 74.8% for an ambient temperature of 31°C.

Mintsa*et al*., (2019) proposed a new numerical simulation aimed at optimizing the design of polymer flat plate solar collectors. Design parameters like (air gap thickness, collector's length), and operating conditions (mass flow rate, incident solar radiation, inlet temperature) were assessed on efficiency. The work outlines the main trends concerning the leading parameters impacting the polymer flat plate solar collector's efficiency.The numerical study was an approach towards understanding the thermal behavior of polymer FPSCs, on the way to a better optimization in order to design in the future more economically competitive thermal solar collectors.

2.2.2 Application of Flat Plate Solar Collectors

In general, for all applications needing solar process heat at levels up to 120°C, advanced flat plate collectors have economic benefits compared to concentrating solar systems. This is especially the case for climates with a high proportion of diffuse radiation. One major use of the flat plate technology is found in residential buildings where the daily hot water demand has negative impact on energy bills. This is mostly noted in situation where the family size is relatively large, and or high hot water demand for laundry use. Commercial applications include laundromats, car washes, military laundry facilities and eateries. The use of this technology for space heating application for buildings as well as drying of crops and other products is profitable and environmentally friendly in situations most especially in areas with unreliable electric-grid or is in nonexistence. Suitable processes are as indicated in Table 1.

Table 1. Process Heat and Their Temperature Range

Process	Temperature, °C
Drying	30-90
Washing	40-80
Cooking	95-105
Thermal treatment	40-60

Source: Henning, 2005.

Flat plate water heating systems ranges in price depending on regions, materials used in the construction as well as their water heating capacity. Collectors capable of heating water in the range of 40 to 80 gallons per day are reported to have been installed for residential houses in developed countries such as the United States of America, while up to 40 to 1700 gallons exist for commercial systems(http://www.flasolar.com/active_dhw_flat_plate.htm, 2020).

3 Conclusion

The commonest type of solar collector which is the flat plate collector is presented in this review.The mode of major heat losses and the major components parts are fully described. The design system components, thermal and thermodynamic analysis of the flat plate collectors developed by various researchers are described also. The selection of materials for overall system improvement and performance including that of evaluation methods are presented. Applications of flat plate collectors notably water heating, space heating, and other uses such as waste treatment, solar cooking, and solar distillation of water are highlighted in the course of the work to demonstrate the practicability of the technology. The application of this technology is environmentally friendly, has the capacity to save energy cost and meet the system load demand with the application of proved design methods, material selection and the use of appropriate construction techniques. The application areas described in this paper show that solar energy flat plate collectors can be used in harnessing solar energy and should be encourage so as to significantlyreduce environmental degradation and enhancement of financial benefit to users.

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