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ARTICLE

Design and Analysis of Parabolic Trough Solar Water Heating System

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ABSTRACT

Renewable energy technology is one of the prospective sources which can meet the energy demand and can contribute to achieve sustainable development goals. Concentrated collectors are widely used in solar thermal power generation and water heating system also. It is very popular due to its high thermal efficiency, simple construction requirements and low manufacturing cost. This paper is concerned with an experimental study of parabolic trough collector for water heating technology. It focuses on the performance of concentrating solar collector by changing the reflector materials (aluminum sheet, aluminum foil and mirror film). In Bangladesh, it is possible to use low cost solar concentrating technologies for domestic as well as industrial process heat applications. The line focusing parabolic trough collectors have been designed, developed and evaluated its performance by collecting solar radiation, inlet and outlet water temperature, flow rate, efficiency etc.

1. Introduction

Energy plays a vital role to represent a country, because it is related to poverty reduction, economic development and security also. Bangladesh has high demand of electricity and to meet up this demand- coal, gas, diesels are being used to produce electricity [1-3]. The main source of energy is natural gas which is going to run out very soon. In the present scenario, the only use of natural gas or non-renewable sources for household use is not a good sign for future and also the massive use of fossil fuel (coal, gas, Oil or petroleum) in the last century has caused the climate change through the greenhouse effect and produced large scale environmental pollution. In the present scenario of a huge energy demand, dependency on natural gas certainly creates crisis in future [4]. To reduce future difficulties in energy sector, Bangladesh Government has taken some initiative by using renewable energy [5]. Bangladesh has a vast potential for renewable energy and the natural availability of alternative energy creates opportunities of growth in power sector [6]. Among many renewable energy sources, solar energy is the most suitable for this country. Bangladesh receives an average daily solar radiation of 4-6.5 kWh/m^2 and it has an average annual solar radiation of nearly 1,900kWh/m^2 [5, 6]. In Bangladesh, which has 200 days of sunlight per year on average, solar energy systems have the potential to achieve high capacity factors with reduced payback time for consumers. Solar energy source made its way into the homes of millions of people throughout the world through solar photovoltaic (PV) and solar thermal energy [7]. By the development of improved materials and technologies with decreasing cost, solar en-

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ergy systems are becoming popular day by day. Solar PV generates electric power for use in the home or commercial places, while solar thermal energy systems are used to produce hot water, cooking or other purposes. In Bangladesh, hot water is only used here in winter for domestic purpose. But in many commercial places and hospitals need a huge amount of hot water for whole year. For this purpose, solar thermal utilization can be a great initiative for environmental protection and conventional energy saving. Solar collector is the major component of any solar system. Solar collectors are special kind of heat exchangers that transform solar radiation energy into heat and transfer this heat to a fluid (usually air, water etc.) flowing through the collector [8]. There are different kinds of solar collectors (concentrating and non-concentrating) which are used worldwide for domestic or industrial water heating [9,10]. The most common concentrating technologies are parabolic trough collector (PTC), linear Fresnel reflector, solar dish, and solar tower, [11] where, parabolic trough collector is one of the most famous technology [12]. This technology uses parabolic shaped reflectors to concentrate the incident radiation onto a receiver tube which is placed at the focal line of the trough [13-23]. Parabolic trough collector (PTC) is having various advantages such as in industrial steam generation [24] and hot water production [25]. The advantage of solar trough is that it is clean, cheap and can be supplied thermal energy. J. Ramesh et al. manufactured a solar water heater using the available materials (plywood, reflective aluminum sheet, storage tanks, and copper tube) and equipment in the workshop. They investigated the performance of the solar parabolic trough collector from total direct radiation on the plane of the collector, ambient temperature, wind speed, water flow rate, and inlet and outlet temperatures of the water inside the absorber tube. They have found that the heat gain increase depends on time and solar intensity [16]. Pradeep Kumar K V et al. described a low-cost method for mass production of PTC with its automated sun tracking system. They analyzed different types of absorbing materials to improve the performance of solar concentrator and the optical properties and degradation of the reflecting surfaces were assessed also [17]. The above-mentioned literature review indicates that there are numerous literature studies which analyze the performance of a parabolic trough collector. However, the studies which investigate the thermal performances of a collector with variation of reflectors are rarely done. Thus, this study suggests a simple design of solar water heater consists of three parabolic trough collectors. Different parameters have been measured (solar radiation, inlet and outlet water temperature, flow rate, efficiency) and the system has been evaluated for different reflectors. The study on PTC solar water heater in Bangladesh is not sufficient and so, system development and data production are important as this country has huge potential on solar energy.

2. Materials and Method

2.1 Experimental Setup

The experimental setup was placed at the roof top of Institute of Fuel Research and Development (IFRD), Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka and performance were evaluated during April -June, 2018. Due to the summer season, this area receives highest solar energy (4-5 Kwh/m^2) and average wind velocity remains here as 3.9 m/s in this time [26]. The experimental setup of the parabolic trough water heater consists of a manual tracking system with three parabolic trough collectors and a storage tank which is placed above the receivers' pipe level so that the heating fluid can flow naturally without pumping system. During the experiment, the parabolic trough solar water heater has been oriented with its focal axis pointed in the East- West (E-W) orientation. A plastic pipe was used to connect the storage tank and inlet of the water heater. Two copper tubes were placed together at the focal axis of each single collector. Here, two tubes have been used to increase the water flow time under the sunshine. The solar radiation intensity, the water flow rate and the water temperature of inlet and outlet were continually measured and the trough was rotated about a horizontal (E-W) axis and adjusted manually so that the solar beam made minimum angle of incidence with the aperture plane at all time during the experiment. The parabolic trough collector for domestic hot water application is shown in Figure 1,

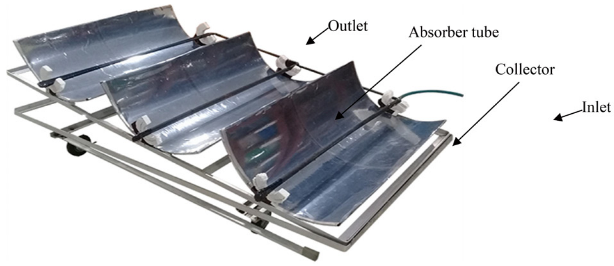

Figure 1. Parabolic trough solar water heater setup

2.2 Design Parameters

The geometric parameters of a PTC are its aperture width and length, rim angle, focal length and diameter of the receiver. The parabolic equation in Cartesian coordinates system can be represented as [22],

$$x^2 = 4fy \quad (1)$$

Using equation (1), the height of the parabola (h) can

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be calculated in terms of the focal length (f) and aperture diameter (D) is [22]:

$$(\frac{D}{2})^2 = 4fh \tag{2}$$

Or, $$h = \frac{D^2}{16f} \tag{3}$$

The rim angle is defined as the angle subtended by the edges of the reflector at the focus. The rim angle Ψ is given by [22]:

$$\tan(\frac{\Psi}{2}) = \frac{D}{4f} \tag{4}$$

Liner diameter

$$S = \left\{ \frac{pq}{t} + t\ln(\frac{p+q}{t}) \right\} \tag{5}$$

Here,

$$P = \frac{D}{2},$$

$$t = 2f$$

$$q = \sqrt{\left(p^2 + t^2\right)}$$

From the selected values of aperture diameter and concentrator height, the focal length, rim angle and the liner diameter of the concentrator were calculated from equations (3), (4) & (5) respectively.

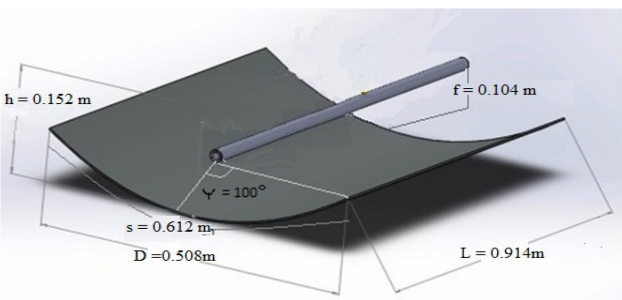

Figure 2. Design specifications of parabolic reflector

Figure 2 describes the design specifications of a parabolic reflector that has been used in our study. The selected data of the designed model has the following values as given by table 1.

Table 1. Different parameters and their values for the fabricated PTC

Item	Sample	Value
Aperture length	L	0.914 m
Aperture diameter	D	0.508 m
Rim angle	Ψ	100°
Focal length	F	0.104 m
Receiver diameter	D	0.013 m
Concentrator height	H	0.152 m
Linear diameter	S	0.612 m

The solar thermal efficiency of the PTC and useful heat gain by the circulating water during flow through the absorber tube are estimated by equations (6) and (7),

Solar thermal efficiency

$$\mu_c = \frac{Q_u}{I_b A} = \frac{mc_p(T_O - T_i)}{I_b A} \tag{6}$$

Heat gained by water

$$Q_u = m \times c_p \times \left(T_O - T_i\right) \tag{7}$$

Where,

Q_u = Useful heat gain-W

T_i &T_O= Inlet and outlet water temperature respectively - °C

m = Mass flow rate of water - kg/s

C_p = the specific heat of water - J/(kg-K)

I_b = direct solar beam radiation - W/m^2

A= aperture area of the collector - m^2

There are basically four major parts of a parabolic trough concentrator system, which are:

(1) Reflecting surface.

(2) Absorber tube.

(3) Supporting structure.

(4) Inlet and outlet pipes.

The collector's reflecting surface is curved in a parabolic shape so that the solar radiations which are colliding are getting reflected most of all the radiations to the receiver tube. In our study, as a reflecting surface, three different types of reflector materials were analyzed named aluminum sheet, aluminum foil and mirror film to evaluate the performance of the parabolic trough collectors. The absorber tube is the part of the system that converts solar radiation to heat energy by the working fluid. The receiver tube was placed at the focal length of the parabola. As an absorber, a black painted copper pipe was chosen because of its high thermal conductivity than aluminum tube or any other plastic tube. Two copper tubes of 0.013m diameter were used at the focal axis of each collector to increase water flow rate. All the components of the receiver tube and parabolic reflector were mounted on a stand which was basically a supporting structure. The accuracy of the parabolic surface depends on the accuracy of the structure frame. The structure frame supports the rotation axis of the parabolic reflecting surface. To reduce cost, the structure was made from iron rods which were welded together. A plastic pipe connected the inlet with the storage tank. The outlet fluid temperature was recorded with the help of a thermometer. For the fabrication of the device, the materials were selected by considering strength, suitability and local availability.

3. Result and Discussion

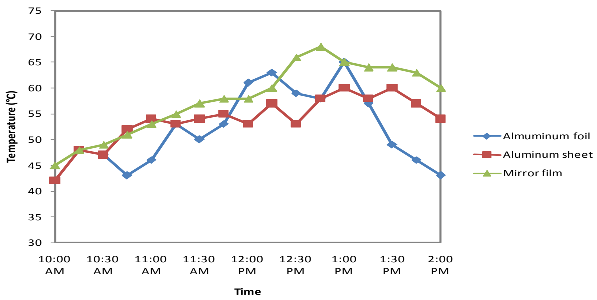

Figure 3. Variation of water temperature with time for different types of reflector

The solar water heater was evaluated in the month of April to June using a flow rate of 0.2 L/min. Figure 3 shows the variation of water temperature with time using different types of reflector. The water coming from a tank (initial temperature was 30°C) was passed through the collector and outlet temperature was measured. The data was taken at the time when solar insolation is available. The reported value indicates the better performance of mirror film as a reflector. It gives more stable and high-water temperature compared to other reflectors like aluminum sheet and aluminum foil. The maximum temperature was 68°C at 12:45 PM. This system is capable to provide 50°C and above from around 10:30 AM which is very suitable for domestic or some commercial purposes also.

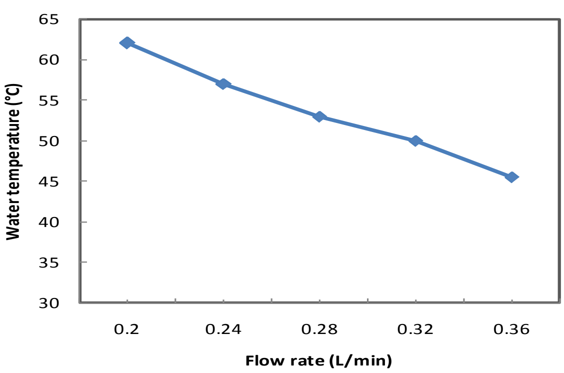

Figure 4. Variation of water temperature for different flow rates (Mirror film)

The solar water heating system can supply 12-liter hot water per day during 5 hr sunshine hour. This rate can be increased by changing the flow rate or increasing the number of units. The test was repeated with different flow rate which is shown in Figure 4. It is observed that the water temperature is decreasing with increasing flow rate.

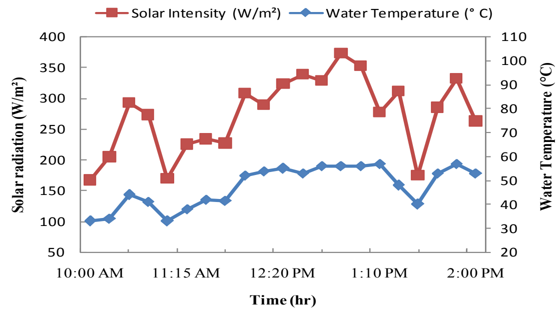

Figure 5. Variation of solar intensity and temperature with time (mirror film)

The dependency of the solar radiation on the solar water heater system was measured by plotting the solar radiation and water temperature in a single graph which is shown in Figure 5. It is clearly observed from this graph that the water heating rate is strongly dependant on solar radiation. The water temperature is increasing with increasing radiation and suddenly it falls when the radiation goes fall down.

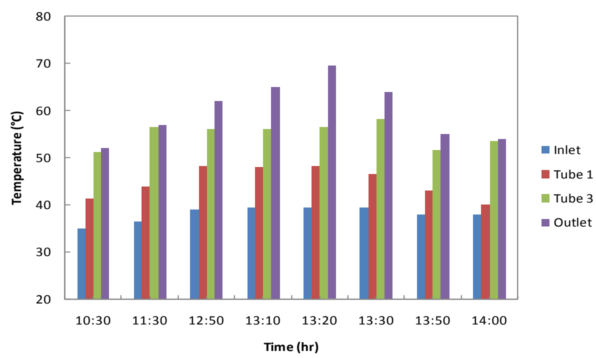

Figure 6. Variation of temperature in different position of solar water heater with time

Figure 6 shows the variation of temperature in different positions of solar water heating system. Water enters into the system with tube 1. So, here the tube temperature is quite low. After passing twice back and forth in a single collector, the third tube shows increased temperature and finally, outlet temperature was also monitored and it was almost same as it was found in tube 3. But when radiation is so high, i.e. at the time of middle of the day, the difference of temperature between tube 3 and outlet is visible. It indicates the heat gain is very high at the middle of the

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day which is also shown in Figure 7.

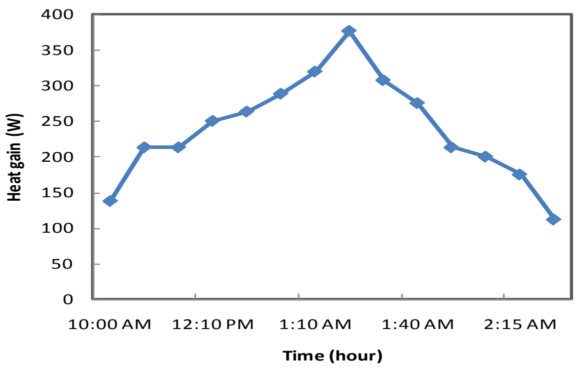

Figure 7. Variation of useful heat gain with time

Figure 7 indicates useful heat gained by the water flowing through the receiver throughout the day. Useful heat gained by the water is affected by various parameters such as wind speed, water temperature and solar radiation. It has been observed that as the beam solar radiation incident on the collector increases, more optical energy is captured by the absorber tube. Figure shows that, at the middle of the day when solar radiation is high and for that water temperature is also high, it is possible to achieve more useful heat gain. Average efficiency of 48% has been achieved with the mirror film reflector.

4. Conclusion

In the present work, parabolic trough collector was developed and investigated the outlet water temperature with solar radiation using three different types of reflectors: aluminum foil, aluminum sheet and mirror film. It is found that mirror film has highest durability and can provide higher outlet water temperature compared to other reflectors. The performance is greatly high even in the mid noon because of the high solar intensity at that time. The heat gain was increased depending on time and solar intensity. The average efficiency was found as 48% for mirror film reflector. So, this low cost parabolic trough water heating system can provide to be beneficial for industrial heating applications as well as domestic heating.

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