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Experimental Study on Effective Utilization of Solar Energy using Parabolic Trough Collector for Domestic Water Heating

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Abstract— ***In recent years, the increasing global interest in environmental protection has resulted in fresh inputs for solar energy usage research. A tremendous amount of research is in progress to limit the usage of conventional sources of energy and exploit the solar energy for various applications. In this paper, a simple solar parabolic trough collector (PTC) is proposed, which can be used to generate hot water and steam, thus the power. It is expected to overcome the limitations of conventional solar collectors, which includes heat loss and lower efficiency. A solar PTC was designed, fabricated, and experimental tests were conducted in different conditions to evaluate its characteristics. Based on the recorded data, the efficiency of the solar PTC was calculated at different times of the day, on different days. The highest thermal efficiency, with approximately 500 ml (0.45 kg) per hour of water, was about 64%, with a maximum temperature of 62 °C at the peak time of one of the days. The amount of heat absorbed by the water was as high as 48 kJ per hour on a particular day. The paper also highlights the difference between the peak efficiency and the average efficiency on a particular day due to varying solar intensity.***

Index Terms— ***Solar Parabolic Trough Collector, Water heating, Sustainable energy, Solar energy***

I. INTRODUCTION

The overall worlds' need for energy is continuously expanding. Hence, many of the countries are looking for ways to tap the free sources of energy viz., solar energy, wind energy, water energy, and many other forms, due to the shortages of non-renewable energy, for various applications such as water heating, electricity production, power generation for small and large scale industries, refrigeration and air conditioning et cetera[1]. Solar energy is the most abundantly available source of energy to the earth. Intensive increment of oil prices, largescale utilization of fossil fuels, rising air pollution, and many other problems has brought nations around the globe to do extensive research in this area.[1] Because of the development of scientific research and technology in the recent past in the solar energy sector, it stands out amongst the free energy sources that possibility will satisfy this climbing energy needs at the same time it will be environment friendly.

One of the methods of utilizing solar energy is by employing solar trough collectors[2]. The solar collector is capable of absorbing and converting solar radiation to heat, adding it to the working fluid. The working fluid used in collectors can be water, oil, air, or any organic solvent, based on its thermal capacities and the applications. The heat energy thus absorbed can then be utilized for various applications[1]. In this era, there are many novel applications where solar energy is of paramount significance. The application of solar energy includes but not limited to the air heating system (air absorbs heat), water heating system (water absorbs heat), desalination process (heat used in desalination process), refrigeration (heat used in refrigerant separation) and air conditioning system, and power plants. Among various types of collectors available, flat plate collectors are mostly used for hot water production because of its temperature range of about 120°C to 140°C. This particular paper maintains its focus on parabolic trough collectors. The typical PTC has following advantages: higher radiation to heat conversion efficiency; usefulness in generating steam and hence power; usefulness in community cooking purpose; can achieve higher temperatures (as high as 400°C) absorber tube[3]; also in thermal energy storage. The objective of the present work is to present a model for domestic water heating, which is a new approach with solar PTC. The solar PTC is also assessed for its performance parameters such as thermal efficiency, temperature of water, and heat absorption.

A. Parabolic Trough Collector

Figure. 1. shows the schematic diagram of the PTC system. Parabolic trough collector as the name indicates consists of a reflecting surface designed in the parabolic shape, which is made up of a relecting stainless steel. The reflector's job is to channel incoming direct radiation to the focal line by reflecting and concentrating it. In order to produce very high reflectivity, the reflector is made from materials such as polished mirrors, anodized aluminium, stainless steel etc. With this, the reflectivity will be as high as 90%. The system has a receiver tube through which working fluid flows. This receiver tube is designed in a way that the solar radiation is irradiated by a parabolic concentrator. The working fluid in the tube thus absorbs the thermal energy. Absorber tube(a.k.a receiver tube) is mostly made of copper material to enhance the absorptivity of the tube. Temperature of working fluid can reach as high as 400°C[4], depending on the type of reflecting surface, absorber tube material, and the fluid in the system, and the rate at which fluid flows. The PTC system should be positioned based on the sun's position. This will ensure that the collector reflects most of the radiation to the absorber tube

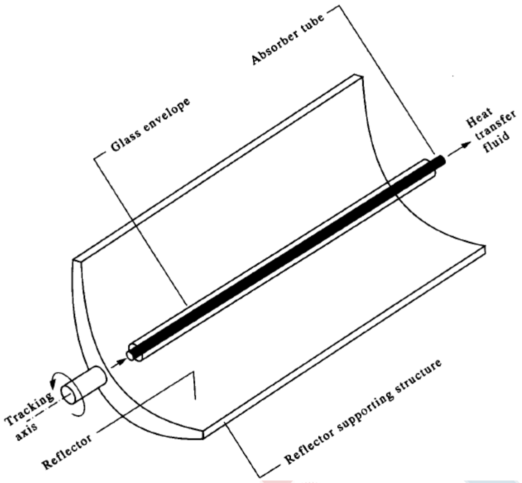
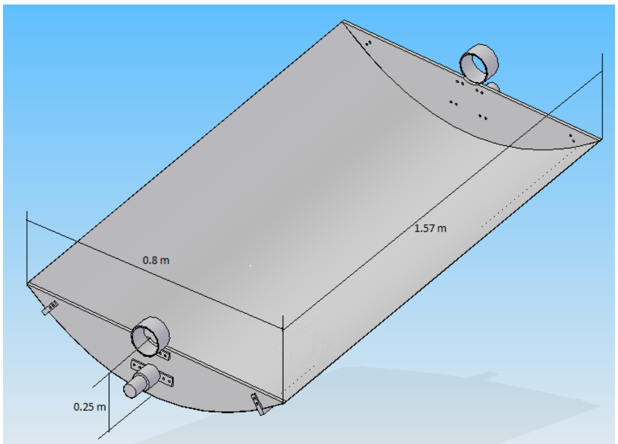


Fig. 1: Parabolic Trough Collector system

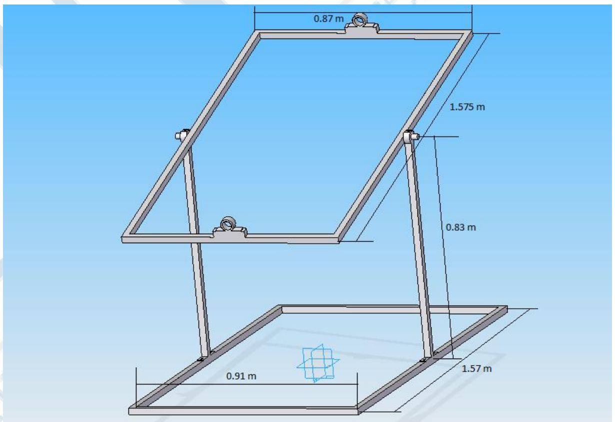
Another important thing in the study of PTC is concentrating ratio (collectors' aperture area divided by absorber tube's a rea). It is one of the essential parameters of PTC. The value of concentrating ranges from 20 to 70. Higher the concentrating ratio, higher will be the working temperatures. Then there's a support structure, a mechanical frame, which provides the essential support to keep the weight in place and offer resistance against wind. A tracking system is also used, whose function is to keep the collector according to the position of the sun. This will ensure maximum radiation absorption as sun moves from sunrise to sunset.

II. Experimental Setup

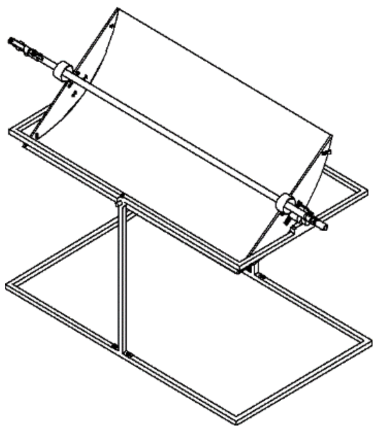
The experimental setup mainly consists of four parts: the reflector, the receiver, the thermal fluid (water), and the measurement system. Fig. 2 (a) to Fig. 2(d) shows a 3D design of PTC assembly and the actual fabricated PTC assembly, where all components can be observed. The setup was built in Mangalore District, Karnataka, as shown in Fig. 2(d). The Figure shows the base supports where the parabolic trough collector PTC will be installed with the rotation axis of the PTC structure, maintaining the absorber tube only a rotational degree of freedom rather than translating. The structure is composed of two central ribs, which are held together by a rectangular frame. The solar PTC was designed and fabricated by considering various factors, as described below.



(a) Parabolic trough



(b) Supporting structure



(c) Assembly

(d) *Actual set up*

Fig. 1. Solar Parabolic Trough collector model

A. Design Considerations

1) Materials

For the fabrication purpose, materials selected were in accordance with the literature available. They were selected based on their properties. For relecting materials, the properties such as being able to endure high temperatures, having superior reflectivity, being corrosion resistant, and having low transitivity and absorptivity are all desirable. Based on these requirements although silver seems to be an ideal material, but they are economically not for various reasons. The other option available to us was to use mirror coating stainless steel as a reflective material as it has good optical efficiency is the range of 70% to 85%. They also have longer life, minimal corrosion tendency[5] and wind-loading deformation free.

The material used for the structure was mild steel as it has good resistance to compression, high strength, and is capable of taking fatigue loading. Mild steel is also preferred material pipe section as it is a good conductor of heat, and can maintain its properties for sufficiently high temperature. It also have good absorptivity, good conductance, low emissivity (to avoid radiation losses from the pipe section). On the inner surface, the working fluid is ordinary water, which can lead to calcification, and rusting. Because of the required mass flow rates and outstanding heat transfer qualities, the receiver tube is made of copper tubes with a diameter of 30mm. [6]. A summary of the various materials used is provided in Table 1 as follows:

Table 1: Material selection summary

Components	**Materials**
Back Plate	Stainless steel
Receiver	Copper
Structure	Mild Steel
Reflecting Surface	Stainless Steel

2) System Design:

The system is designed to provide a temperature of 65°C, raising the temperature of the fluid from the ambient temperature i.e. 30°. The Mass flow rate for the required temperature rise and the velocity of flow is calculated as below.

For 1 kWh,

Mass flow rate ($\dot{m}$) $= \dfrac{\text{power}}{C_p \times \Delta T} = \dfrac{1000}{4180 \times 35}$

$= 6.84 \times 10^{-3} \text{kg/s}$

Velocity of flow, V $= \dfrac{\dot{m}}{\rho \times A_{inner}}$

$= \dfrac{6.84 \times 10^{-3}}{1000 \times 2.85 \times 10^{-4}}$

$= 0.0239 \text{ m/s}$

Time required for one pass of the fluid $= \dfrac{\text{total length}}{\text{velocity of flow}}$

$= \dfrac{1.828}{0.0239} = 76.51 \text{ sec}$

3) Power input (Solar energy)

Irradiation, $I_b = 584\ W/m^2$

Intensity of radiation on the collector $= I_b \times Ac$

$= 584 \times 1.379$

$= 805.336\ W/m^2$

For an optical efficiency of 70%,

Intensity of radiation on the receiver, I_r $= 0.7 \times 805.336$

$= 563.735\ W/m^2$

For an incident intensity of $563.735\ W/m^2$ and mass flow rate of $0.00684\ kg/s$, the temperature rise for a single pass can be found out as follows:

$\Delta T = I_r/(\dot{m} \times C_p) = 563.735/(6.84 \times 10^{-3} \times 4180)$

$\Delta T = 19.71℃ \approx 20℃$

B. Fabrication

All components of the closed type PTC were first designed by using a software (Solid Edge), based on the dimensions shown in Table-2. The supporting structure was made by using square steel iron pipe. For reflector sheet support, a 1-inch-square iron rod is used where the stainless steel reflective sheet is placed, which can be observed from the Fig. 2. Copper pipe was used as a receiver, and it was inserted at the focal axis of the parabolic trough. This whole assembly was assembled on the rooftop of the PA College of Engineering, Mangalore, Karnataka, India. The parabolic trough, as constructed, is a non-tracking collector. The axis of this collector is thus a fixed one and does not include automatic rotation of the trough depending on the direction of the sun. The setting, and thus the positioning of the reflector, is done manually, according to the sun's position. Various other parameters that were considered during its design and fabrication and are given in Table 3.

Table 2 Dimensions of the collector

Items	Symbol	Value
Length	L	1.5748 m
Aperture	α	1.3799 m^2
Rim Angle	Ψ	90°
Focal Length	f	0.2554 m
Receiver Diameter	d	0.0254 m
Concentrator Height	h	0.2554 m

C. Procedure

The experiments were conducted from 10:00 AM to 4:00 PM with a time interval of 60 minutes between the readings. In order to ensure proper reading the flow rate of the heat transfer fluid has been kept constant. The procedure is repeated for 6 consecutive days. In this experimental setup, the main objective was the heating of water of receiver pipes at day time in every hour. As mentioned earlier, the setting and positioning of the reflector is manually done according to the sun's position.

III. EXPERIMENTAL RESULTS AND PERFORMANCE ANALYSIS

A. Temperature Observation

The temperature of the water recorded on a particular day for every hour is tabulated, as shown in table 8. Water is still in the receiver tube, and its volume is equal to the volume of the copper tube. The temperature was recorded for the most part of the day, as presented in the Table 4. The same data is presented by a line chart in Fig. 3, and for different days is presented in Fig. 4.

Table 3: Parameters of the Solar PTC

Item	Value
Width	0.8763 m
Length	1.5748 m
Projected area (Ac)	1.379 m^2
Rim angle(ϕ)	90°
Focal distance (a)	0.254 m
Copper tube (Receiver) Inner diameter	0.023 m
Copper tube (Receiver) Outer diameter	0.025 m
Copper tube Inner volume	0.000448818 m^3
Area of receiver exposed to rays (A_R)	0.0729 m^2
Inner cross-sectional area (A_i)	$2.85 \times 10^{-4} m^2$
Outer cross-sectional area (A_o)	$5.067 \times 10^{-4}\ m^2$
Concentration Ratio (CR)	18.91
Density of copper	8940 kg / m^3
Thermal conductivity of copper	385 W/mK
Thermal fluid	Water

Table 4 Temperature observation at the various time interval

Time	Temperature (°C)	
	Inlet	Outlet
10:00	30	49
11:00	32	53
12:00	34	56
01:00	34	57
02:00	33	54
03:00	31	51
04:00	31	47

It is observed from Fig. 3 and Fig. 4 that the thermal performance (temperature) of the collector (water) first starts to increase till it reaches a maximum value at around in the range of 12:00 to 14:00 hrs., and then gradually starts to decrease as the time passes. The difference in temperature is around 20°C. This temperature is noted for approximately 0.449 kg of water in the receiver tube.

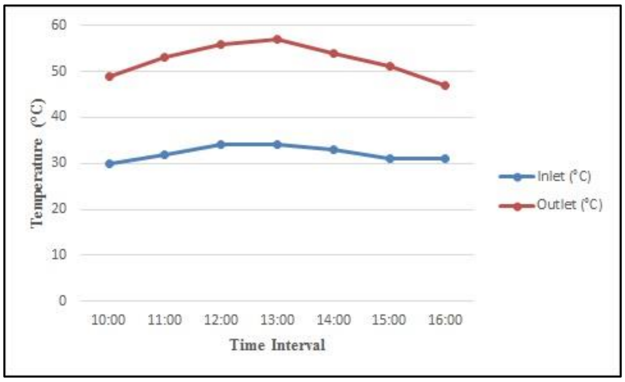


Fig. 3. Temperature vs Time interval on a particular day

Based on the temperatures obtained, the amount of heat (Q) absorbed by water is also calculated by using the given equation below.

$$Q = mC_p\Delta T$$

where, m is the mass of water in the receiver pipe, C_p is the specific heat of water, ΔT is the increase in temperature of water in an hour. The mass of water is calculated by using the following formula:

$$m = (\rho_w) \times (\frac{\pi d^2}{4} \times L)$$

Where ρ_w is the density of water, d is the inner diameter of the copper tube, and L is the length of the tube. The heat observed per hour is calculated and presented for different days in Fig. 4. The heat absorption follows the same trend as that of the temperature with the time interval. The maximum amount of heat absorbed is about 45kJ in the mid of the day, i.e., between 12:00 to 14:00 hrs.

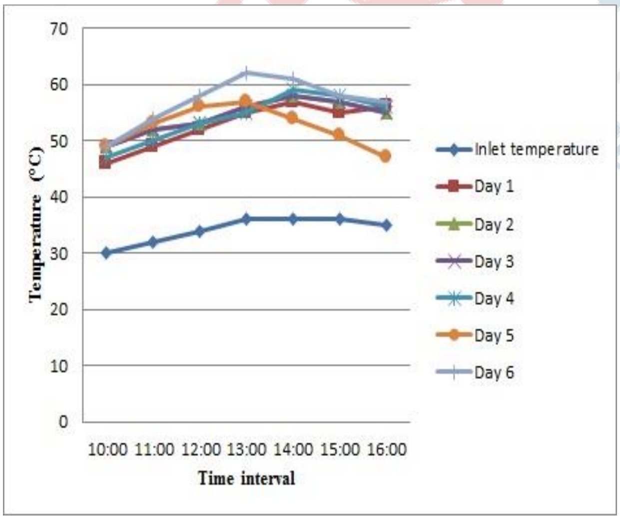


Fig. 4 Temperature vs Time interval on different days

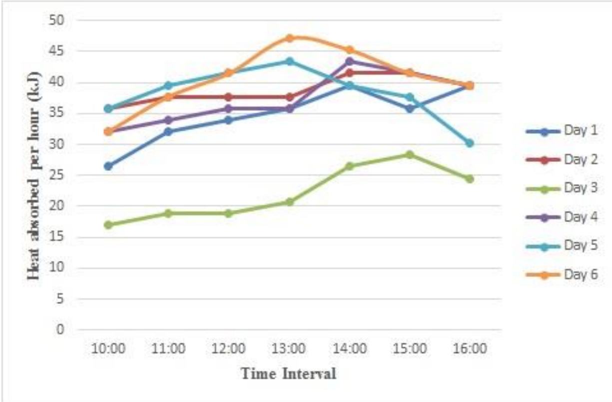


Fig. 5. Heat absorbed per hour vs. Time interval on different days

B. Variation of Efficiency With Day

The higher efficiency can be seen during the period between 12:00 to 15:00 hours. The thermal efficiency of solar PTC on different days is evaluated by using equation given below. In Fig. 6., below, we can see the average efficiency and peak efficiency on different days. It can be observed that the thermal performance of the collector is different for different days. Depend upon the solar intensity, the efficiency of the system also changes. In Fig. 6, the blue line depicts the peak efficiency due to which water absorbs the maximum heat from the copper tube.

$$\eta_{th} = \frac{\dot{m}C_p(T_o - T_i)}{A_a I_b}$$

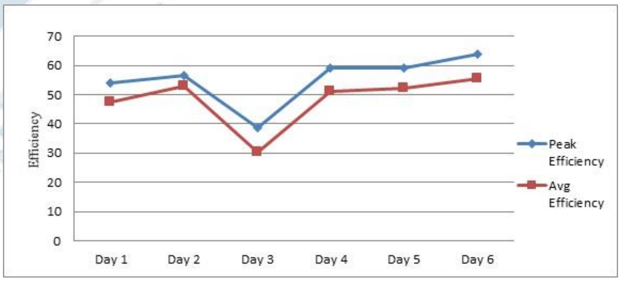


Fig. 6. Variation of Peak Efficiency and Average efficiency

IV. CONCLUSION

As per the records, if 0.1% of the total renewable energy is utilized, then it's possible to fulfill five times the total world energy demand. This research is a contribution to the energy analysis of the Parabolic trough Collector with Manual Tracking. This work presents an easy to build, low cost, and potential design and fabrication of a solar PTC.

The test results indicated that for 0.45 kg of water, the maximum temperature noted is as high as 62 °C, during peak hours. The results obtained suggest that its performance will significantly improve during a clear sunny day and with appropriate design modification. In this paper, we have presented one of its kind usage of solar PTC as an energy source for domestic water heating applications. This work also highlights that automatic dual-axis tracking can be

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implemented to increase the accuracy of tracking. Also, with the implementation of troughs in large numbers, the amount of output can be increased, which may then be utilized for domestic purposes successfully. The size of the trough should be increased, and the material with high reflectance can be used to generate the steam with high potential.

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