SSRG International Journal of Mechanical Engineering Volume 6 Issue 12, 1-6, December 2019
ISSN: 2348 – 8360 /doi: 10.14445/23488360/IJME-V6I12P101

Feasibility Study of Parabolic Trough Collectors for Residential Water Heating

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Abstract
In this paper, a customarily fabricated parabolic trough collector (PTC) prototype is tested for residential water heating purposes. The testing location and time are Silchar, Assam, INDIA in mid-summer of 2015. We tested the instrument for two types of receiver tubes made from Copper and Stainless Steel with two types of working fluids (diatherm (Therminol VP-1) and water). Diatherm performed well compared to water, with an average of 51% greater efficiency at the receiver tube. The device's maximum response rate for an increase in storage water temperature is recorded 0.18^{0}C/min when diatherm was used as the working fluid. Maximum efficiency at the receiver is reported 37% when diatherm is at work. Since the aperture area of PTC is limited in residential applications compared to large scale applications, low efficiencies and low receiver temperatures are reported. Therefore, the application of PTC systems for residential water heating is challenging based on its limitations.

Keywords — *Parabolic Trough Collectors, Residential Water Heating, Diathermic Liquids, Solar Thermal Devices, Direct Water Heating, Indirect Water Heating*

I. INTRODUCTION

The application of renewable energy systems became unavoidable in modern days. The depletion of fossil fuels forced researchers to focus more on alternative energy sources. In this regard, renewable energy sources became one of the imperative sectors. Besides, the population growth rate is faster than decades before, demand for alternative energy sources is increasing [1].

Solar energy becomes attractive among all renewable energy systems because of its wide availability and accessibility [2]. In the quest to observe the most cost-effective and reliable solar energy extraction systems, concentrative solar power (CSP) systems gain wide attention. Though CSP systems meet its limitations compared to photovoltaic technologies, reduced cost in the manufacture and high efficiencies pushed them to be used in solar thermal power generation on a large scale [3]. Among the few solar concentration technologies, parabolic trough collector (PTC) systems can be presented as the most mature technology to produce heat in temperatures up to 400^{0}C. They can also be given as one of the most advanced solar thermal technologies in the present due to its considerable experience with the systems and accessibility of small commercial industries to build and market those systems [4]. As another advantage of PTCs, they can be sufficiently operated by single-axis tracking where parabolic dish and Fresnel lens systems require multi-axis tracking [4]. To extract another positive contribution of PTCs, a study performed by Gharbi et al. [5], on assessing collector efficiencies of PTC systems and linear Fresnel lens collectors, they concluded that PTCs performed better in its efficiency of 55.8% that of the 45.75% of Fresnel lens system. They also concluded that this effect is a reason for applying PTCs for the Rankin cycle power generation [5].

PTC systems work with heat carrier fluids; the current most popular fluids in the application can be given as synthetic oils, molten salts, and pressurized gases for indirect steam generation and water for direct steam generation. Achievable high temperatures of synthetic oils are limited up to 393^{0}C, but they can be operated in relatively low pressures. Direct steam can be used as the receiver fluid, but high pressures are required. Due to leakages' vulnerability, a direct steam system is not widely applied in large scale power generation. Molten salts are commonly utilized in PTC power generation due to its high working temperatures (290^{0}C-565^{0}C) and relatively low costs. The most common drawback of a molten salt application is its high melting temperatures. In low solar insolation periods, the molten salts must be completely drained from process systems to avoid intermediate solidification. Pressurized gases do not have a limiting temperature, and they are popular for their low cost. However, pumping losses are higher for gases than liquid heat transfer fluid (HTF) due to high-density differences. Therefore, currently, no commercial power plant uses gases as heat-carrying fluid [3].

Focusing on the construction of PTC systems, evacuated tubes are widely applied as receiver tubes. Evacuated tubes reduce the radiation loss from the working fluids and successfully transfers radiative heat to the working fluid. In general, the receiver's outer tube is made from glass material, and the inner tube or the absorber tube is made from metallic material [16]. A detailed description of the design process and parametric analysis is given by Thomas et al. [7]. Also, Thomas et al. extracted a few of the common reflector materials for PTC applications.

Black silvered glass plates, anodized aluminum sheets, and aluminized plastics are common [7]. They also concluded that the PTC unit's efficiency largely depends on the reflective properties of the reflective mirror. Current reflective materials possess an order of 92% reflectivity of the solar spectrum [7].

Parametric analysis of PTC systems is prevalent in literature. Most research is focused on PTC receiver tube performance and its application on power generating cycles. Odeh et al. [16] introduced a complete thermal model to quantify the receiver tube's efficiency when steam as the working fluid. Their model included empirical relations to obtain heat transfer coefficients in heat gains and losses by introducing collector optical efficiency calculations. Also, Arasu et al. [8] introduced another model to calculate the PTC system's thermal efficiency presented by ASHRAE. Instantaneous collector thermal efficiency is presented by Kalogirou [9] based on the temperature change of working fluid and direct normal solar radiation. This parametric calculation process is adopted in our work for evaluating the thermal performance of PTC in subsequent sections.

Though there is a wide range of research presentations on the application of PTCs for large-scale power generation [10] [11] [12] [13], research in the application of PTCs for residential purposes is scarce in the literature. Islam et al. [14] performed a detailed review of solar thermal technologies available for domestic water heating. In their review, they reported that the mean daily efficiencies of PTC systems on domestic applications fall between 37-60%. Hussain et al. [15] simulated a collector model with a receiver temperature increase of 10-15^{0}C. Their analysis reported that useful energy collected is about 57% of the total incident energy. In this work, we attempt to contribute to this research gap by testing a small-scale PTC system for residential water heating purposes. Low fabrication costs and contributions from domestic manufactures created the motivation to perform this study.

II. MATERIALS AND METHODS

A. Experimental Setup

Experiments are done using a parabolic trough collector unit fabricated for the Department of Mechanical Engineering of NIT-Silchar. The collector has an aperture area of 24ft^2 with size details and specifications presented in Table 1. As in figure 1, two liquids (Diatherm, Water) are used as working fluids to extract heat from the receiver tube. Two evacuated receiver tubes are constructed for each fluid as Cu based tube for Diatherm and a steel tube for water. The outer tube of the receiver is made from reinforced glass. The reflective mirror is fabricated of stainless steel with a reflective coating (anodized aluminum). This measure is taken to avoid any corrosive effects from diatherm on the receiver tube. Temperature sensors are located at each entry and exit of the receiver tubes to record inlet and exit temperatures (T_i and T_o) of fluids. Besides those main temperature sensors, individual temperature sensors are placed at each storage tank. Storage tanks are insulated by aluminum foil and thick resin material to minimize heat losses to the surrounding. This allows us to observe any energy losses of fluids when flowing through the apparatus. Also, volume flow sensors are located near each receiver tube to measure the volume flow rate value (VFR) for each fluid, ultimately calculating the mass flow rates (MFR) of fluids. Two circulatory pumps are used for each receiver tube for diatherm and water. In the diatherm pump, there are two settings possible, low and high. But for the water pump, there is only one setting is possible (1.2kg/s). Average mass flow rates of the diatherm pump are presented in figures 3 and 4. As the residential water supply tank, two separate water supply tanks are installed with the unit. A heat exchanger is located inside this water supply tank to transfer heat from diathermic liquid to storage water. However, when water is applied as the working fluid, storage tank water is directly allowed to flow through the receiver tube. The apparatus is located at Silchar, Assam (788010), in a large open flat space where scattered solar radiation is minimized. All experiments are performed on clear sunny days, which produce maximum direct solar radiation. The trough collector is always tracked with the sun's movement to maintain the receiver tube as the focal point (Tracked manually). Direct solar radiation is an important parameter in calculating receiver tube performance. Therefore, direct solar radiation is measured by a solar radiation meter [Davis- 6450] near the experimental apparatus. The maximum global solar radiation measured for testing location rounded to the nearest decimal place is 1100W/m^2.

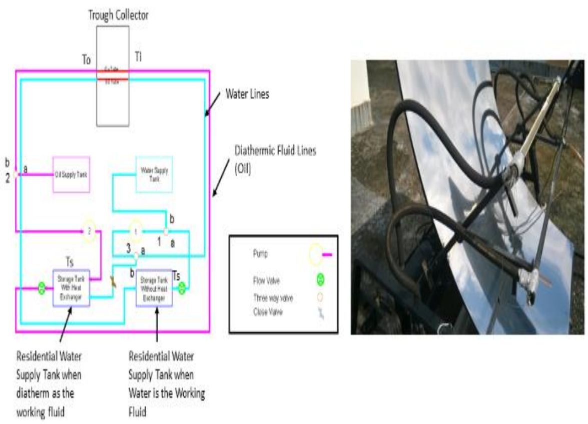

Figure 1: Left: Schematic diagram of the apparatus, Right: Fabricated Module

Table 1: Specifications of the PTC system

S. No	Components	Specifications
1	Heat generating unit with the tracking system	
	Parabolic reflector • Length • Arc length • Depth • Focal length • Material	 4ft 6ft 0.68ft 1.99ft SS with mirror film
	Sun tracker	Single-axis
	Absorber tube • Length • Diameter • Absorber material • Insulation material (for pipe) • Piping material	 4ft 1inch Copper, SS PUF GI and Copper
2	Storage unit	
	Supply tanks • Capacity • Material Storage tank • Capacity • Material • Insulation used • Tank insulation thickness • Pipe insulation thickness • Working fluid	2(one for water and other for oil) 46ltr (for water) and 10ltr (for oil) SS 2(one with heat exchanger and other without heat exchanger) 28ltr (for water) and 10ltr (for oil) SS Glass wool with Rexene 2cm 1cm Water and oil
3	Pump unit	Non-variable
	Pump (for water) • Power rating • Head Pump (for diatherm) • Power rating • Head	 0.1HP 6m 0.5HP 10m

B. Formulation

In our current study, we are only focused on the trough system's instantaneous efficiency. This measure can provide a direct parameter to identify the system performance without complex analysis of system losses. Instantaneous efficiency can be given as the ratio between heat gained by working fluid at the receiver to total solar energy exposed to the trough. Useful heat gain (Qu) at the receiver tube is obtained as [9],

$$Q_u = MFR \times C_p \times (T_o - T_i)$$
(1)

The mass flow rate through the receiver tube C_p is the fluid's specific heat capacity T_o and T_i is the receiver outlet and inlet temperatures measured in ^{0}C, respectively. Efficiency at the receiver tube is given by the ratio of useful heat gain (Q_u) and total solar energy (Q_T)focused by the parabolic trough. Q_T can be simply obtained as,

$$Q_T = DSR \times A \qquad (2)$$

Where DSR is the direct solar radiation is measured at the location in W/m^{2,} and A is the aperture area? Therefore, efficiency at the receiver tube (η) at the receiver tube can be given as,

$$\eta = \frac{Q_u}{Q_T} \qquad (3)$$

Adjacently, direct solar radiation can be obtained by subtracting diffuse solar radiation from global solar radiation. Figure 2 represents some of the radiation data observed at the testing location in testing periods.

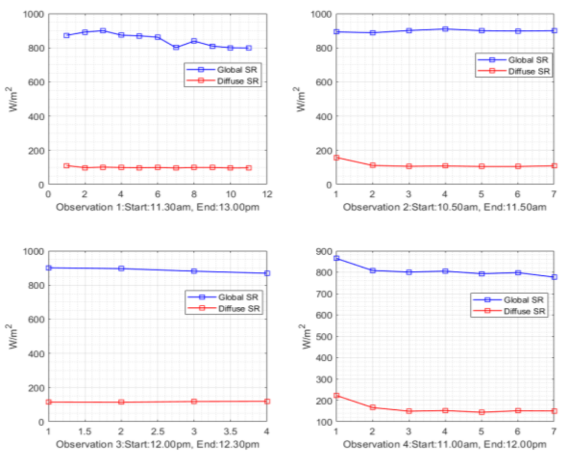

Figure 2: Global and diffuse solar radiation values obtained for 10minute intervals for 4 observations in a mid-summer day at the testing location.

The above observation shows that global solar radiation fluctuates near 900W/m^2 on a clear mid-summer day at the testing location. Two sets of separate experiments are performed respectively for diathermic fluid and water as the receiver fluids.

III. RESULTS

Figure 3 presents the parameter values calculated for observation 1 when diatherm as the receiver tube fluid. The water temperature of the residential water supply tank is denoted as T_s. It is observed that the diathermic pump has a mean mass flow rate of 5.4kg/s with a ±10% variation. Therefore, Q_u and η values do not follow the smooth temperature variation, as depicted in figure 3-(a). Figure 4 represents the results of an experiment performed using a very low mass flow rate. Figure 5 presents the data for two separate experiments using water as the receiver tube fluid. These measurements are taken in the range of minimum solar radiation of 494W/m^2 and maximum solar radiation of 721W/m^2. An average mass flow rate of 1.2kg/s of water is maintained during the experiments. Here the collector efficiency (η) is plotted concerning storage tank water temperature (T_s). Cabs denote direct incident solar energy on the collector in graphs.

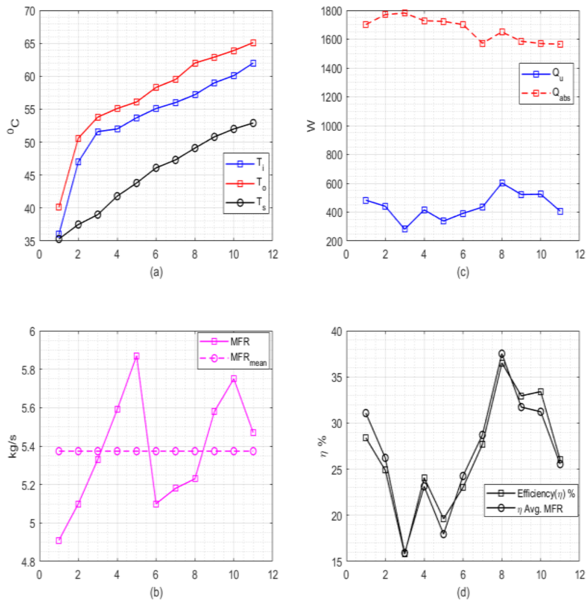

Figure 3: For observation 1, with an average ambient temperature of 29^{0}C, (a). T_i, T_o, T_s, variation with time, (b). Useful heat gain (Q_u) with time, (c). Mass flow rate (MFR) variation with time, (d). Variation of efficiency (η) with time, each data point is recorded with 10minute time interval; Start: 11.30 am, End: 1.00 pm, (ηAvg. MFR: Efficiency values computed with average mass flow rate)

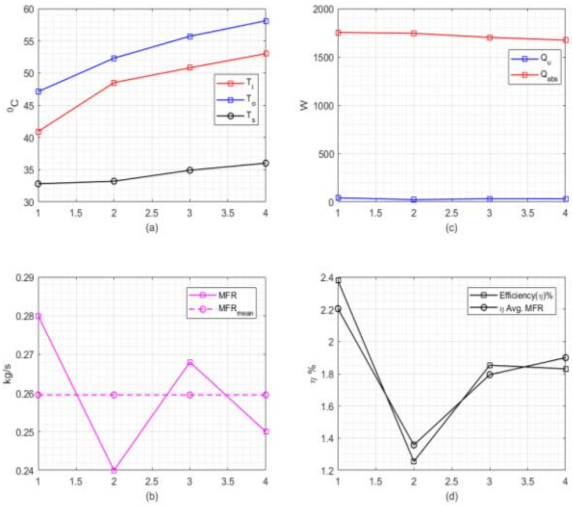

Figure 4: Experiment performed with very low mass flow rates for diathermic fluid with an average ambient temperature of 30^{0}C, (a). T_i, T_o, T_s, variation with time, (b). Useful heat gain (Q_u) with time, (c). Mass flow rate (MFR) variation with time, (d). Variation of efficiency (η) with time, each data point is recorded with 10minute time interval; Start: 12.00 pm, End 12.30 pm, (ηAvg. MFR: Efficiency values computed with average mass flow rate)

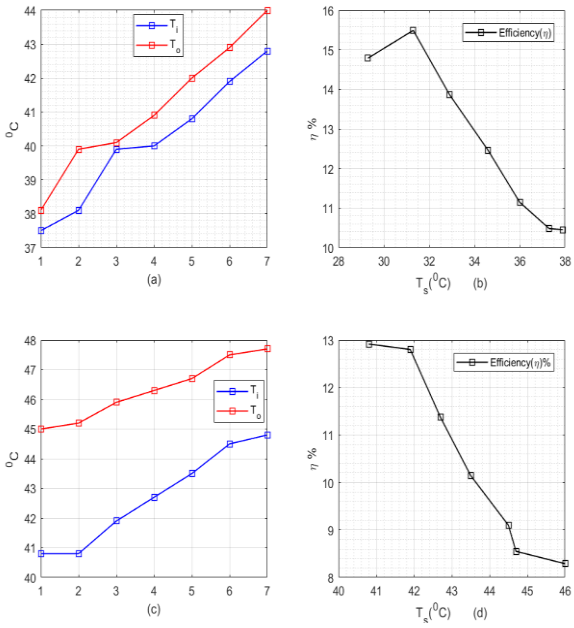

Figure 5: Experiments performed with water as the receiver tube fluid with a mean mass flow rate of 1.2kg/s (a). T_i, T_o, T_s, variation with time, (b). Variation of efficiency (η) with time [For reading set 1], and (c) and (d) that of the same for reading set 2, each data point is recorded with a 10minute time interval [(a). Based on observations 2 and (b). Based on observation 4]

IV. DISCUSSION

From the experiments performed for both diatherm and water as the receiver tube fluid, it is observable that relatively high-efficiency values are recorded for diathermic fluid compare to water (Average difference of 22%). Also, T_o-T_i values are higher for diatherm to that of water, demonstrating better heat gain at the receiver tube. With higher mass flow rates compared to diatherm, water is demonstrating poor performance as a receiver fluid. In diatherm application, efficiency at the receiver tube does not depend on the storage tank (T_s), but efficiency depends largely on the diatherm mass flow rate. On the contrary, it is observed that for water, efficiency at the receiver tube is dramatically decreasing with the increase of storage water temperature (T_s). This causes another negative impact on the water as an efficient fluid. Considering maximum storage water tank temperature increase during experiments, 17^0C rise is observed when a diathermic application and 8.1^0C rise in water. Since both the storage tanks were built in an equal volume, this reading is a good factor in comparing two fluids' performance. Besides, Figure 5, (a)-(b), and (c)-(d) graphs were obtained for two separate experiments on water based on radiation observations 2 and 4 in figure 2, respectively. In the first case, measurements were started when storage tank water temperature (T_s) is equal to an ambient temperature of 29 ^{0}C. In the second case, measurements are started on a new day after the storage tank water temperature reached 40.8^0C. In the first case, efficiency (η) starts with 14.8% and decreases with the increase of T_s. However, in the second case, even with higher storage tank temperature (Ts), higher starting efficiency (12.96%) is recorded compared to the first case and follows the same pattern as the first case.

V. CONCLUSION

In this paper, a parabolic trough collector module fabricated for a residential scale is tested for two receiver tube working fluids: diatherm and water. It is observed that diatherm has higher efficiency at the receiver tube compared to the application of water. Also, diathermic fluid has a low response time on its temperature increase and can be operated in relatively low mass flow rates compared to water. The parabolic trough size can be varied up $10m^2$ for a typical residential application; however, the maximum efficiency is limited up to 40% in this size range. In addition, unlike the application of flat plate collectors in residential water heating, PTC systems respond only for the direct solar radiation. Therefore, a precision tracking process is crucial for its performance. A small cloud cover can eliminate the PTC performance hindering water heating. Considering the time required for storage tank temperature to rise, 17^0C is observed for 1 1/2-hour period in heavy sun hours. This rise is not sufficient for domestic purposes because there is a continuous demand for hot water in a full day period. Based on these results, we conclude that PTC systems cannot meet residential water heating purposes' continuous requirements. However, PTCs are highly efficient for large scale applications such as solar thermal power generation due to large aperture areas and thermal storage systems.

ACKNOWLEDGMENT

Naveen Weerasekera, Ah-med Abdulla, Dawa Shingdon, and Kiplangat Cheruiyot wish to thank Dr. Agnimitra Biswas for his constant support and motivation for the succession of this project.

FUNDING

This work is performed by the Department of Mechanical Engineering, National Institute of Technology, Silchar, Assam, INDIA, 788010.

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