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Parametric Study of Solar Parabolic Trough Collector System

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ABSTRACT

This study suggests a theoretical performance study of an existing solar Parabolic Trough Collector (PTC). A study of the trough thermal analysis is necessary to evaluate the performance of a PTC. The parametric study of the existing PTC makes use of the mass flow rate, the concentration ratio, the different Heat Transfer Fluid (HTF), the solar insolation and the heat removal factor. The results showed that the efficiency of PTC decreases for various mass flow rates and HTF, as the inlet fluid temperature increases. This is because the radiation losses increased as the collector temperature increases. It is also observed that the useful energy from the PTC decreases for various concentration ratios and insolation, as the inlet fluid temperature increases.

Key words: Parabolic trough collector, solar insolation, heat removal factor, concentration ratio, useful heat gain, intercept factor

INTRODUCTION

Solar energy currently represents the most abundant, inexhaustible, non-polluting, effective and free energy resource available in almost all parts of the world (Safari and Gasore, 2009; Sreejaya *et al.*, 2011; Andoh *et al.*, 2007). If the available solar energy on the earth is properly harnessed the world may not have need for fossil fuel any more (Efurumibe *et al.*, 2012; Chattopadhyay *et al.*, 2011). In recent years, considerable attention has been paid to solar thermal concentrating systems which are regarded as environmentally friendly alternatives to conventional thermal power systems. In solar thermal concentrating systems, incident solar radiation is converted into thermal energy at the focus (Khatib *et al.*, 2009). These systems are classified as either point focus concentrators (parabolic dishes and central receiver systems) or line focus concentrators (parabolic trough collectors and linear Fresnel collectors).

The PTC focuses Direct Normal Irradiance (DNI) or beam radiation onto a focal line on the collector axis. An absorber tube with water or temperature stable synthetic oil flowing inside, absorbs the concentrated solar energy and raises its temperature at the focal line.

There are several promising developments going on in the field of PTC and their applications. A comprehensive review of the usage of the PTC for various applications of thermal energy up to 400°C was presented by Fernandez-Garcia *et al.* (2010). Lupfert *et al.* (2007) summarized the various techniques available for the analysis of the PTC's optical performance. Brooks *et al.* (2006) conducted the baseline performance study of the PTC, using ASHRAE standard 93. Kalogirou studied the viability of PTCs for industrial process heat by Kalogirou (2002). In an effort to obtain the maximum possible collector efficiency, special attention was given to the intercept factor and mode of tracking (Kalogirou, 1996). An extensive survey on various types of solar thermal collectors and applications was conducted by Kalogirou (2004). The PTC optical test and thermal test up to 200°C with pressurized water was performed by Kruger *et al.* (2008). These studies showed a significant improvement in the reduction of radiative and convective losses. Opitmisation of the collector's aperture, the rim angle and the selection of the receiver's diameter was performed by Kalogirou *et al.* (1994). The idea of using thermal storage for parabolic trough power plants was widely accepted to ensure continuous power delivery even during off sunshine hours. The performance test of the PTC power plant integrated with solid media thermal storage at Plataforma Solar de Almeria in Spain was performed by Laing *et al.* (2006). The design and manufacture of a 90° rim angle fibre glass reinforced PTC for hot water generation was described by Arasu and Sornakumar (2007). The thermal performance of the newly developed fibre glass reinforced parabolic collector was determined according to ASHRAE Standard 93. A stand alone single axis tracking parabolic trough system was designed by Odeh *et al.* (2004). The system can operate independently at remote area to produce hot water or steam pressure close to ambient for small factories. Odeh and Morrison (2006) developed a transient simulation model for analyzing the performance of industrial water heating systems using parabolic trough solar collectors. This model aims to optimize the size of the collector aperture area and thermal storage tank by considering sudden changes in solar radiation such as passing cloud.

The objective of this work is to investigate the viability of the available PTC for solar cooking application. For this purpose, the parameters like the mass flow rate, solar radiation, concentration ratio and heat removal factor have been considered and addressed, for various inlet fluid temperatures. The required mass flow rate and HTF is thus finally identified for an ongoing solar cooking research.

THERMAL ANALYSIS-PARABOLIC TROUGH COLLECTOR

A PTC generally includes the receiver tube, the concentrator and collector structure. The receiver is the element of the system where solar radiation is absorbed and converted into thermal energy. The receiver is covered by a glass tube to reduce thermal radiation as well as convection heat loss to the free air which moves around the receiver. The heat loss from the receiver is further reduced by evacuating the air from the space between the receiver and the glass cover.

A prototype PTC model has been developed, installed and experimented at the Institute for Energy Studies, Anna University, Chennai. The PTC model uses mirrored surfaces curved in a parabolic shape that linearly extend into a trough shape. The mirror is made of a glass (Saint Gobain make) with a thickness of 6 mm. In general, the concentrating collectors are found to have less heat gain values, because they use only direct irradiation. This disadvantage is compensated by the tracking device. The PTC rotates around the horizontal N-S axis and a single axis tracking is adopted in the E-W direction to track the sun to obtain the maximum energy incidence. The technical specifications of the prototype PTC are tabulated and given in Table 1.

The performance analysis of the existing PTC is carried out by considering its aperture width W_a, length L and rim angle ϕ_r (Fig. 1). The absorber tube has an inner diameter D_i and an outer diameter D_o and it has a concentric glass cover inner diameter D_{ci} and outer diameter D_{co} around it. The HTF being heated in the collector has a mass flow rate $\dot{m}$ a specific heat C_p, an inlet temperature T_{fi} and an outlet temperature T_{fo}. For a particular set of HTF inlet temperatures under constant insolation, the corresponding HTF outlet temperatures, the heat gained by the HTF and

Table 1: PTC specifications

Specification	Values
Collector aperture area (A_a)	7.5 m^2
Concentrator length (L)	3.00 m
Concentrator aperture (W_a)	2.5 m
Rim angle (ϕ_r)	65°
Tracking mechanism	Mechanical (semi automatic)
Collector material	6 mm thick Saint Gobain glass
Absorber tube material	Stainless Steel
Reflectivity of the reflecting surface (ρ)	0.90
Absorptivity of the absorber (α)	0.90
Emissivity of the absorber (ϵ)	0.90
Overall heat loss coefficient from the absorber (U_l)	8.0 W/m^2 K
Stefan Boltzmann constant (σ)	5.67×10^{-8} W/m^2 K^4

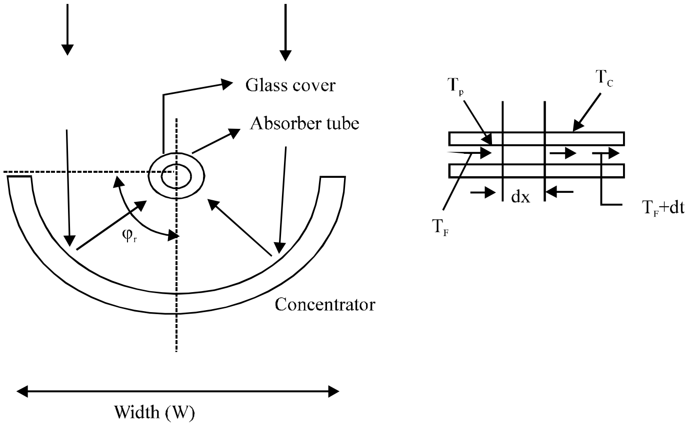

Fig. 1: Cross sectional view of the PTC

the efficiency of the PTC were obtained. The graphs are plotted for the above parameters by varying the mass flow rate, the heat removal factor of the fluid, the solar insolation and the concentration ratio. The efficiency of the PTC is also obtained for different HTFs.

The concentration ratio of the collector is given by Eq. 1:

$$C = \frac{\text{Effective aperture area}}{\text{Absorber tube area}} = \frac{(W - D_o)}{\pi D_o} \quad (1)$$

The performance analysis of the PTC is, in many respects, similar to the analysis of a liquid flat-plate collector. Figure 1 shows the elementary slice dx of the absorber tube, at a distance x from the inlet. The steady state Eq. 2 describes the energy balance of an elementary slice dx:

$$dq_u = [I_b r_b (W - D_o) \rho\gamma(\tau\alpha)_b + I_b r_b D_o (\tau\alpha)_b - U_l \pi D_o (T_p - T_a)]dx \quad (2)$$

Where:

dq_u = Useful heat gain rate for a length dx
ρ = Specular reflectivity of the concentrator surface
γ = Intercept factor
$(\tau\alpha)_b$ = Average value of the transmissivity - absorptivity product for beam radiation
U_l = Overall loss coefficient
T_p = Local temperature of the absorber tube
T_a = Ambient temperature

The first term on the right hand side in Eq. (2) represents the incident beam radiation absorbed in the absorber tube after reflection and the second term represents the absorbed incident beam radiation which falls directly on the absorber tube. The second term is small in comparison with the first, but cannot be ignored when the concentration ratio is small. The third term represents the loss by convection and reradiation.

The absorbed solar flux S is given in Eq. 3:

$$S = I_b r_b \rho \gamma \left(\tau\alpha\right)_b + I_b r_b \left(\tau\alpha\right)_b \left(\frac{D_o}{W - D_o}\right) \tag{3}$$

The substitution of Eq. 3 in 2 gives the expression for useful heat gain rate for a length dx, as given in Eq. 4:

$$dq_u = \left[S - \frac{U_l}{C}\left(T_p - Ta\right)\right]\left(W - D_o\right)dx \tag{4}$$

The useful heat gain rate, dq_u can also be written as:

$$dq_u = h_f \pi D_i (T_p - T_f)dx \tag{5}$$

$$dq_u = \dot{m} C_p dT_f \tag{6}$$

Where:

h_f = heat transfer coefficient on the inside surface of the tube
T_f = local fluid temperature

The useful heat gain rate Eq. 7 is obtained by combining Eq. 4 and 5, so as to eliminate the absorber tube temperature T_p:

$$dq_u = F'\left[S - \frac{U_l}{C}(T_f - T_a)\right](W - D_0)dx \tag{7}$$

where, F' is the collector efficiency factor, given in Eq. 8:

$$F' = \frac{1}{U_l\left[\frac{1}{U_l} + \frac{D_o}{D_i hf}\right]} \tag{8}$$

Equation 9 is obtained by the combination of Eq. 6 and 7:

$$\frac{dT_f}{dx} = \frac{F'\pi D_0 U_l}{\dot{m}C_P}\left[\frac{CS}{U_l} - \left(Tf - Ta\right)\right] \tag{9}$$

Equation 10 is formed by integrating and using the inlet condition at $x = 0$, $T_f = T_{fi}$ in Eq. 9:

$$\frac{\left(\frac{CS}{U_l} + T_a\right) - T_f}{\left(\frac{CS}{U_l} + T_a\right) - T_{fi}} = \exp\left\{-\frac{F'\pi D_o U_l x}{\dot{m}C_p}\right\} \tag{10}$$

Equation 11 is formed by substituting $T_f = T_{fo}$ and $x = L$ in Eq. 10 and then subtracting both sides of the resulting equation from unity:

$$\frac{\left(T_{fo} - T_{fi}\right)}{\frac{CS}{U_l} + T_a - T_{fi}} = 1 - \exp\left\{-\frac{F'\pi D_o U_l L}{\dot{m}C_p}\right\} \tag{11}$$

Thus, the useful heat gain rate is given in Eq. 12:

$$q_u = \dot{m}C_p(T_{fo} - T_{fi}) \tag{12}$$

Equation 13 is obtained by introducing Eq. 11 in Eq. 12:

$$q_u = \dot{m}C_p\left[\frac{CS}{U_l} + T_a - T_{fi}\right]\left[1 - \exp\left\{-\frac{F'\pi D_o U_l L}{\dot{m}C_p}\right\}\right] \tag{13}$$

Equation 14 is obtained by introducing a heat removal factor in Eq. 13:

$$q_u = F_R(W - D_o)L\left[S - \frac{U_l}{C}(T_{fi} - T_a)\right] \tag{14}$$

where F_R is the heat removal factor, given in Eq. 15:

$$F_R = \frac{\dot{m}C_p}{\pi D_o U_l L}\left[1-\exp\left\{\frac{F'\pi D_o U_l L}{\dot{m}C_P}\right\}\right] \qquad (15)$$

Equation 15 is the equivalent of the Hottel-Whillier-Bliss equation for a flat-plate collector.

The instantaneous collector efficiency(η_i) is given in Eq. 16:

$$\eta_i = \frac{q_u}{\left(I_b r_b + I_d r_d\right)WL} \qquad (16)$$

The instantaneous efficiency (η_{ib}) as shown in Eq. 17 is also calculated on the basis of the beam radiation by neglecting the ground reflected radiation, in which case:

$$\eta_{ib} = \frac{q_u}{I_b r_b WL} \qquad (17)$$

The efficiency of the collector (η) with respect to the concentration ratio is given by Eq. 18:

$$\eta = F_R\left(\eta_o - \frac{U_l(T_i - T_a)}{I \times C}\right) \qquad (18)$$

RESULTS AND DISCUSSION

In order to have a numerical appreciation of the results, the PTC parameters given in Table 1 are utilized to determine the thermal behavior of the prototype PTC. The effect of the mass flow rate, the efficiency, the useful energy, the concentration ratio of the collector and the heat removal factor are studied and the results are discussed.

When the HTF inlet temperature increases, the temperature of the absorber tube surface also increases. As a result, the losses due to radiation and convection to the surroundings also increase, resulting in a decrease in efficiency. It is clear from Fig. 2a that the value of efficiency for various mass flow rates decreases significantly with the HTF inlet temperature. This is due to the less heat transfer coefficient for a less mass flow rate and thus, the efficiency of the collector is also less.

The efficiency of the PTC for different heat transfer fluids is calculated and plotted in Fig. 2b. When the inlet temperature of the HTF increases, the efficiency of the PTC decreases. This is due to the less useful heat gain from the PTC. The useful heat gain from the collector is the maximum, when water is used as the HTF. The efficiency of the PTC is less when castor oil is used as the HTF. This is due to water having more specific heat than castor oil that reflects in the PTC efficiency variation.

The energy of the solar insolation value reaching the earth's surface varies from place to place and also from time to time. The useful heat gain of the HTF is evaluated for various solar insolation values and depicted in Fig. 2c. It is seen that as the solar insolation increases, the useful heat gained by the HTF also increases. Figure 2d shows the variation of the useful heat energy with the

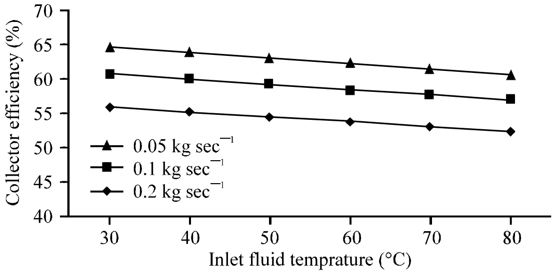

Fig. 2a: Efficiency vs. inlet fluid temperature for various mass flow rates

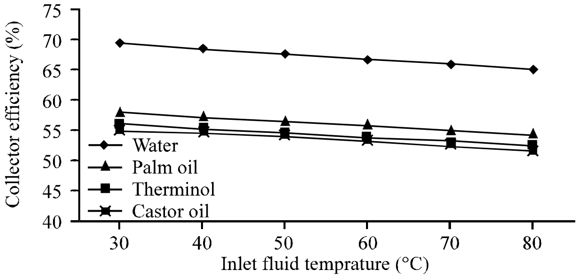

Fig. 2b: Efficiency vs. inlet fluid temperature for various heat transfer fluids

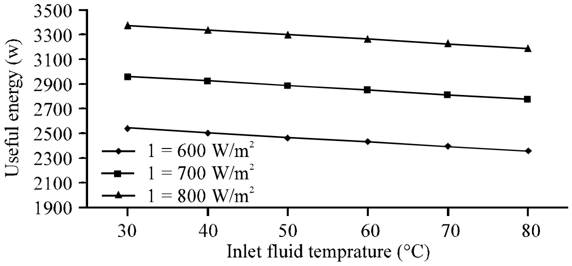

Fig. 2c: Useful energy vs. inlet fluid temperature for various solar insolation values

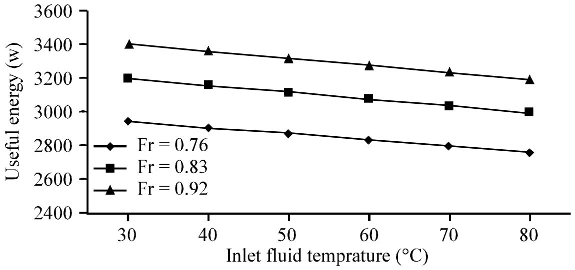

Fig. 2d: Useful energy vs. inlet fluid temperature for various heat removal factors

the heat removal factor increases (this can be achieved by increasing the mass flow rate) the useful energy gained by the collector also increases.

The effect of increasing the concentration ratio by decreasing the size of the absorber tube is shown in Fig. 2e. It is evident that the useful energy increases as the concentration ratio increases. This is because when the concentration ratio is high, the losses from the PTC absorber tube decrease and thus the collection of useful energy increases.

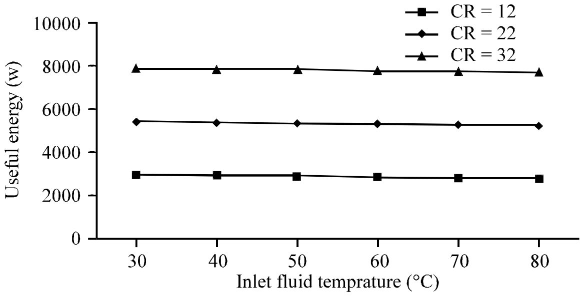

Fig. 2e: Useful energy vs. inlet fluid temperature for various concentration ratios

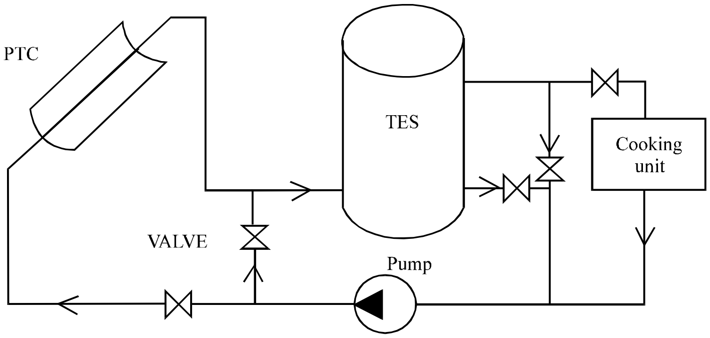

Fig. 3: Proposed experimental setup

In the proposed work, the solar cooking system using D-Mannitol as the phase change storage medium (Kumaresan *et al.*, 2011) is under investigation and Fig. 3 shows the planned setup of the test field. This system consists of a PTC, Thermal Energy Storage (TES) tank and the cooking unit which is kept inside the room. Therminol 55 is considered as the HTF to transfer the heat between the PTC and the indoor cooking unit. The PTC provides heated oil to the TES tank. The stored heat thus could be retrieved by the HTF, even during off sunshine hours. The PTC considered in the proposed study is designed and fabricated, based on the local available technologies and raw materials in Chennai, India.

CONCLUSION

The aim of the proposed work is to present a novel system, in which the solar parabolic trough collector has been introduced to the thermal energy storage system, integrated with a residential type cooking unit. For this purpose the thermal analysis of the available PTC by considering the mass flow rate, efficiency, useful energy, the concentration ratio of the collector and the heat removal factor are theoretically studied and the results are presented in this proposed work. The results showed that most of the performance parameters, such as thermal efficiency and useful heat gain rate increase as the solar insolation increases. The thermal efficiency of the PTC is also found to increase when the mass flow rate and concentration ratio increase for a given value of the solar intensity. The system performance is compared for different heat transfer fluids. These theoretical results are well considered as input parameters for further development of the experimental work.

NOMENCLATURE

C_P : Specific heat of fluid (J kg^{-1} K^{-1})
I : Solar intensity (W m^{-2})
S : Absorbed solar flux (W m^{-2})
m : Mass flow rate of fluid (kg sec^{-1})
Q : Useful heat gain (W)
T : Temperature (°C)
U_l : Overall loss coefficient (W K^{-1} m^{-2})
E_o : Energy output (W)
k : Thermal conductivity (W K^{-1} m^{-1})
W : Width of collector (m)
L : Length of collector (m)
D : Diameter (m)
F_R : Heat removal factor
F' : Efficiency factor
Re : Reynolds number
Pr : Prandtl number
C : Concentration ratio

Greek letters:

α : Absorptivity
E : Emissivity
H : Efficiency
P : Reflectivity
σ : Stefan's Constant
γ : Intercept Factor

Subscripts:

a : Ambient
I : Inlet
u : Useful
b : Beam radiation
d : Diffuse radiation
o : Outlet
f : Fluid
m : Mean

REFERENCES

Andoh, H.Y., P. Gbaha, P.M.E. Koffi, S. Toure and G. Ado, 2007. Experimental study on the comparative thermal performance of a solar collector using coconut coir over the glass-wool thermal insulation for water heating system. J. Applied Sci., 7: 3187-3197.

Arasu, A.V. and T. Sornakumar, 2007. Design, manufacture and testing of fibreglass reinforced parabolic trough solar collectors. Solar Energy, 81: 1273-1279.

Brooks, M.J., I . Mills and T.M. Harms, 2006. Performance of a parabolic trough solar collector. J. Energy Southern Africa, 17: 71-80.

Chattopadhyay, A.B., A. Choudhury and A. Nargund, 2011. State variable model of a solar power system. Trends Applied Sci. Res., 6: 563-579.

Efurumibe, E.L., A.D. Asiegbu and M.U. Onuu, 2012. Mathematical modelling of electron transport through the anode (TiO_2) of a standard dye-sensitized solar cell. Asian J. Appl. Sci., 5 : 33-42.

Fernandez-Garcia, A., E. Zarza, L. Valenzuela and M. Perez, 2010. Parabolic-trough solar collectors and their applications. Renewable Sustainable Energy Rev., 14: 1695-1721.

Kalogirou, S., 1996. Parabolic trough collector system for low temperature steam generation: Design and performance characteristics. Applied Energy, 55: 1-19.

Kalogirou, S.A., S. Lloyd, J. Ward and P. Eleftheriou, 1994. Design and performance characteristics of a parabolic-trough solar-collector system. Applied Energy, 47: 341-354.

Kalogirou, S.A., 2002. Parabolic trough collectors for industrial process heat in Cyprus. Energy, 27: 813-830.

Kalogirou, S.A., 2004. Solar thermal collectors and applications. Prog. Energy Combust. Sci., 30: 231-295.

Khatib, T.T.N., A. Mohamed, R.J. Khan and N. Amin, 2009. A novel active sun tracking controller for photovoltaic panels. J. Applied Sci., 9: 4050-4055.

Kruger, D., Y. Pandian, K. Hennecke and M. Schmitz, 2008. Parabolic trough collector testing in the frame of the REACt project. Desalination, 220: 612-618.

Kumaresan, G., R. Velraj and S. Iniyan, 2011. Thermal analysis of D-mannitol for use as phase change material for latent heat storage. J. Applied Sci., 11: 3044-3048.

Laing, D., W.D. Steinmann, R. Tamme and C. Richter, 2006. Solid media thermal storage for parabolic trough power plants. Solar energy, 80: 1283-1289.

Lupfert, E., K. Pottler, S. Ulmer, K.J. Riffelmann, A. Neumann and B. Schiricke, 2007. Parabolic trough optical performance analysis techniques. J. Solar Energy Eng., 129: 147-152.

Odeh, S., S. Nijmeh, M. Ashhab, Y. Zakaria and A. Amra, 2004. Design of a single-axis tracking parabolic collector for moderate temperature applications. EuroSun, 1: 527-532.

Odeh, S.D. and G.L. Morrison, 2005. Optimization of parabolic trough solar collector system. Int. J. Energy Res., 30: 259-271.

Safari, B. and J. Gasore, 2009. Estimation of global solar radiation in Rwanda using empirical models. Asian J. Scientific Res., 2: 68-75.

Sreejaya, K.V., Hussain H. Al-Kayiem and Syed Ihtsham Ul-Haq Gilani, 2011. Analytical analysis of roof top solar chimney for power generation. J. Applied Sci., 11: 1741-1748.