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Performance of Closed Cylindrical Parabolic Trough Collector for Solar Thermal Application

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P A P E R I N F O

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A B S T R A C T

A Cylindrical parabolic trough (CPT) collector of aperture width 1.03 m and length of 1.82m was designed and fabricated. CPT was covered with glass of thickness of 3 mm to avoid convective heat loss. Reflector coated with polished aluminum sheet having reflectivity 0.87 and receiver tube made of mild steelcoated with black zinc having absorptivity of 0.94 were used for CPT. mass flow rate of working fluid was 4 l/h. Thermal performance of CPT collector was tested according to ASHRAE Standardmethods. Average instantaneous efficiency of closed cylindrical parabolic trough collector system was found to be 66%. The overall efficiency of CPT system is 71% which is best suited for solar thermal applications.

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NOMENCLATURE

CR	Concentration ratio
CR_g	Geometric concentration ratio
W	Aperture Width (m)
L	Length of Trough (m)
Do	Outer diameter of absorber tube (m)
S	Absorbed solar radiation
Ib	Incident beam solar radiation (W/m^2)
Rb	Tilt Factor
(τα)b	Transmittance-absorbance factor of beam radiation
Qu	Useful heat gain (W)
Fr	Heat removal factor
F’	Collector efficiency factor
Ul	Heat loss (W/m^{2}K)
m	Mass flow rate
T_{fi}	Water inlet temperature(ºC)
To	Water outlet temperature (ºC)
Tpm	Mean receiver tube temperature (ºC)
Ta	Atmospheric temperature (ºC)
η_i	Instantaneous efficiency
η_o	Overall efficiency
R^2	Root mean square value

INTRODUCTION

Rapidly growing industrialization, urban development has resulted in higher rate of electricity consumption all over the world, which created a huge demand of energy. The use of non-renewable sources of energy like coal, natural gas, petroleum products etc. are major contributors towards electricity generation. A power plant based on non-renewable energy sources creates air pollution, global warming and human health problems. Non-renewable energy sources are limited, and may not support the process of sustainable development. Thus, there is need to identify and utilize the renewable energy sources, which satisfy the energy demand without creating environmental problems.Renewable energy sources include solar, wind, biomass, ocean energy etc., which can be harnessed by developing technology for generation of power and electricity. The solar energy is a clean, abundantand inexhaustible source of energy. Sun generates huge amount of energy at the rate of 3.8 x 10^{23} kW in the form of radiation out of which earth intercepts only 1.8 x 10^{14} kW very small fraction of it, which is many thousands times larger than present consumption rate of commercial energy sources all over theearth [1].

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Thus, solar energy is apromising energy resource to be utilized directly or indirectly for generating electricity and power.

Hot water is the primary requirement for industrial process heat, domestic and other applications. Electrical equipment's used for water heating consumes huge amount of electricity. Solar energy can be used for water heating purpose. Solar power technology is mainly divided in to two types i.e. flat plate collectors and concentrating collectors. Flat collectors have plain surface area mostly used for producing hot air and water for domestic and small scale industrial purpose. High initial cost and less efficiency is the main disadvantage of flat plate collector system. Concentrating collectors can generate high temperature water or steam more efficiently. Among the various concentrating collectors such as parabolic dish, linear Fresnel, compound parabolic, solar towers; parabolic troughs collectors were found to be more suitable than others and have wide range applications in power plant technology for producing power and electricity.

Concentrating solar power technologies consist of arrays of parabolic troughs, which concentrates solar radiation at a point or line. The absorbed heat isutilized to generate hot waterindustrial process heat or for domestic consumption and other applications.

Cylindrical parabolic troughs (CPT) are line focusing devicesuses curved mirrors or reflectors in desired shape to focus sunlight on receiver tube lies on focus of parabolic profile. Heat transfer fluid or working fluid is then passed through receiver tube. CPT absorbs only direct beam radiations so tracking system is very important to keep solar radiation exactly perpendicular to surface of trough. This paper evaluate thermal performance of prototype CPT fabricated using two different reflecting material and tested in Indian climatic conditions to produce hot water.

Price et al. [2]have reviewed current status and research and development activities taken towards enhancement in the performance of parabolic trough technology. This paper focus on the improvement in trough design, support structure, reflector, receiver, heat transfer fluid and storage, operation and maintenance and plant economics. Parabolic trough technology can compete with conventional power plant technology but there is need to reduce of overall cost and efficiency of project [2].

Rongrong et al. [3] have developed a dynamic model of parabolic trough collector considering oil as heat transfer fluid bysimple Euler transformation method. Main objective of the work was to study heat transfer analysis between glass cover, receiver tube and heat transfer oil under variable conditions and altering system parameters over a period of time. Real operating plant data of SEGS-VI collected during summer and spring days was used to validate this mathematical model. This dynamic model can be used for forecastingperformance of parabolic trough power plant under varying atmospheric and working conditions [3].

A computation program was written by Sangotayo et al [4] in C++ language to investigate the heat transfer phenomenon in absorber tube of cylindrical parabolic solar collector in Ogbomosho climatic conditions. Different heat transfer fluids, twisted tape of ratio and various system parameters were considered to study the effect of on performance of trough. It was observed that oil has high heat transfer capacity, twisted tape increases the friction factor causes enhanced heat transfer with instantaneous efficiency of 47.38% [4].

Mokhtari et al. [5] observed that in the process of designing and installation of parabolic collectors requires about half of the cost of power plant. So there is need to optimize the various parameters of parabolic collectors like concentration ratio, rim angle, length of collector, mass flow rate of heat transfer fluid etc.to achieve highest efficiency with least cost. A computer code was written in MATLAB to obtain economic performance of collector and same code was used to predict performance collectors manufactured by Luz Company. An energy cost analysis was performed to study the competitiveness of solar power plant with the conventional power plants. Optimization shows that the overall performance in terms of economy was strongly depend on various input parameters and properly controlled parameter can give best thermal performance of solar collectors [5].

Kinyua et al. [6] have fabricated a roof top parabolic trough for steam production. Three different reflector materials were selected and thermal performance of trough was evaluated with and without glass cover. Maximum temperature obtained by this system was 248.3°C with an average value of steam was 150°C. It was observed that trough covered with glass yields 50 to 55% efficiency which is 20% more as compared to trough without glass cover further efficiency can be enhanced by installing automatic tracking system [6].

Parabolic trough collector of two plate plate's type was tested for air heating. Thermal analysis of trough was performed on data collected for three days form morning 10AM to 5PM at different mass flow rate of air. Trough manufactured by locally available material can generate hot air up to 97^{0}C with 65%. This system was found to be most suitable for household and industrialdrying purpose in middle and northern part of Nigeria where abundant solar radiations are available [7].

Thermal performance of parabolic trough collectors can be further improved by direct steam generation using water as working fluid instead of oil. Odeh et al. [8] developed a mathematical model to evaluate thermal loss through parabolic trough using Syltherm 800 oil as heat transfer fluid at Sandia national laboratory. This model considers absorber tube temperature rather than working fluid temperature so this model is applicable to all type of working fluids. Water was used for direct steam generation and it is observed that heat losses incase of oil are more than water, other factor such as mass flow rate, inlet water temperature, radiation level etc. affects thermal performance of trough were optimized using designed simulation model [8].

Arasu et al. [9] has fabricated parabolic trough collector with well mixed hot water storage system for hot water generation. As water was circulated in close loop system, no heat was withdrawn from system. Maximum water temperature was 73.84^{0}C at an average beam radiation of 699 W/m^2. All the performance parameters such as outlet water temperature, storage tank water temperature, useful heat gain, instantaneous efficiency was strongly depend on incident beam radiations and follows its variations [9] further same authors developed a computer simulation program to compare theoretical and experimental performance of parabolic collectors in closed loop water circulation system. There was only 10% variation in the theoretical and actual performance due to heat losses from receiver, collector that were not considered by computer simulation program [10].

The main problem associated with the use of parabolic trough technology is the high capital cost of project and low efficiency. This work represents a step taken towards utilization of CPT for hot water generation with least manufacturing cost using locally sourced material and an attempt has been made to improve thermal efficiency of plant by covering whole trough with glass cover to reduce convective heatloss.

Material and design of CPT collector system

Concentration ratio is an important parameter which determines the amount of solar energy concentrated by CPT out of available radiation. Geometric concentration ratio is defined as the ratio of area of aperture to the surface area of receiver tube [11]. Highest concentration ratio was achieved by adjusting receiver tube inside the trough. As the tube comes inside the CPT it can be easily covered with glass cover to reduce heat loss.

$$CR_g = \frac{A_a}{A_r} \quad (1)$$

$$CR = \frac{(W - D_0)L}{\pi D_0 L} \quad (2)$$

$$CR = \frac{(1030 - 19)}{\pi * 19}$$

$$\underline{CR = \ 16.94 \sim 17}$$

CPT collector system has major component viz. reflector, receiver, support structure, working fluid circulation system and tracking system. Manual tracking system was adopted in this project to reduce overall cost. The CPT rotates around the horizontal N-S (North/South) axis to track the Sun. The axis of rotation is located at focal line. Reflector was coated with polished aluminium sheet (0.18 mm thickness) having reflectivity of 0.87. Receiver tube of mild steel was coated with black zinc having absorptivity of 0.94. Thin layer of coating was applied so as to minimize the resistance of flow of heat through the coat to the pipe and to the working fluid. Support structure builded using steel to provide strong mechanical support during high wind speed and harsh environmental conditions. The aperture width (1.03 m) and outer diameter of receiver tube (19 mm) are decided based on available size of reflector sheet and receiver tube. Parabola calculator 2.0 a freeware program available to calculate aperture area, focal length, exact location on receiver tube and depth of parabolic trough. Table 1 contains all the dimensional specifications of CPT and other parameters calculated by above formula and parabola calculator 2 software. Figure 1 shows parabola calculator.

TABLE1. Specifications of CPT Collector

Parameter	Value / Dimensions
Concentration ratio	17
Focal distance	221 mm
Rim angle	134.52^0
Collector area	1.87 m^2
Length of receiver tube	1.82 m
Aperture Width	1.03 m
Aperture Depth	1.82 m
Receiver tube inner diameter	17 mm
Receiver tube inner thickness	2 mm
Glass cover thickness	3 mm
Reflectivity of polished aluminium sheet	0.87
Absorptivity of black zinc on receiver tube	0.94
Storage water tank capacity	100 litres

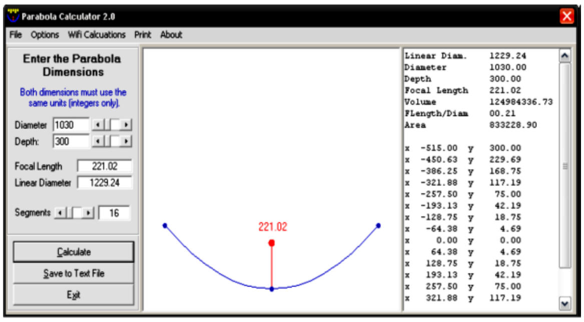

Figure 1. Display of parabola calculator 2.0

Instrumentation and Experimental setup

Experimental setup and data collection equipment's are shown in above Figure2. Experimental setup consist of storage water tank of 100 litres capacity kept at 6 feet above from ground to maintain natural flow of working fluid (Water) inside CPT. Mass flow rate of waterwas measured by Rotameter. Receiver tube located inside trough and full trough is covered with glass. Storage tank and tube containing working fluid are well insulated with asbestos to avoid heat loss and inward heat flow in cold water storage tank to evaluate actual performance of trough.

Mass flow rate of water and inlet water temperature was kept intentionally kept constant at 4 liters/h. and 26ºC respectively to observe highest temperature that can be achieved at outlet of trough.

Data logger with display system consist of k type thermocouples to collect temperature at various locations ex. inlet, outlet and on five different points receiver tube, glass cover etc. at fixed interval of time. Wind anemometer is used to measure wind speed and Pyranometer for measuring global radiation, beam radiation was calculated manually.

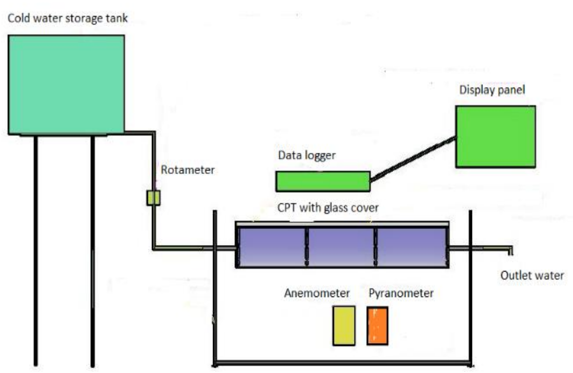

Figure 2. Experimental setup for evaluation of thermal performance

Thermal performance evaluation of CPT collector

Various parameters like beam radiation, wind speed, atmospheric temperature, Mean receiver tube temperature, outlet water temperature, temperature of glass cover and reflector were collected in month of May form morning 10 AM to 4 PM for three days at Shivaji university, Kolhapur, M.H. India (Latitude: 16.42° N, Longitude: 74.13°W).

Thermal performance of CPT was evaluated by the detail procedure explained in book 'Solar energy: principles of thermal collection and storage' [12]. Useful heat gain, heat loss factor, instantaneous and overall efficiency of CPT was evaluated based on experimental data as follows,

Absorbed solar radiation can be calculated by

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

The useful gain by CPT,

$$Q_u = Fr(W - Do) * L * \left[S - \frac{U_l}{C}(T_{fi} - T_a)\right] \quad (4)$$

Following equation used to calculate heat removal factor, equivalent to 'Hotel-Whillier-Bliss' equation for the flat plate collector.

$$Fr = \frac{\dot{m} * Cp}{\pi * Do * U_l * L}\left[1 - e^{-\left\{\frac{F' * \pi * Do * U_l * L}{\dot{m} * Cp}\right\}}\right] \quad (5)$$

where, F' is the collector efficiency factor and U_l is heat loss

$$F' = \frac{1}{U_l\left[\frac{1}{U_l} + \frac{1Do}{Di * h_f}\right]} \quad (6)$$

$$U_l = \frac{q_t/A_{abs}}{(T_{pm} - T_a)} \quad (7)$$

The Instantaneous efficiency determined after every one hour on the basis of beam radiation alone, neglecting radiations reflected from ground

$$\eta_i = \frac{Q_u}{I_b * r_b * W * L} \quad (8)$$

Overall efficiency of the CPT collector system can be determined by,

$$\eta_o = \frac{S}{I_b * r_b} * \frac{(W - Do)}{W} \quad (9)$$

RESULTS AND DISCUSSION

ASHRAE Standard methods [12] were used to evaluate thermal performance of CPT collector. Following graphs are plotted to establish the relationship between various parameter and effect on performance.

Figure 3 shows the beam radiation available for three days over time of day from 10 AM to 4 PM. Beam radiation increases as day passes from morning to noon and gradually reduces after 3PM. Beam radiation available in the range of 300 to 1100 W/m^{2}for all three days. Sudden fall in beam radiation at 12 PM for day first is because of presence of clouds.

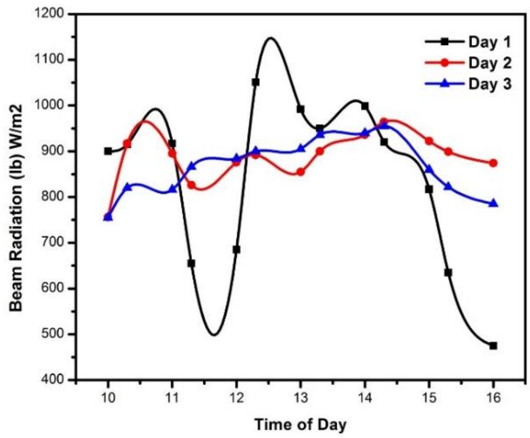

Figure 3. Time of day vs. Incident beam radiation for all three days

Figure 4 shows the effect of beam radiation on receiver outlet temperature of water for all three days. It is observed that as beam radiation increases from 300 W/m^2 to 1100 W/m^2, outlet temperature of water also increases linearly in the range of 42 to 64^{o}C. For day first and second there is fall of temperature at some point may due to increase in heat loss.

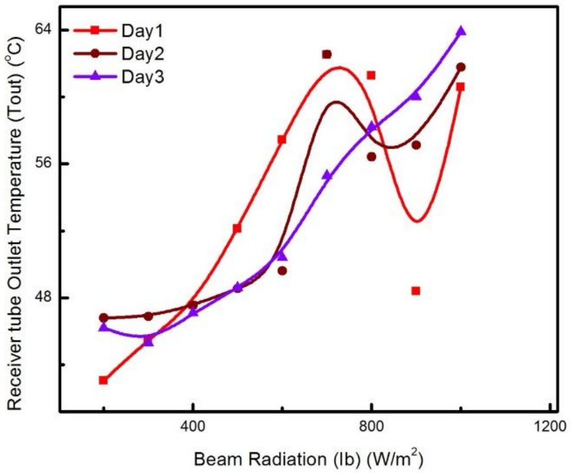

Figure 4. Incident beam radiation vs. Receiver tube outlet temperature for all three days

Wind speed adversely affects the outlet temperature of water. Convective heat transfer increases from receiver tube to glass cover and glass cove to atmosphere as wind speed increases. Average wind speed for three days is plotted along X axis and Outlet temperature on Y axis. Outlet water temperature falls as wind speed increases as shown in Figure5.

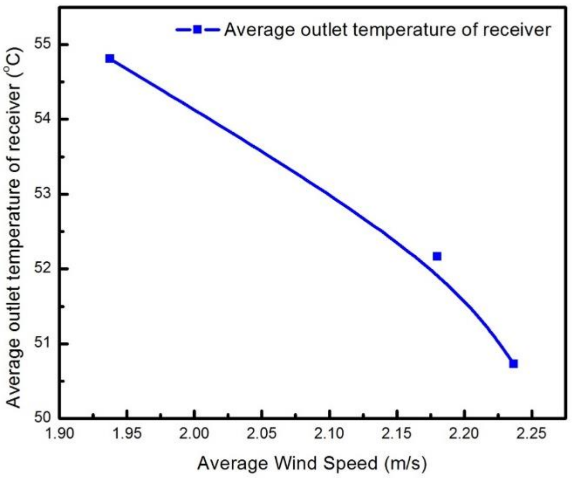

Figure 5. Average wind speed vs. Average receiver tube outlet temperature for all three days

Figure 6 establishes a relationship between glass cover temperature and mean receiver tube temperature and outlet temperature of water over day1. It was observed that during morning all radiation were readily absorbed by receiver tube so mean tube temperature and outlet water temperature increases at minimum heat loss. During noon but there is loss of heat by convection so glass cover temperature increases to 45.5^{o}C there is decrease in both mean tube temperature and outlet temperature to 45 and 42.5^{o}C, respectively, similarly this phenomenon was observed at 3 PM.

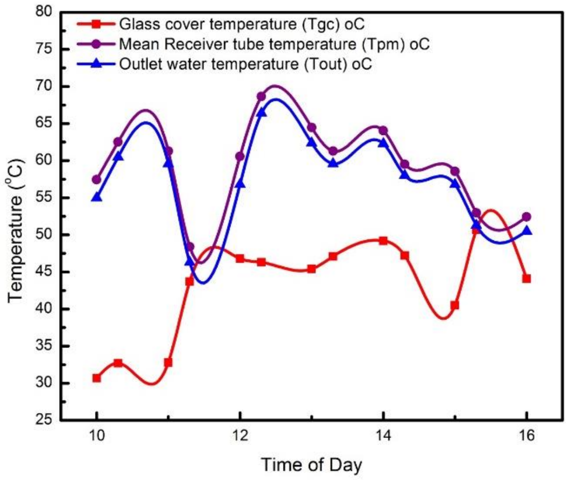

Figure 6. Time of day vs. various temperatures for day1

Effect of useful heat gain and heat loss on outlet water temperature over a day 1 was is shown in Figure7. Useful heat gain supports rise in outlet water temperature but heat loss reduces outlet temperature. At evening time heat loss is more than heat gain so there is drop in outlet water temperature as compared to noon.

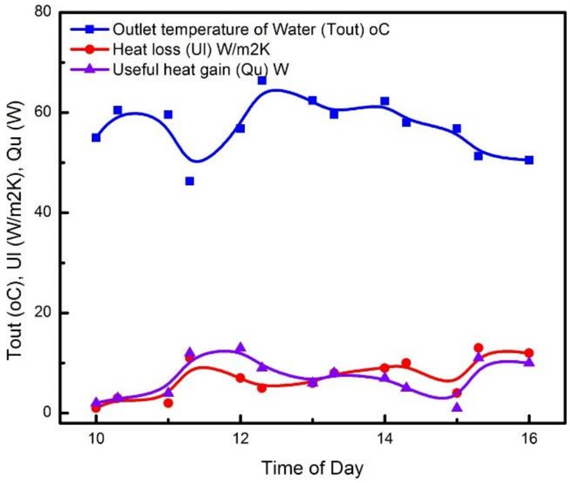

Figure 7. Time of day vs. receiver tube outlet temperatures, useful heat gain, and heat loss for day1

Performance of CPT was observed to be better on day 2 as shown in Figures 8 and 9. Glass cover temperature falls to 25 to 30^{o}C nearly atmospheric due to maximum absorption of beam radiation, increase in useful heat gain and minimum heat loss. From 8.30AM up to 3PM outlet temperature of water increases uniformly.

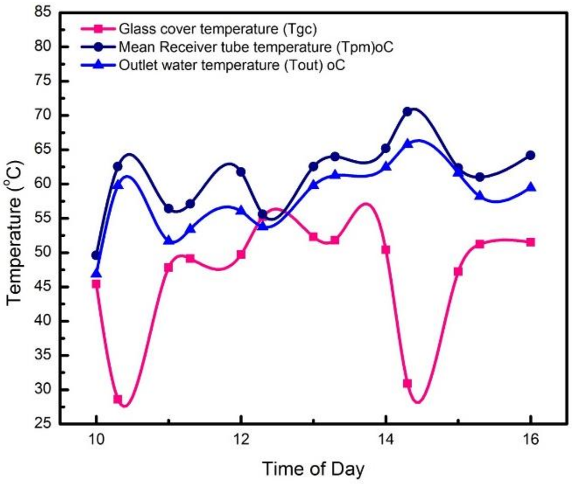

Figure 8. Time of day vs. various temperatures for day 2

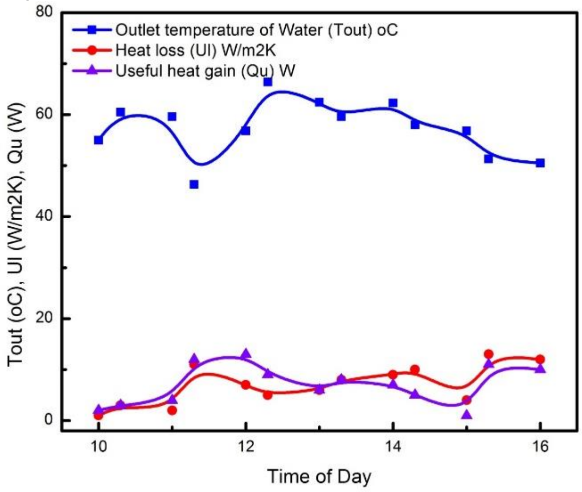

Figure 9. Time of day vs. various temperatures for day3

Heat loss phenomenon was more in day3 during morning and evening of day3 as shown in Figures 10 and 11. Higher wind speed is another reason of convective heat loss, though CPT is covered with glass but it was not evacuated. So there is chance of convective heat loss and transfer of heat form receiver tube to glass cover so fall in outlet water temperature but there is constant increase in mean tube temperature and outlet temperature from 10AM to 2PM.

Regression equations and root mean square value that establishes relation between various parameters were developed based on above graphs and experimental data are given as follows

(Average for all three days)

Beam radiation (x) and Outlet temperature of water (y)
$y=0.0214x+36.458R^2 = 0.2767$

Mean receiver tube temperature (x) and Outlet temperature of water (y)
$y=0.4989x+25.481R^2 = 0.4791$

Atmospheric temperature (x) and Outlet temperature of water (y)
$y=0.3415x+41.85R^2 = 0.3603$

Wind speed (x) and Outlet temperature of water (y)
$y=-12.817x+79.713R^2 = 0.9696$

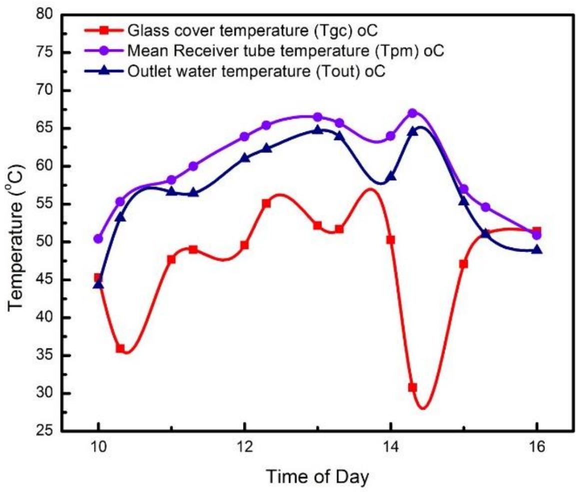

Figure 10. Time of day vs. receiver tube outlet temperatures, useful heat gain, and heat loss for day3

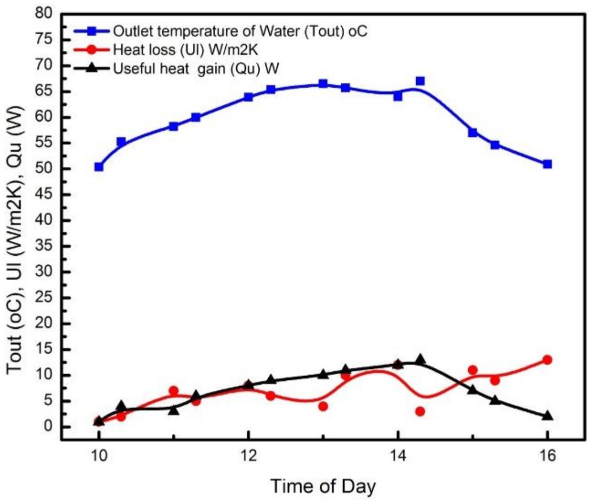

Figure 11. Time of day vs. receiver tube outlet temperatures, useful heat gain, and heat loss for day3

CONCLUSION

To meet the energy requirement for sustainable development without disturbing environment, technology has to be developed to harness energy from renewable energy sources.This paper deals with the design and fabrication of a closed cylindrical parabolic trough to use solar energy for generation of hot water suited for domestic and industrial process heat application.

The data was collected after every half an hour from morning 10 AM to 4 PM for three days and performance is evaluated as per ASHRAE Standard methods of testing [12]. From experimentation and thermal performance evaluation following conclusion were drawn

i. Incident beam radiation is very important parameter which directly affect the performance of CPT.
ii. During testing it was observed that increase in wind speed adversely affect outlet temperature of water.
iii. This CPT collector generates hot water at from 41to 66ºC.
iv. Glass cover helps in reduction convective heat loss and increases useful heat gain, further enhances efficiency of CPT collector.
v. Average Instantaneous efficiencyand overall efficiency of this prototype CPT was found to be 66 and 71%, respectively.

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REFERENCES

1. Goswami, D.Y., The CRC handbook of mechanical engineering2004: CRC press.
2. Price, H., E. Lupfert, D. Kearney, E. Zarza, G. Cohen, R. Gee and R. Mahoney, 2002. Advances in parabolic trough solar power technology. Journal of solar energy engineering, 124(2): 109-125.
3. Rongrong, Z., Y. Yongping, Y. Qin and Z. Yong, 2013. Modeling and characteristic analysis of a solar parabolic trough system: thermal oil as the heat transfer fluid. Journal of Renewable Energy, 2013.
4. Sangotayo, E.O. and M.A. Waheed, Parametric Study of Heat Characteristics of Fluid in Cylindrical Parabolic Concentrating Solar Collector.
5. Mokhtari, A. and M. Yaghoubi. *Thermo-Economic Design of a Parabolic Solar Collector*. in *Proceedings of the Middle East Mechanical Engineering Conference MEMEC*. 2007.
6. Kawira, M., R. Kinyua and J. Kamau, 2012. A prototype parabolic trough solar concentrators for steam production. JAGST, 14: 90-103.
7. Nasir, A., 2004. Design, construction and experimental study of the thermal performance of a parabolic cylindrical trough solar air heater. AU Journal of Technology, 8(1): 21-26.
8. Odeh, S., G. Morrison and M. Behnia, 1998. Modelling of parabolic trough direct steam generation solar collectors. Solar energy, 62(6): 395-406.
9. Arasu, A.V. and T. Sornakumar, 2008. Life cycle cost analysis of new FRP based solar parabolic trough collector hot water generation system. Journal of Zhejiang University SCIENCE A, 9(3): 416-422.
10. Valan-Arasu, A. and T.S. Sornakumar, 2007. Theoretical analysis and experimental verification of Parabolic trough solar collector with hot water Generation system. Thermal Science, 11(1): 119-126.
11. Geyer, M. and W.B. Stine, 2001. Power from the Sun (Powerfromthesun. net). JT Lyle Center.
12. Standard, A., 1977. Methods of testing to determine the thermal performance of solar collectors. ANSI/ASHRAE: 93-1986.

Persian Abstract

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چکیده

یک جمع‌کننده استوانه‌ای سهموی (CPT) با عرض منفذ ۱/۰۳ و طول ۱/۸۲ متر طراحی و ساخته شد. بر روی این وسیله لایه‌ای از شیشه با ضخامت ۳ میلی‌متر پوشانیده شد تا از انتقال حرارت جابجایی گرما و اتلاف آن جلوگیری شود. رفلکتور توسط ورقه آلومینیومی، با خاصیت انعکاسی ۰/۸۷ و لوله دریافت‌کننده از جنس فولاد معمولی(mild steel) توسط black zinc (روی سیاه)، با خاصیت جذب ۰/۹۴ روکش شد. شدت انتقال جرم سیال کاری ۴ لیتر بر ساعت بود. کارآیی حرارتی جمع‌کننده CPT مطابق با روش استاندارد ASHRAE ارزیابی گردید. بازدهی آنی حرارتی میانگین سیستم جمع‌کننده استوانه‌ای سهوی بسته ۶۶ درصد محاسبه شد و بازدهی کل این سیستم ۷۱ درصد بدست آمد که برای کاربردهای حرارتی خورشیدی بسیار مناسب است.