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Design and Development of Cylindrical Parabolic Collector for Hot Water Generation

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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

Today's India is in need of generating power at higher rate to maintain adequate supply of electricity to users for development and growth of Nation. Non renewable energy sources like coal and petroleum products are the major sources utilized for power production. To reduce the gap between demand and supply of energy and maintain sustainable development, renewable energy sources need to be considered as an alternative source of energy. The solar energy has been identified as one of the promising energy source which can be used directly or indirectly for generation of electricity, hot water and power. A prototype of cylindrical parabolic collector (CPC) is designed and developed to utilize solar energy for hot water generation. Prototype of CPC is tested from 10AM to 4PM in the month of May and thermal performance is evaluated based on solar standards available through literature. Hot water at 60^0C is produced throughout a day by varying mass flow rate of water. The instantaneous efficiency is calculated after every half an hour and found to be 69% and overall efficiency of system is 71%. This prototype CPC system can deliver hot water at required temperature to meet industrial, domestic demands and saves electricity.

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NOMENCLATURE

CR	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/m2)
Rb	Tilt Factor
(τα)b	Transmittance-absorptance factor of beam radiation
Qu	Useful heat gain (W)
Fr	Heat removal factor
F'	Collector efficiency factor
Ul	Heat loss (W/m2K)
m	Mass flow rate
ηi	Instantaneous efficiency
ηo	Overall efficiency

INTRODUCTION

Growing population, rapid urbanization and Industrialization in India demands huge amount of enegy. Energy is the basic and most required element for maintaining economic growth at 8 to 9% for upcomming decades [1]. According to the report of International Energy Agency published in 2012 and as shown in Fugure 1, India's energy demand incresed from 5.5% in 2009 to 8.6% in 2035 as comapred to world energy requirement [2]. To satisfy this demand share of renewable energy sources has to be raised from 2 Mtoe to 36 Mtoe.

India has huge potential of renewable energy sources like solar, wind, biomass, ocean and hydro power. Among them solar energy is cosidered as the most abundantly available energy source throughout the india. Average solar radiation falls over India varies from 4 to 7 kWh/day and about 5,000 trillion kWh/year. But, there is need to develop the technology which can harness maximum amount of solar energy with least cost. Solar energy collection devices can collect solar energy and convert it into usable form and are classified into flat plate, parabolic trough, solar tower, solar photovoltaic collectors.

Concentrating solar power (CSP) technology uses arrays of curved mirrors or reflectors to collect large

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amounts of heat by concentrating it at a specific location where receiver tube is located, further heat is transferred to working fluid and used in a conventional power cycle, industrial process heat or other applications. CSP power plants can generate large amounts of power (hundreds of megawatts) for utility-scale applications [3].

Table 1 gives detail information about the current status of concentrated solar power (CSP) projects based on parabolic trough technology for power generation in India.

TABLE 1 .Status of CSP Projects in India [3]

Sr. No.	Name of Project	Location	Turbine capacity (Net)	Status	Start Year
1	Abhijeet Solar Project	Phalodi (Rajasthan)	50.0 MW	Under construction	2015
2	Dhursar	Dhursar (Rajasthan)	125.0 MW	Operational	2014
3	Gujarat Solar One	Kutch (Gujarat)	25.0 MW	Under construction	2014
4	Megha Solar Plant	Anantapur (Andhra Pradesh)	50.0 MW	Operational	2014
5	Godawari Solar Project	Nokh (Rajasthan)	50.0 MW	Operational	2013
6	Diwakar	Askandra (Rajasthan)	Net: 100.0 MW	Under construction	2013
7	KVK Energy Solar Project	Askandra (Rajasthan)	100.0 MW	Under construction	2013
8	National Solar Thermal Power Facility	Gurgaon	1.0 MW	Operational	2012
9	ACME Solar Tower	Bikaner (Rajasthan)	2.5 MW	Operational	2011

Price et al. [4] have made a comprehensive review on advances in parabolic trough collector technology. Efforts made by various international organization for development, effective performance and cost reduction of all components parabolic trough technology such as support structure, reflector, receiver, heat transfer fluid, storage and process of design and development, operation and maintenance, plant economics are reviewed in detail. Parabolic trough collector can compete with traditional fossil fuel based power plants. Further efforts are needed to make it economically viable, improve performance and capability of parabolic trough technology for solar electric power generation [4].

Singh et al. [5] have designed a procedure for evaluation of performance of solar thermal parabolic trough collector by simulation. Design procedure involves selection of specific parameters which directly affects performance and output of trough. A user friendly MATLAB program was developed to evaluate various performance parameters of trough. The equilibrium must be achieved between aperture area, heat loss coefficient, heat gain and optical losses to improve output through parabolic trough. Malaysian government has taken a step towards utilization of renewable source of energy to meet their energy demand and this work deals with the improvement and utilization of solar energy for power production [5].

Kalogirou [6] developed a mathematical model in engineering equation solver (EES) to evaluate thermal performance of parabolic trough collectors. This model takes account of all modes of heat transfer i.e. convective heat loss in receiver pipe, conduction form pipe to glass cover walls and radiation heat loss from receiver pipe to glass cover and to atmosphere. EES can estimate various properties by specifying any two properties such as temperature and pressure. The equation balances energy between receiver pipe, atmosphere and includes all equation required for evaluation of performance. Model was validated by testing known performance of existing systems and will be used to develop Archimedes Solar Energy Laboratory at Cyprus University of Technology [6].

Nasir [7] presented experimental study of thermal performance of parabolic cylindrical trough for air heating. Trough was covered with two glass cover and performance is tested for three days from 10AM to 4PM. Centrifugal fan was used to blow air into trough. Experimental study shows that this air heater can produce hot air up to 97ºC with an overall efficiency of 65%. Solar air heater fabricated using locally sourced material and has potential application for domestic and industrial drying purpose [7].

Odeh et al. [8] determined the thermal performance of parabolic trough. Two different working fluid such as Syltherm 800 oil (currently for solar electric power generation) and water (future use) were used. Performance was evaluated by considering absorber wall temperature not working fluid temperature so it can predict performance using any working fluid. This simulation model considers all factors causes heat transfer from receiver tube to glass cover and to atmosphere such as wind speed and absorber emissivity. Other factors such as mass flow rate of working fluid, beam radiation level also considered for evaluation of collector efficiency [8].

Arasu et al. [9] investigated thermal performance of solar parabolic trough collector for hot water generation. Working fluid was re-circulated back into well insulated storage tank, SOLARFLEX foil of reflectivity 0.974 and copper tube with sealed glass cover was used for construction of collector. Trough rotates in horizontal north/south direction and axis of rotation located at the focal length. A 12 Volt D. C. motor with an electronic control system was implemented for tacking sun. Mass flow rate of working fluid was maintained at 1 liter/minute. Maximum water temperature achieved by this system was around 73.84 °C and it was observed that incident beam radiation strongly affects other parameters such as outlet water temperature, useful heat gain, collector efficiency [9]. Further simulation program was developed to compare the difference between actual and predicted values of storage tank water temperature. Simulation program predicts the performance with nearly 10% accuracy and can be used for developing parabolic tough technology for hot water generation [10].

Kruger et al. [11] reported the performance of parabolic trough between temperature ranges of 150 to 190^{0}C. Four parabolic troughs were connected in series under project, aiming of implementation of parabolic trough technology to supply heat for desalination, cooling and electricity generation. Thermal performance evaluation reveals low thermal loss but more optical losses. Optical tests were conducted to determine intercept factor and recommendation were suggested to improve optical efficiency [11].

This paper deals with the design and fabrication of prototype cylindrical parabolic trough collector (CPC) for hot water generation having domestic, residential buildings, small scale industrial application where hot water is basic requirement. CPC fabricated with low cost locally sourced material to reduce cost of project and make it economically viable.

Design and fabrication of cpc system

Cylindrical parabolic collector (CPC) consists of mild steel reflector coated with silver foil of reflectivity 0.85 and absorber tube is copper material coated with black copper of absorptivity 0.94. Reflector sheet is curved into desired shape of parabola to reflect solar radiations on absorber tube located at focal point and runs throughout the length of trough. Whole area of trough is covered with glass cover to reduce convective heat losses.

Water is considered as heat transfer fluid which absorbs maximum heat from receiver tubes. Support structure made up of steel gives strong mechanical support to CPC system during harsh environmental conditions such as heavy rainfall and high wind speed. Manual tracking system was implemented to reduce cost of project. The CPC rotates in the horizontal North/South (N-S) axis to track the sun as it moves through the sky during the day. The axis of rotation is located at the focal length. Primary energy demand in India is illustrated in Figure 1.

Length of trough decided based on available size of reflective foil i.e. 1.82 m. Aperture width, depth of trough and exact location of absorber tube was determined using a freeware program [12] as shown in Figure 2. Here,diameter means aperture width of CPC and depth is chosen in such a way to adjust absorber tube inside the CPC to improve overall heat transfer.

The thermal performance of CPC is based on level of concentration of solar radiation falls on it. An important

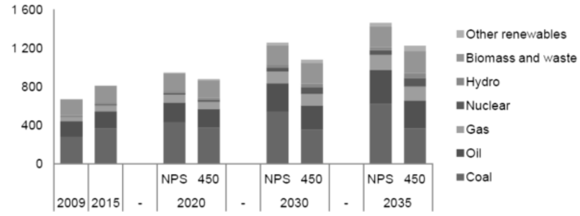

Figure 1. Primary energy demand in India [2]

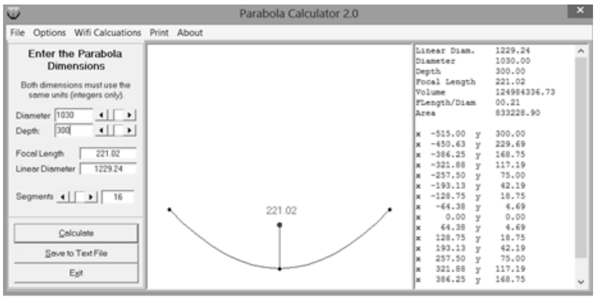

Figure 2. Screenshot of Software Parabola Calculator 2.0

is called concentration ratio (CR). CR is defined as it is the ratio of aperture area to the absorber tube area.

$$CR = \frac{Aperture\ area}{Absorber\ tube\ area}$$
$$CR = \frac{W - D_o}{\pi \cdot D_o} \tag{1}$$

$$CR = \frac{1030 - 19}{\pi \cdot 19}$$
$$CR = 16.94 \sim 17$$

design parameter which directly affects the performance From above figure and calculations, dimensions of CPC are obtained and mentioned in Table 2.

TABLE 2. Specifications of CPC system

Parameters	Values
Collector Width	1.03 m
Collector length	1.82 m
Focal distance	0.221 m
Absorber tube (inner diameter)	0.017 m
Absorber tube (outer diameter)	0.019 m
Concentration ratio	16.94 ~ 17
Storage tank capacity	100 liters.
Insulation material	Asbestos
Rim angle	134.52°
Glass cover thickness	2 mm

EXPERIMENTS AND DATA COLLECTION

Experimentation was conducted on prototype CPC in the month of May from 10AM to 4PM over a day at Shivaji University Kolhapur (M.S.) India (Latitude: 16.42° N, Longitude: 74.13°W). Data collection system includes data logger consist of k type thermocouples to measure temperature at various locations, wind anemometer to measure wind speed, pyranometer for measuring global radiationas CPC absorbs only beam radiations, it is calculated indirectly from global radiation, rotameter controls and measure mass flow rate of water.

Data collection was done after each half an hour and thermal performance was evaluated. The whole experimental setup with data collection system is as shown in Figure 3.

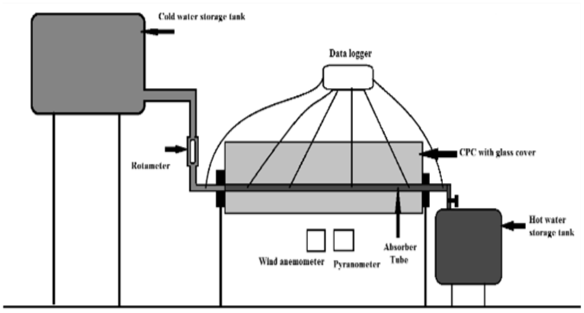

Figure 3. Experimental setup of CPC system for thermal performance evaluation

Performance of cpc system

Thermal performance of CPC system was evaluated by the procedure reported in literature [13]and ASHRAE Standard 93, [14]. Following formulae were used to calculate the performance of CPC over a day. The absorbed solar radiation (S) parameter can be calculated following equation

$$S = I_b r_b \rho\gamma(\tau\alpha)_b + I_b r_b Do(\tau\alpha)_b \left(\frac{Do}{W - Do}\right) \quad (2)$$

The useful gain rate can be expressed as follows:

$$Q_u = Fr(W - Do) \cdot L \cdot \left[S - \frac{U_l}{C}(T_{fi} - T_a)\right] \quad (3)$$

Where Fr, the heat removal factor can be calculated as follows:

$$Fr = \frac{\dot{m} \cdot Cp}{\pi \cdot Do \cdot U_l \cdot L}\left[1 - e^{-\left\{\frac{F' \cdot \pi \cdot Do \cdot U_l \cdot L}{\dot{m} \cdot Cp}\right\}}\right] \quad (4)$$

The above equation is equivalent of the “Hotel-Whillier-Bliss” equation for the flat plate collector. F’ is called as collector efficiency factor which can be calculated by following formula

$$F' = \frac{1}{U_l\left[\frac{1}{U_l} + \frac{1Do}{Di \cdot h_f}\right]} \quad (5)$$

The parameters U_l are the overall heat loss coefficient, it can be evaluated by trial and error method depends on the inlet temperature, outlet temperature and temperature of glass cover.

$$U_l = \frac{q_t / A_{abs}}{(T_{pm} - T_a)} \quad (6)$$

The Instantaneous efficiency can also be determined on The basis of beam radiation alone, if the ground reflected radiation is neglected

$$\eta_i = \frac{Q_u}{I_b \cdot r_b \cdot W \cdot L} \quad (7)$$

Overall efficiency of CPC system can be evaluated by the following relation:

$$\eta_o = \frac{S}{I_b \cdot r_b} \cdot \frac{(W - Do)}{W} \quad (8)$$

RESULTS AND DISCUSSION

From experimental data and thermal performance evaluation following graphs are plotted with detailed explnation of each graph.

Figure 4 shows the varation of incicent beam of radiation over a period of day from morning 10AM to 4PM. Experiments were conducted in the month of May so radations are high enough i.e. in the morning its nearly 850 W/m^2 and gradually increases to 1050 W/m^2 in noon and again falls down to 825 W/m^2 in the evening.

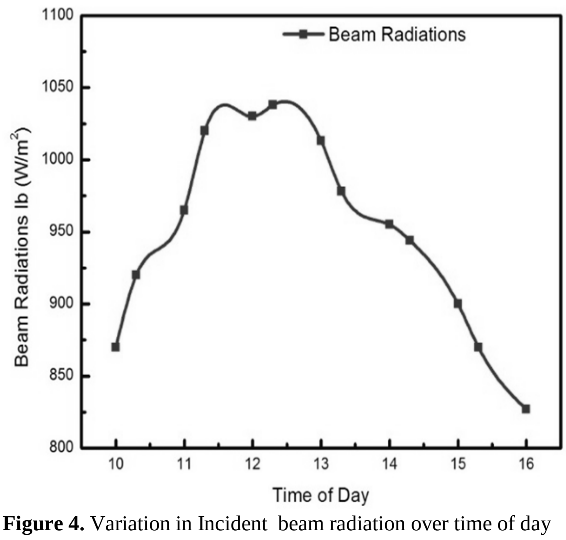

Figure 4. Variation in Incident beam radiation over time of day

Figure 5. elaborates the varation of mean absorber tube temperature over a day. From Figures 4 and 5 it is observed that mean absorber tube temperature temperature increases with increase in beam radation i.e. in linear relationship. In the morning tube temperature is aound 40^{0}C and rises uniformly to 75^{0}C at noon when beam radations are at 1050 W/m^2.

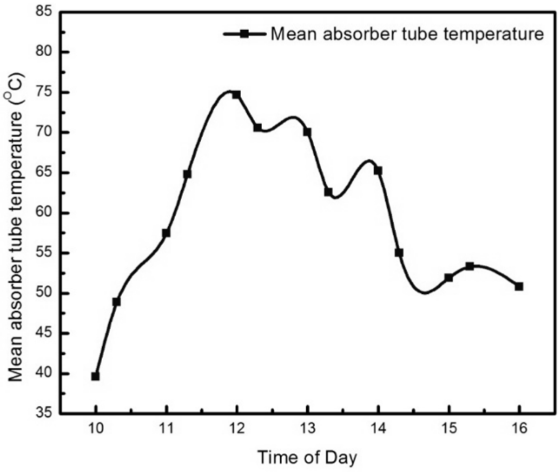

Figure 5. Variation of Mean absorber tube temperature over time of day

Figure 6. explains the important relationship between wind speed and mean absorber tube temperature. Graph shows the effect of variation of wind speed on mean absorber tube temperature. Wind speed is scaled 1:10 to explain the proper relationship. Though the CPC is fully covered with glass to avoid convective heat loss but it is not fully evacuated or air tight so there are some chances of flow of air inside the collector and removes heat from CPC. During morning period wind speed is very less i.e. 1 to 2m/s at the same time abosorber tube temperature is very high. After 1 PM wind speed increases to 4.5 m/s causes loss of heat so there is sudden fall in mean tube temperature by 20^{0}C.

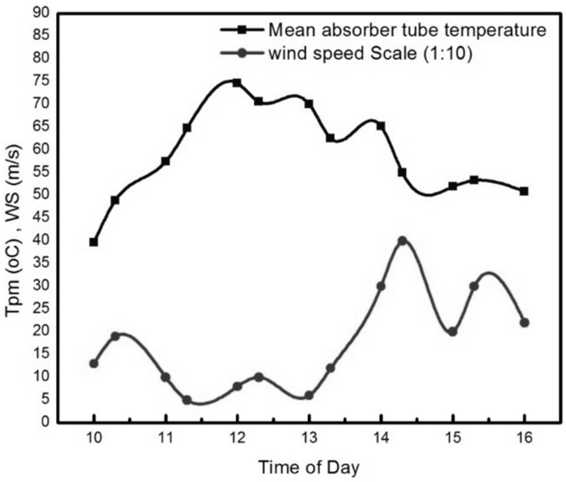

Figure 6. Effect of variation in wind speed on Mean absorber tube temperature over time of day

Figure 7 establishes the relation between mean absorber tube temperature, mass flow of water over time of day. Form previous dissusion it is observed that mean absorber tube temperature temperature varies directly with incident beam radiation over a day and the same variation is shown with the mass flow rate. As absorber tube temperature increases more heat is available to increase the temperature of water. But as per our output requirement of 60^{0}C temperature, mass flow rate is incresed.

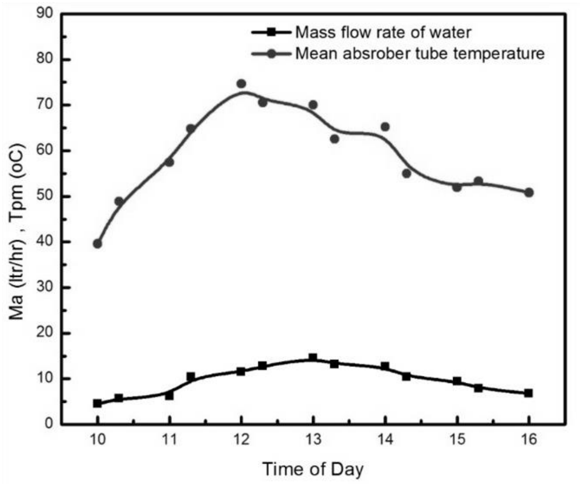

Figure 7. Variation in Mean absorber tube temperature and mass flow rate over time of day

Figure 8 shows effect of useful heat gain on mean absorber tube temperature. This graph also proves that useful heat gain increses linearly with increse in beam radiation and increase in absorber tube temperature.

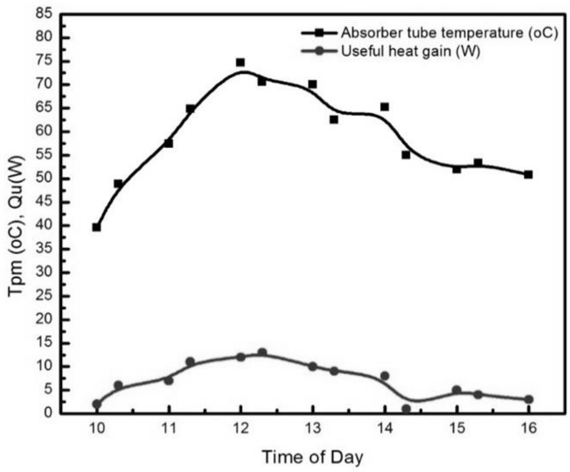

Figure 8. Effect of useful heat gain on Mean absorber tube temperature over time of day

CONCLUSION

Cylindrical parabolic trough solar power technology is capable of generating hot water, steam for industrial, domestic and power plant and many more application. But high intial cost and lower efficiency of plant is the main problem to implement this technology.

To solve this issue, a attempt has made by designing and fabricating a low cost cylindrical parabolic solar collector with locally available material for hot water generation. Thermal performance evalaution shows that this prototype CPC can produce 80 liters of hot water at 60^0C per day. Average istantaneous and overall efficiency CPC found to be 69% and 71% respectively. This CPC system is easy to install and less cost of mainteanace. Connecting large number of CPC in arrays and installing automatic tracking system, CPC can be used in solar electric power generation and provide a clean way of generating power and electricity.

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Persian Abstract

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چکیده

برای پیشرفت و توسعه هندوستان و تامین برق مورد نیاز شهروندان نیاز است که بتوان با سرعت بیشتری الکتریسیته تولید کرد. منبع اصلی مورد استفاده تجدید ناپذیر مورد استفاده ذغال سنگ و نفت است. به منظور کاهش فاصله میان نیاز و تامین و توسعه پایدار باید منابع تجدید پذیر به عنوان جایگزین در نظر گرفته شوند. انرژی خورشیدی به عنوان یک منبع انرژی امیدوار کننده که می¬تواند به صورت مستقیم و غیر مستقیم جهت تامین برق و آب گرم مورد استفاده قرار گیرد شناسایی شده است. یک نمونه اولیه از کالکتورهای استوانه ای سهموی طراحی و توسعه داده شد و به منظور تولید آب گرم مورد بهره برداری قرار گرفت. نمونه ساخته شده از ساعت ۱۰ صبح تا ۴ بعد از طهر در ماه می مورد آزمایش قرار گرفت و بعد از هر نیم ساعت عملکرد حرارتی آن مورد ارزیابی قرار گرفت. آب گرم با دمای ۶۰ درجه سانتی گراد با تغییر دبی های جرمی مختلف تولید شد. بعد از هر نیم ساعت بازدهی سیستم محاسبه شد که عدد ۶۹٪ بدست آمد و بازدهی کلی سیستم نیز عدد ۷۱٪ بدست آمد. این نمونه ی اولیه می¬تواند آب گرم مورد نیاز مصارف خانگی و صنعتی را تامین کند و در مصرف برق صرفه جویی کند.