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SOLAR ENERGY CONCENTRATORS

Performance Analysis of 2 in 1 Parabolic Trough Collector for Both Hot Water and Hot Air Production for Domestic Household Applications

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Abstract—Parabolic trough collectors (PTC) are solar thermal energy collectors designed to capture the sun's direct radiation over aperture area and concentrate it onto a focal point. Parabolic shaped mirrors are used to focus the solar radiation on the pipe that carries water to heat it. The concentrated heat from the parabolic collector heats up the water and helps in producing hot water which can be used domestically. Drying is one of the important and energy consuming processes. Especially foragricultural product processing open yard drying is widely adapted, without proper hygienic condition. The presently designed cost effective two in one PTC setupcanheat water and air simultaneously. In the box shaped structure the hot water isgenerated at the top of the box. The unused absorbed heat on the collector is used to heat the air which is passed via bottom chambers. As a result, hot water (60°C) and hot air (45°C) can be obtained which is used mainly for heating purpose. Manual tracking type of design is chosen for cost effectiveness and simplicity in structure. This Combined water and air heating design improves the total efficiency of the system up to 4.3% when compared with the conventional PTC design. In addition, the emission reduction of 1 kg of CO_2/day can be achieved and simple payback period is 2 years when compared to electric heaters which can be easily affordable by common man.

Keywords: 2 in 1 parabolic trough collector, drying, efficiency, emission reduction, hot air, hot water

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INTRODUCTION

Attention towards improvement in conventionally existing renewable system design is need of the hour to improve the contribution of green energy in overall energy demand. In the present scenario, increase in energy demand and constraints in supply of energy becomes an important priority. Non-renewable energy sources are depleting drastically in one side, on the other sidethe gap between demand and supply is drastically increasing mainly due to population growth and improvement in standard of living of developing countries like India, Russia and China. To overcome this, usage of renewable energy isthe only feasible solution available. Out of various renewable forms of energy, solar energy is most effective one. Two forms of solar energyi.e. both sun light and heat can be used in various applications in our day to day life. Some of the widely seen solar energy basedapplications aresolar water heating thermo siphon systems, solar hot air systems [1], space heating [2] and cooling, solar heat pumps, refrigeration, industrial process of heat for air and water systems, steam generation systems, desalination and thermal power systems [3]. Apart from conventional applications of solar thermal energy, it is used to reduce the viscosity of petrol using heat pipes techniques [4], anaerobic sewage treatment by solar water heating system and anaerobic reactor [5]. Solar thermal collectors are used to collect heat by absorbing sunlight. Major divisions of solar collectors are concentrated and non-concentrated. Flat plate collectors (FPC) are categorized under the non-concentrating type. Parabolic dish, parabolic trough collectors are notable concentrating collectors [6, 7]. Usually parabolic trough collectors (PTC) are used for solar steam generation because temperature of about 300°C can be obtained without any degradation in collector's efficiency.

For domestic applications flat plate collectors or evacuated tube collectors [8–10] are used for producing hot water by thermo siphoning system. But the cost of the system is high due to copper receivers in the FPC. Hence the concept of using the PTC in domestic applications is tried by many researchers and found to be more effective too [11–14].

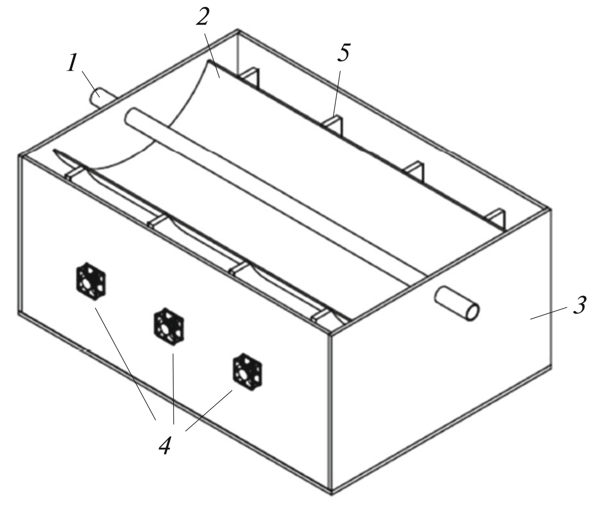

Fig. 1. Structural diagram of 2 in 1 PTC.

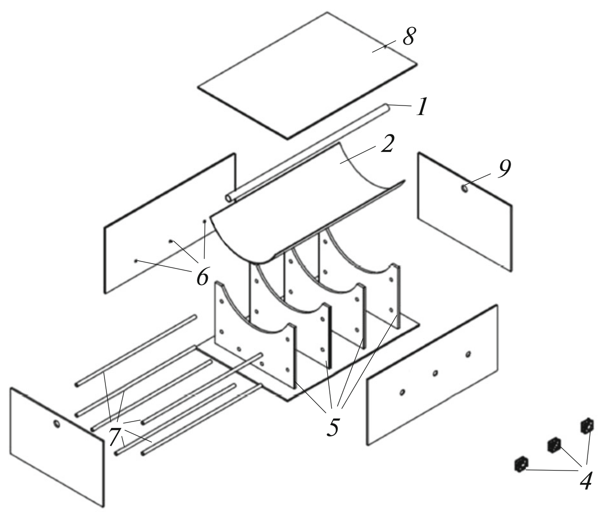

Fig. 2. Assembly view of 2 in 1 PTC.

Considering the proven benefits, in the present design PTC is developed as box like structure [15] for domestic hot water applications [16] and it is made up of the curved (parabolic) aluminum reflective sheet as a reflector surface with the help of reflector supports, supporting pipe and stand using locally sourced materials. In PTC, tracking is the area where complexity and cost involvementis high [17]. In the present PTC design, for rural application manual tracking is followed in order to avoid automatic tracking cost. Further in order to reduce the manual effort, it is proposed to keep the PTC in the orientation such that focal axis of the receiver is parallel to east west direction [18]. Hence PTC can be tracked only once in a day (preferably at the morning).

Generally, in rural and urban areas electricity (electric heaters) is used for hot water generation and people still follow open sun drying method to dry agricultural products, which is less hygienic. In open sun, it takes prolonged time for drying the products and environmental threats (insects, climatic conditions) which are major drawbacks. Hence indirect or direct type air heaters are being used [19–21] which needs additional set up apart from water heaters. Lot of researches is being carried out in the area of air heaters for innovative design and performance improvement [22–24] which ultimately reduces the cost. In the present research, PTC is designed in a way to generate both hot water and hot air simultaneously under same aperture area.

The concept of combining PTC to generate domestic household hot water and hot air paved the way to two in one (2 in 1) solar parabolic trough collector which can save space, energy and cost.

Experimental Set Up

The structural diagram and assembly view of the 2 in 1 PTC are shown in the Figs. 1 and 2, respectively.

The components in the 2 in 1 PTC are:

1. Copper pipe receiver at focal point coated with black paint [6, 25].
2. Parabolic aluminium reflective sheet.
3. Plywood Side cover box.
4. DC fans for air flow (3 numbers).
5. Hylam sheet supporting structure (4 numbers).
6. Outlet ports for hot air (3 numbers).
7. Aluminium supporting pipes (6 numbers).
8. Top glass cover [26].
9. Hole to hold copper pipe receiver at focal point.

The dimensions of the 2 in 1 PTC are mentioned in Table 1. PTC was fabricated for 40 L per day, but can be scaled up with small increase in the investment cost by parallel connections of PTC or by increasing the aperture area.

The schematic of experimental setup is given in the Fig. 3. Make up water tank was kept in order to fill the water during dawn of the day or after the usage of hot water in storage tank. After refilling the makeup water tank was isolated. Hot water storage tank bottom port was connected with the inlet of the 2 in 1 PTC. The outlet of the PTC was connected with the top of storage tank and water was filled up to this level in order to favor the thermo syphon effect. The calibrated *k* type thermocouples (T1 to T9) using standard air bath (AMETEK CT650B) were usedand coupled with data logger (Yokogawa GX20) to measure and store the temperature readings. Thermocouples T1 to T4 were kept at top, upper middle, lower middle and bottom of the storage tank respectively. The copper receiver inlet and outlet water temperature were measured using thermocouples T5 and T6, respectively. The temperatures of air from the outlet of 2 in 1 PTC compartments were measured using thermocouples T7 to T9.

The atmospheric air temperature was measured using Thermocouple T10. Total global radiation was measured using Pyranometer (KIPPZONEN DELFT CM11) and instantaneous Beam radiation was measured using the Pyrheliometer (KIPPZONEN CHP1). The details of instruments and its accuracy are mentioned in Table 2. The experimental view and air flow set up are given in Figs. 4 and 5, respectively.

Working Principle

2 in 1 Parabolic trough collector (PTC) was positioned such that the copper pipe receiver at focal point was oriented longitudinally in East–West direction. It was preferred over the North south direction orientation in order to reduce the manual effort of tracking continuously in latter orientation whereas the former orientation demands per day tracking alone along with minor day adjustments. Hence the 2 in 1 PTC was oriented such that the direct solar beam radiation falls perpendicular to the aperture area and falls on the parabolic aluminium reflective sheet. Due to the nature of parabolic profile of reflective sheet, the solar rays perpendicular to the directrix of parabola were converged to the focal point where the copper pipe receiver was kept. Hence the water which was inside the copper pipe was heated. Because of the inlet side pressure head due to storage tank water and thermo syphon effect (reduction in density due to relatively high temperature), the hot water started to flow naturally from left to right i.e. inlet to outlet of the receiver and reach the top of the storage tank. As a result, the fresh cold water occupied the copper receiver and the process was repeated. As the solar radiation was

Table 1. Dimensions of PTC

Parameters	Value
Focal length, F	0.18984 m
Aperture Angle, Φ_a	94.84°
Width of the aperture, W	0.826 m
Aperture area, A_a	0.6788 m^2
Collector length, L	0.845 m
Concentration ratio, CR	11.31
External diameter of receiver, D_O	0.0226 m
Internal diameter of receiver, D_i	0.0186 m
Reflectivity, ρ	0.9
Emissivity of the receiver, ε_r	0.965
Conductivity of receiver, K_r	401 W/(m K)

reflected by the parabolic aluminium sheet, it was also heated. In order to retrieve this heat, air was sucked with help of DC fans (3 numbers) which were fixed in the parallel side sheet (with respect to copper receiver) of Plywood cover box. The air was induced through inlet ports and came in contact with the back side of aluminium reflective sheet (shown in Fig. 5) in order to retrieve heat by forced convection mode. The hot air which came out of the PTC through the DC fans vanes could be used for drying applications.

Efficiency Calculation [6, 17]

Heat collected by receiver over the time 't' up to 'n' s (n can be the final time in seconds at which the

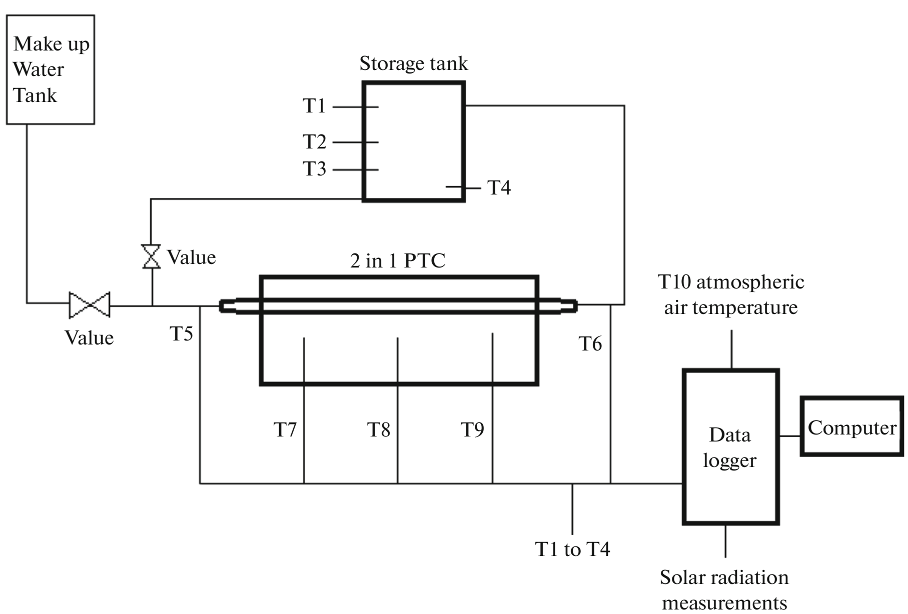

Fig. 3. Schematic of experimental setup.

Table 2. Instruments and its accuracy

Instruments/sensors	Accuracy/sensitivity
K type Thermocouples	+3.6°C but calibrated using standard air bath. Calibration equation $T_{calibrated} = 0.9393T_{indicated} + 2.2854$
Pyranometer (KIPPZONEN DELFT CM11)	7 to 14 μV /W/m^2
Pyrheliometer (KIPPZONEN CHP1)	7 to 14 μV /W/m^2
Vane type Anemometer (Lutron AM-4201 Digital Anemometer)	±(2% + 0.1 m/s)

experiment was stopped or individual time interval up to which the required parameter needs to be calculated. 't' could be incremented with the value of 1 s as the minimum storage interval of data logger used is 1 s) i.e. E_c can be found out in Joule.

$$E_c = \dot{m}C_p\sum_{t=1}^{n}\left\{\left[t\int_{T_{\text{inlet}_t}}^{T_{\text{outlet}_t}} dT\right]-\left[(t-1)\int_{T_{\text{inlet}_{t-1}}}^{T_{\text{outlet}_{t-1}}} dT\right]\right\}, \quad (1)$$

where '$\dot{m}$' mass flow rate of water through the receiver in kg/s, C_p is is the specific heat capacity of water at constant pressure in J/(kg K), T_{Outlet_t} & T_{inlet_t} are the water temperatures at receiver outlet and inlet respectively in kelvin at 't^{th}' s, $T_{\text{Outlet}_{t-1}}$&$T_{inlet_{t-1}}$are the water temperatures at receiver outlet and inlet respectivelyin kelvin at '$(t-1)^{th}$' s.

Input heat given by sun (E_i) in Joule overthe time 't' up to'n' s is given as:

$$E_i = A_a\sum_{t=1}^{n}\left[I_{b_t}t - I_{b_{t-1}}(t-1)\right], \quad (2)$$

where A_a is the aperture area in m^2, I_{b_t} is the instantaneous beam radiation in W/m^2 at 't^{th}' s and $I_{b_{t-1}}$ is the instantaneous beam radiation in W/m^2 at '$t-1^{th}$' s.

The collection efficiency η_{Coll} over the time 't' up to 'n' s is given by

$$\eta_{\text{Coll}} = (E_c/E_i). \quad (3)$$

The heat which is stored or charged in the storage tank (E_s) in Joule is given as:

$$E_s = mC_p\sum_{t=1}^{n}[T_{st_t} - T_{st_{t-1}}], \quad (4)$$

where m is the mass of water in kg stored in the storage tank and T_{st_t} is the temperature (average of T1 to T4) of water in storage tank at 't^{th}' s in kelvin, $T_{st_{t-1}}$ is the temperature (average of T1 to T4) of water in storage tank at '$t-1^{th}$' s in kelvin. The storage efficiency (η_{stor}) is given by

$$\eta_{\text{stor}} = (E_s/E_c). \quad (5)$$

The system efficiency i.e. η_{sys} is given by

$$\eta_{\text{sys}} = (E_s/E_i), \quad (6)$$

E_a is heat carried by air

Fig. 4. Experimental view of closed loop setup of PTC.

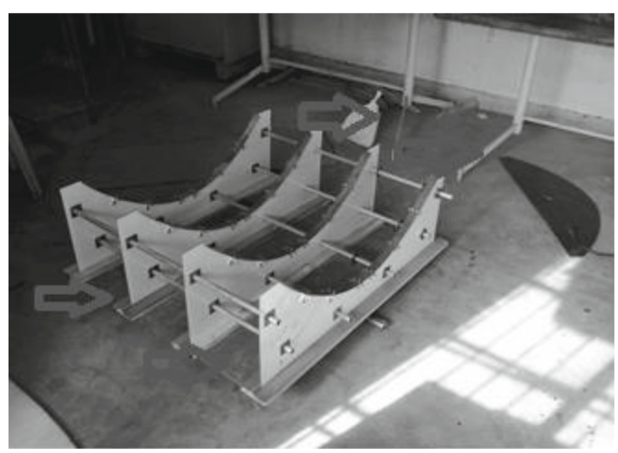

Fig. 5. Air flow compartments in PTC.

$$E_a = \dot{m}_{\mathrm{air}} C_{p_{\mathrm{air}}} \times \sum_{t=1}^{n} \left\{ \left[t \int_{T_{\mathrm{air\,inlet}_t}}^{T_{\mathrm{air\,Outlet}_t}} dT \right] - \left[(t-1) \int_{T_{\mathrm{air\,inlet}_{t-1}}}^{T_{\mathrm{air\,outlet}_{t-1}}} dT \right] \right\}, \tag{7}$$

where $\dot{m}_{\mathrm{air}}$ total mass flow rate of air sucked by 3 DC fans in kg/s, $C_{p_{\mathrm{air}}}$ is the specific heat capacity of air at constant pressure in J/(kg K), $T_{\mathrm{air\,Outlet}_t}$ & $T_{\mathrm{air\,inlet}_t}$ are the air temperatures at PTC outlet and inlet respectively in kelvin at 't^{th}' s, $T_{\mathrm{air\,Outlet}_{t-1}}$ & $T_{\mathrm{air\,inlet}_{t-1}}$ are the air temperatures at PTC outlet and inlet respectivelyin kelvin at '$(t-1)^{th}$' s.

The total system efficiency η_{tot} considering both water and air is the ratio of sum of amount of heat stored by water over the time period and heat carried by air to input heat given by the sun over the aperture area in given time period. It is given by,

$$\eta_{\mathrm{tot}} = (E_s + E_a)/E_i. \tag{8}$$

RESULTS AND DISCUSSION

Analysis of Water Heating (Excluding Air Heating)

The experimental set up was connected and the continuous readings were measured and recorded. Initially the performance of conventional type PTC (i.e. only for heating the water at focal point) was done and the temperatures of the water at inlet of the PTC, outlet of PTC and at storage tank (measured at four different places say top T1, upper middle T2, lower middle T3 and bottom T4) were recorded continuously and shown in Fig. 6. The system efficiency and collection efficiency were calculated as per equations described in previous section and it is shown in Fig. 7. The heat analysis is done in the Fig. 8 and the input heat, heat collected and heat stored are reported.

Initially, PTC receiver's outlet water temperature raised in steep manner because of lack of movement of water inside the receiver. This was mainly due to inertia in thermo syphon effect at the beginning stage. Once the heating continued, water became less dense due to high temperature and motive force for thermo syphon effect increased. There was some drop in collection efficiency till the attainment of thermal stratification which was the main motive force for natural water circulation in the circuit. Because of the high beam radiation and better motive force, till 13:30 pm the collection efficiency reached the maximum value of 81%. The system efficiency too attained the maximum of 72.08% at 12:20 pm. One of the main reasons for reduction in system efficiency after 12:20 pm was because of the temperature raise of water which was linearly proportional to heat losses to the atmosphere. At the end of the experiment, the instantaneous system efficiency was 41% which is appreciable. The summary of the performance of PTC is enlisted in Table 3. It was observed that the final temperature attained by the water at the end of experiment was 64.45°C for the average beam radiation of 536 W/m² over the time period. The average of system efficiencies considering the time slot was 55.9%.

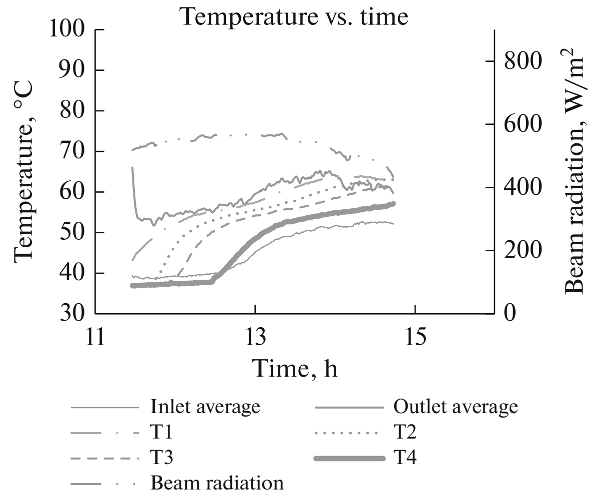

Fig. 6. Temperature distribution over the time period.

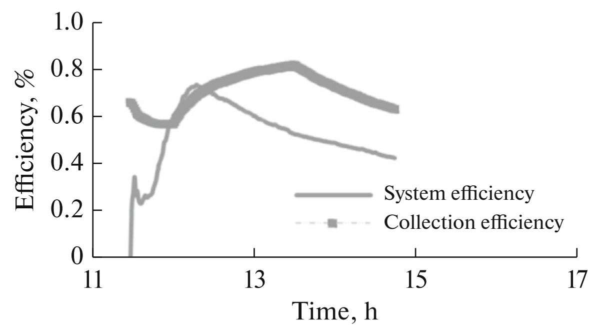

Fig. 7. Comparison of collection efficiency and system efficiency.

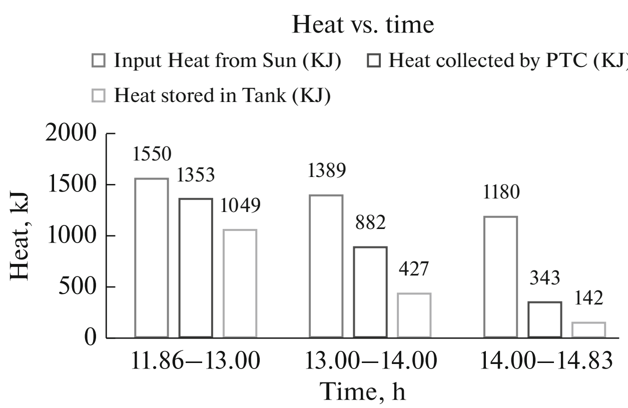

Fig. 8. Heat analysis over the time period.

Table 3. Combined water and air heating

Condition	Beam Radiation, W/m^2	Final temperature of 20 L of water, °C	Average of system efficiencies by considering water alone, %	Average of system efficiencies by considering air alone day, %	Average of total efficiencies i.e. both water and air, %
Only water heating	536	61.45	55.9	0	55.9
Both water and air heating	580	62.3	54.9	5.44	60.34

Combined Hot Water and Hot Air Generation

In this section 3 DC fans were switched on and air was induced to the bottom compartments. Along with the readings regarding water and solar radiation measurements like previous conventional experiment, inlet and outlet air temperatures were measured continuously. The efficiencies were calculated similar to previous experiment and compared. From the Table 3, it is evident that the final temperature attained by the water at the end of the conventional as well as modified experiment is almost same. It showed that the heating effect of water had not been affected significantly due to simultaneous air heating. In the second experimental case i.e. both water and air heating set up an additional percentage of 5.44% increase in system efficiency was found out because of heating the air at back part of the parabolic trough. The improvement in efficiency is evident because of the retrieval of waste heat mainly from back part of concentrator. Hence hot air could be obtained as by product which can be useful for all drying and hot air requirements.

CONCLUSIONS

An experimental investigation on solar PTC which can give both hot water and hot air was conducted. Apart from the hot water of 60°C, air of 45°C was obtained which raised the system efficiency by 4.35% which is highly appreciable. Apart from savings in energy and cost, the box like structure can provide closed space which can be used to keep the agricultural products and hence it leads to closed drying which can avoid lot of environmental threats due to insect and bad weather. Because of the unique modification in 2 in 1 PTC savings in electricity (i.e. 4682 kJ per day i.e. 1.3 kW h per day), and reduction in emissions (1.06 kg of CO_2/day) can be achieved. For the 2 in 1 PTC, simple payback period is 2 years. The scope of the designed PTC is strictly limited to low capacity (100-liter capacity, 3–4 members) domestic house hold solar hot water requirements which will be more suited in semi urban and rural areas.

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