

Experimental Investigation and Performance Evaluation of Parabolic Trough Solar Collector for Hot Water Generation

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Abstract—The parabolic trough solar collector (PTSC) is one of the most established solar concentrated systems in the solar thermal applications worldwide. The current paper presents experimental results on a PTSC designed and tested under Hungarian weather conditions in October and November 2020 regarding generation of hot water. The PTSC was made of aluminum sheet of parabolic shape to reflect and concentrate solar radiation into an absorber tube located at the focus point. The absorber tube was made of copper or stainless steel with diameters of 12 and 10 mm, respectively, with and without a glass cover tube. The efficiency of the PTSC was investigated depending on the time of the day at four flow rates under various conditions. The experimental results show that the copper tube coupled with the glass cover worked well at a mass flow rate of 0.0035 kg/s. Furthermore, the glass cover reduced the heat loss, and the performance of the PTSC was enhanced through improvement of the greenhouse effect between the glass and tube.

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1. INTRODUCTION

The global energy request is continuously growing because of the depletion of the traditional energy sources [1]. Therefore, it is essential to extract energy from other sources [2]. Fossil fuels are a non-renewable energy source, and their usage should be minimized in view of the greenhouse effect, environmental pollution, and climate change [3, 4]. Solar energy can be utilized, converted to thermal energy using parabolic trough solar collectors (PTSCs) [5].

PTSCs are used for several techniques, e.g., industrial steam production and generation of hot water [6]. The PTSC is designed to concentrate the solar radiation at a receiver located at the focal point. The radiant solar energy is absorbed by the receiver tube, and then it can be converted to thermal energy [7], which in turn can be converted into electricity using an engine generator. The thermal energy can also be transported through pipes to a central power-conversion system. This system can yield a temperature rise of 400°C [8].

For investigation of the thermal performance of PTSC, many experimental tests were implemented following ASHRAE 93–1986 standard [9]. The thermal efficiency, cooling and heating and the occurrence angle modifier of the collector were measured. It is necessary to increase the efficiency of the solar collector. Therefore, the radiation absorption and the rate of heat transfer to the fluid must be enhanced for improvement of solar collectors, and the heat transfer loss between the surroundings and the working fluid should be minimized [10].

Some parameters that influenced the parabolic trough solar receiver performance were investigated [11]. The mass flow rate of the working fluid, the ambient temperature, and the solar radiation incidence angle increase and decrease the solar receiver heat loss [12]. The exergy losses of the solar receiver grow

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as the inlet temperature of the working fluid, wind velocity, and inner diameter of the glass cover increase [13, 14]. The heat convection losses of the glass cover dominate in the heat loss of solar receiver based on thermal efficiency, but the exergy losses from the absorber ends make the major part [15].

The absorber tube material affects the heat transfer between the metal and fluid and thus the performance [16]. The absorber tube is made of copper or stainless steel or iron with a black thermal resistant coating. Generally, the tube is enclosed by a glass cover for loss reduction [17]. The reflection surface is made of curved parabolic form to focus the solar radiation on the receiver tube. Kasaeian et al. investigated a surface collector having an area of 1.5 m^2 with a steel mirror reflector [18]. They used the coated tube absorber surface to compare the thermal and optical efficiency, and the results were compared with ASHRAE standard 93, 2010. The thermal efficiency was enhanced in the cover absorber tube as compared with an uncovered absorber tube.

Selvakumar et al. [19] studied the performance on an evacuated tube using therminol D-12 as the heat transfer fluid. A new system was developed with an evacuated tube collector using synthetic oil, and the generation of hot water at low solar irradiance was studied. This system enables analysis of the consumption of fossil fuel and electrical energy to generate hot water in the house.

Two different receiver tubes are used in the current work at four mass flow rates. The efficiency of their geometries was investigated experimentally. The new PTSC with a manual tracking system built for production of hot water, the manufacture and design of a solar parabolic trough is carried out using locally sourced materials. Significant advantages of solar trough collectors are their low cost, cleanness, and absence of environmental pollution.

2. DESIGN PARAMETERS

The design of the PTSC included solar collector concentration. The receiver tubes absorbed the incoming solar radiation and converted it to thermal energy. The PTSC used an aluminum sheet of parabolic shape to reflect, concentrate, and direct the solar radiation on the absorber tube located at the focus point. Generally, the PTSC axis was north-south or east-west oriented. The fluid passed via the absorber tube got the thermal energy from solar radiation concentrated on the receiver tube. The absorber tubes were made of copper and stainless steel and covered by glass tubes. The PTSC system is shown in Fig. 1.

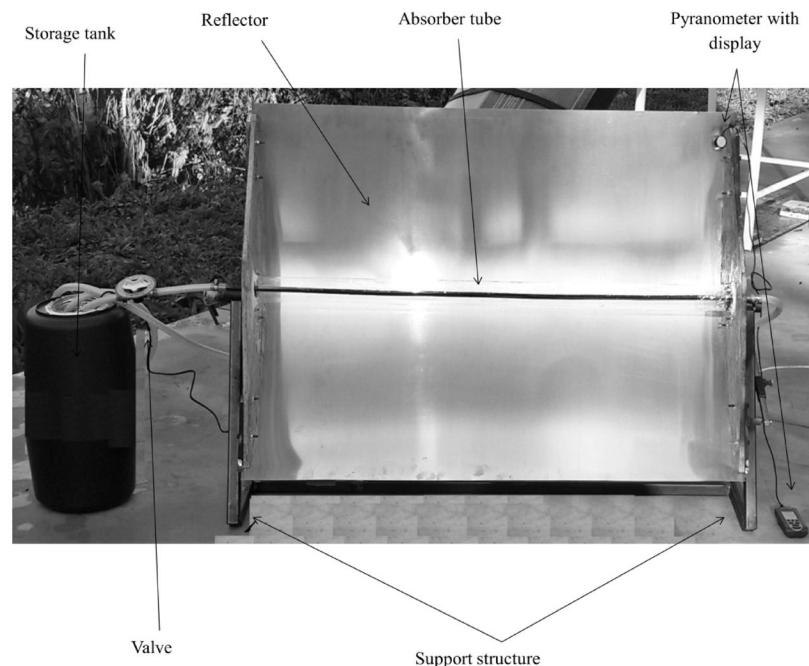


Fig. 1. Components of PTSC.

3. MANUFACTURING OF PROTOTYPE PTSC

The main components of the parabolic trough solar collector were used in the manufacture of the prototype. The reflector surface was an aluminum sheet of 1200 mm $\times$ 930 mm area, fixed with a piece of wood in a parabolic curve. The piece of wood was fixed with the structure of the parabolic solar collector. Advantages of the aluminum sheet are its flexibility, resistance to different weather conditions, very high reflectivity, configuration, and easiness of installation.

The absorber tube material affects the heat transfer between the metal and fluids and thus the performance. In this research, two types of tube material were used: copper and stainless steel. The absorber tubes were painted in black for higher absorptivity and minimum losses. The copper tube diameter was 12 mm, and the diameter of the stainless steel tube was 10 mm. The glass tube cover was 58 mm. The cover was to reduce the losses because of conduction, convection, and radiation.

A 15 l water storage tank made of special plastic and a 15 W pump power were used for the delivery of water to the absorber tube inlet. Then the water came back to the same position. The water gained heat when the absorber tube and the water returned to the container.

The parabolic trough solar collector structure was made of iron of 40 mm $\times$ 40 mm in area with a thickness of 2 mm. The iron was solid enough to withstand wind load, stress load etc. A piece of wood was used to connect the structure and the surface collector. The wood was very flexible and was able to take the parabolic shape, which enabled reduction of the design and fabrication error. The wood was easy to connect with the structure and to make a joint for tracking the sunlight.

Manual tracking was applied in this prototype from cost considerations. In this case, one axis was used for tracking, east-west alignment, and the system rotation through a required angle every 1 hour. The measurement device recorded the solar radiation (both the beam and diffusion of the solar radiation) and the temperature during the experiment. The device measured the amount of radiation in the units of W/m² and displayed the digital results. This device had 4 digital readings in the units of °C. The table shows the overall specifications and dimensions of the prototype of the PTCS.

The steps taken during the experiment included the removal of dust particles from the absorber tube and reflector surface, as well as the collector positioning toward the Sun for not less than 30 min before beginning the experiment. The tank was filled with fresh water, the reflector was set as indicated by the

Overall specifications of PTCS prototype

Parameter	Specifications
Collector aperture	1.2 m
Collector length	1.2 m
Inner diameter of copper absorber	0.01 m
Outer diameter of copper absorber	0.012 m
Inner diameter of stainless steel absorber	0.01 m
Outer diameter of stainless steel absorber	0.008 m
Focal distance	0.2 m
Aperture area	0.96 m ²
Working fluid	Water
Mass flow rates	0.00867 kg/s, 0.0067 kg/s, 0.005 kg/s, and 0.0035 kg/s
Storage tank	15 l
Specular reflectivity of concentrator	0.80
Glass cover transitivity	0.85
Emissivity of absorber	0.15
Emissivity of glass	0.85

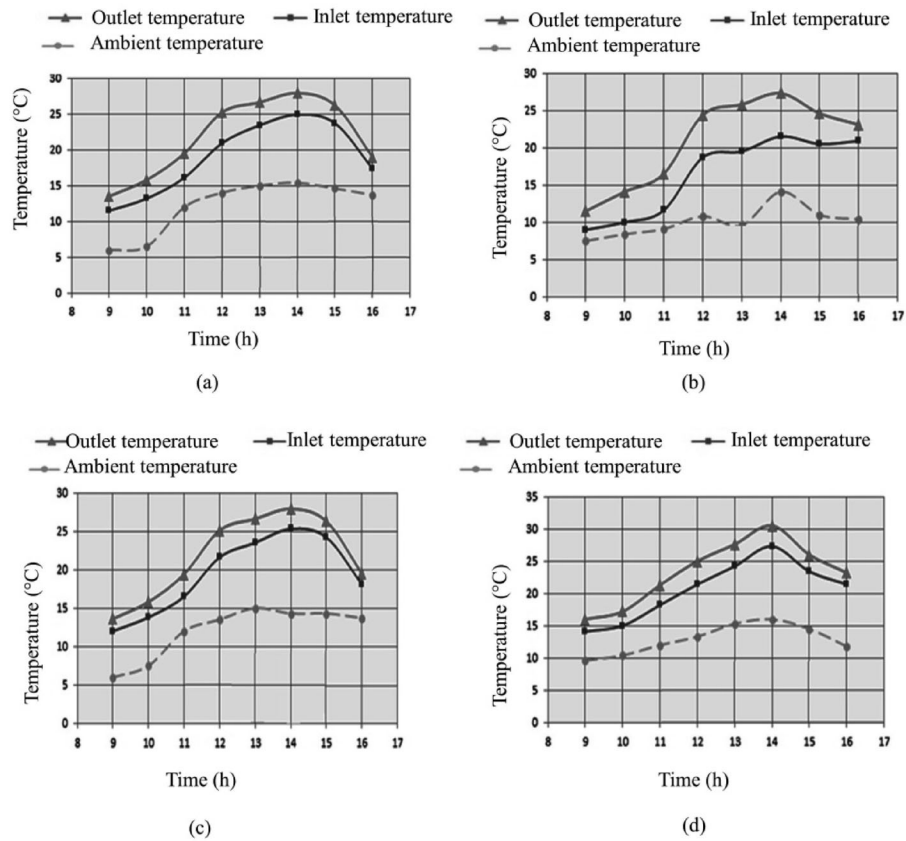


Fig. 2. Variation of temperature at mass flow rate of 0.0087 kg/s.

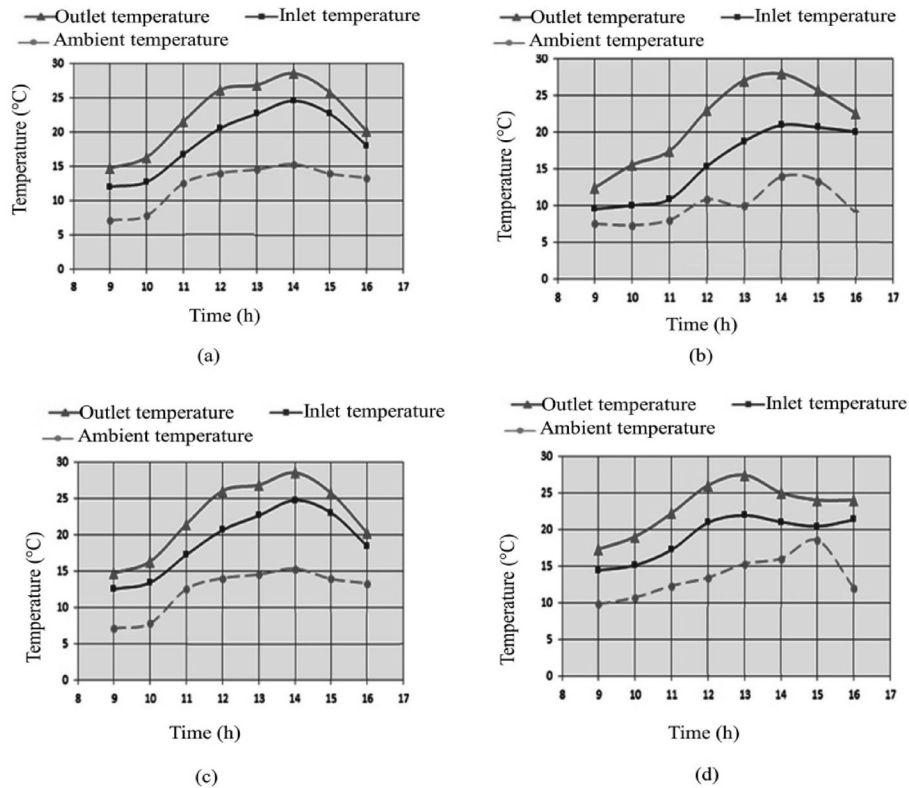


Fig. 3. Variation of temperature at mass flow rate of 0.0067 kg/s.

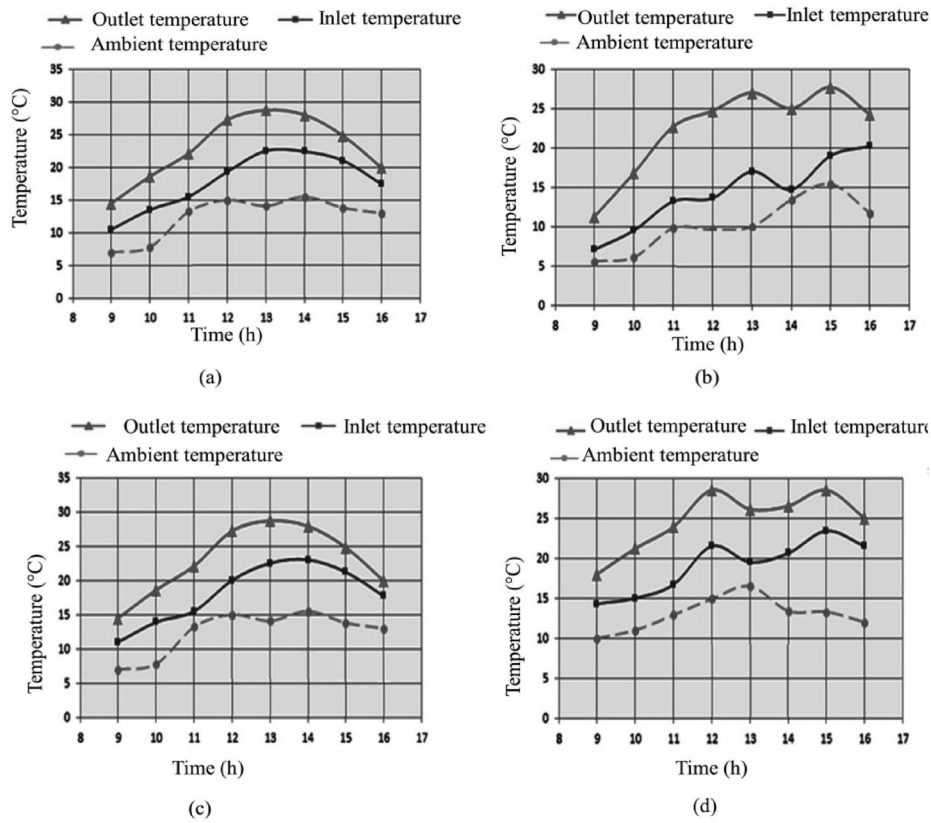


Fig. 4. Variation of temperature at mass flow rate of 0.005 kg/s.

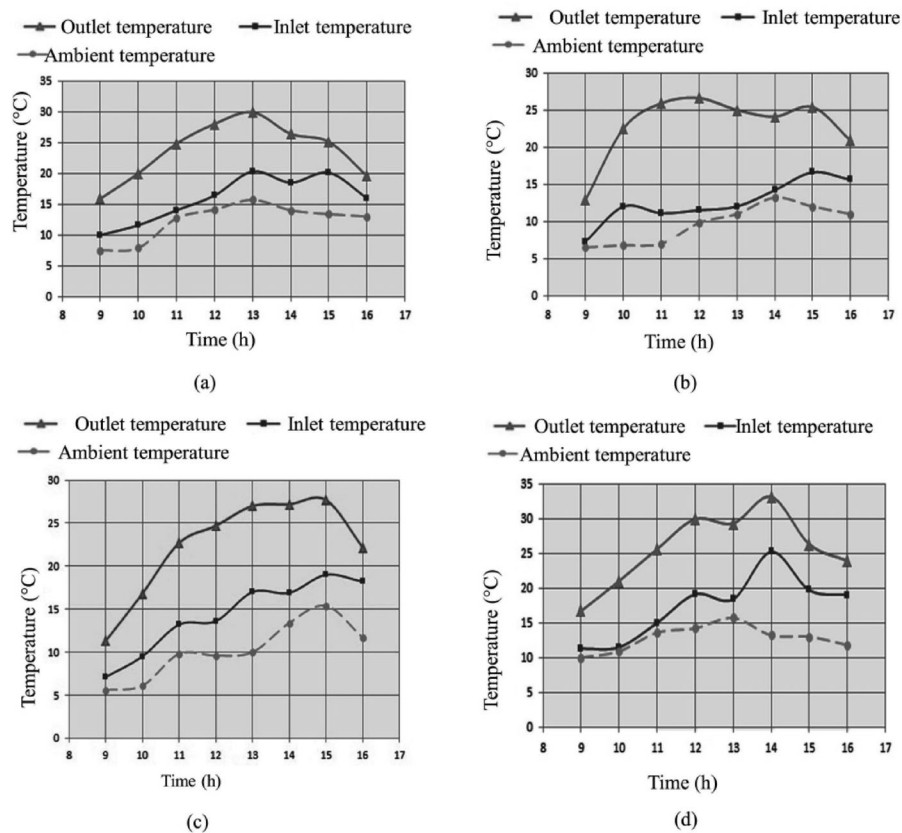


Fig. 5. Variation of temperature at mass flow rate of 0.0035 kg/s.

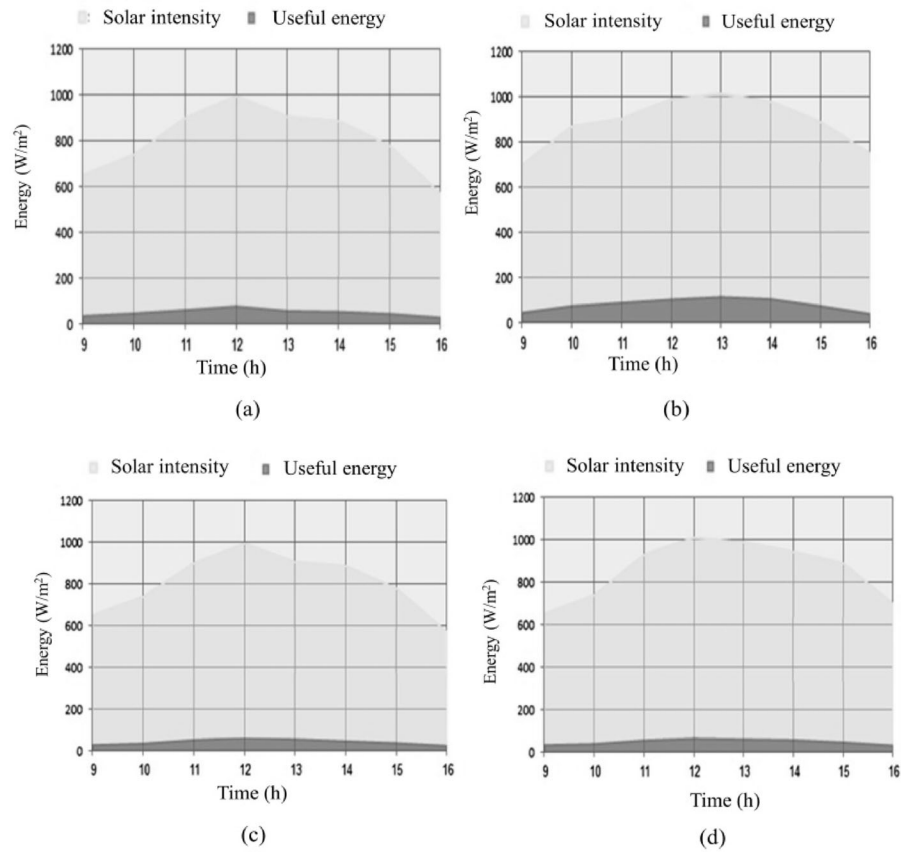


Fig. 6. Variation of Useful Heat Gain and Solar Intensity at mass flow rate of 0.0087 kg/s.

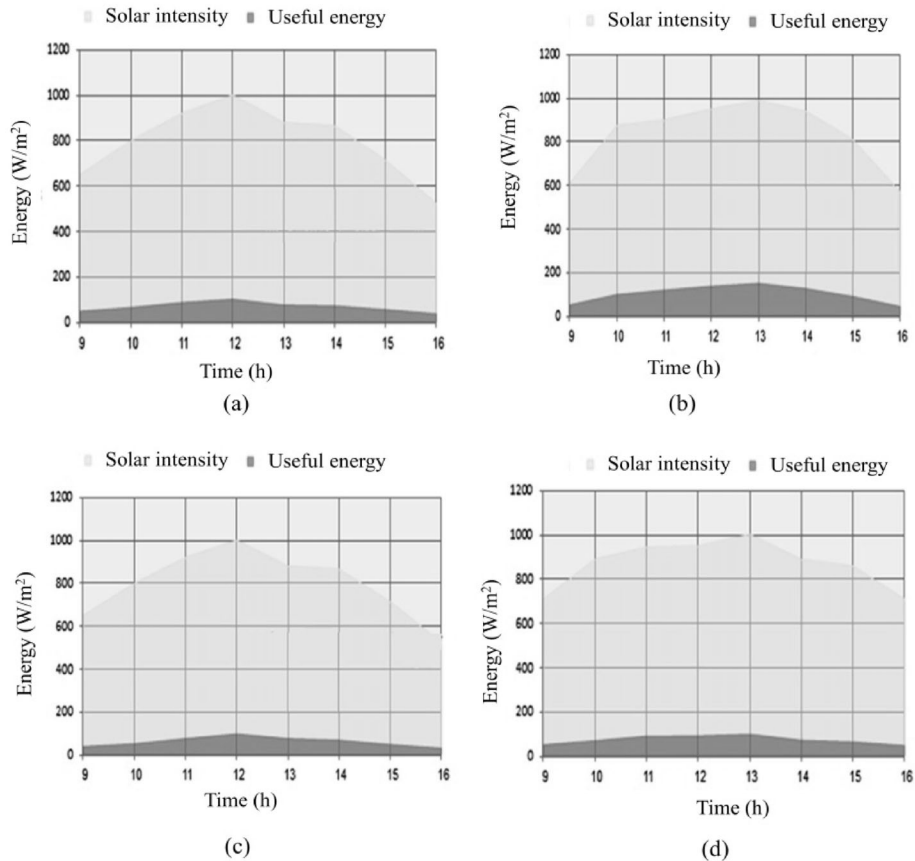


Fig. 7. Variation of Useful Heat Gain and Solar intensity at mass flow rate of 0.0067 kg/s.

Sun position, and the pump was switched on about 20 min before recording the first reading. The system started operation at 8.30 a.m., and the records were taken from 09:00 a.m. to 05:00 p.m. every half an hour. The period between every reading was 30 min. The flow rate was steady, and the heat transfer was kept constant for one to be sure that the correct reading was recorded. Four different mass flow rates were recorded for the receiver tube.

4. THERMAL EFFICIENCY AND USEFUL GAIN OF COLLECTOR

The thermal efficiency η of the collector [20], which is the ratio of the useful heat gain to the total input solar energy under steady-state conditions, can be obtained mathematically. The following equation calculates the thermal efficiency of the parabolic trough solar collector for hot water:

$$\eta = \frac{Q_u}{I.A_a} = \frac{\dot{m}c_p(T_o - T_i)}{I.A_a},$$

where Q_u is the useful heat gain, [W], $\dot{m}$ is the mass flow rate of water through the collector, [kg/s], c_p is the specific heat capacity of water, [J/kg·K], T_o is the water temperature at the collector outlet, [K], T_i is the water temperature at the collector inlet, [K], A_a is the collector aperture area, [m²], and I is the intensity (beam or direct radiation), [W/m²].

The rate of energy gained by the water in the storage tank for a time interval of 1 hour is given by the following expression [21]:

$$Q_s = m_w c_p (T_o - T_i),$$

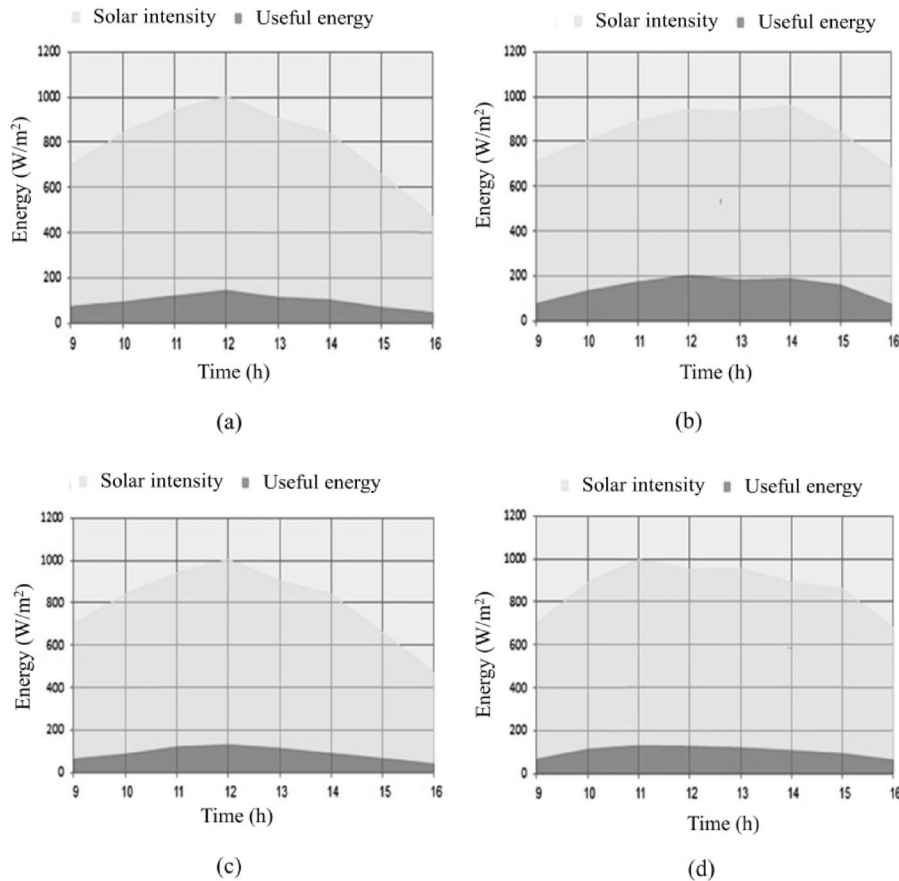


Fig. 8. Variation of Useful Heat Gain and Solar Intensity at mass flow rate of 0.005 kg/s.

where Q_s is the energy storage in the storage tank [KJ/hr] and m_w is the mass of water in the storage tank [kg].

5. RESULTS AND DISCUSSION

The experimental work was performed on a parabolic trough solar collector with an aluminum reflector, tubes of different materials and diameters, and various flow rates. A digital thermocouple sensor measured the fluid temperature at the receiver tube inlet and outlet. A pyranometer measured the solar radiation intensity.

The overall thermal efficiency of the parabolic trough solar collector was calculated. The thermal efficiency was measured at different solar radiation intensities during the day. The measured parameters were calculated under steady-state conditions as functions of time for one hour period.

The PTSC had various components such as the structure, tracking system, reflector absorber tube etc. In this experiment, copper and stainless steel tubes were used, as well as a glass cover tube of 58mm in diameter. The components were as follows:

- copper tube;
- stainless steel tube;
- copper tubes with glass cover tube;
- stainless steel tubes with glass cover tube.

The parabolic trough solar collector system was subjected to experimental analysis regarding the generation of hot water. The results showed the thermal efficiency, useful heat gain, temperature change between the inlet and outlet of the absorber tube, intensity, and time. Each parameter was represented graphically. The results showed four cases for four different mass flow rates.

The results were compared for different parabolic trough solar collectors with two materials of absorber tube: copper and stainless steel and four mass flow rates. As shown by the results, the best

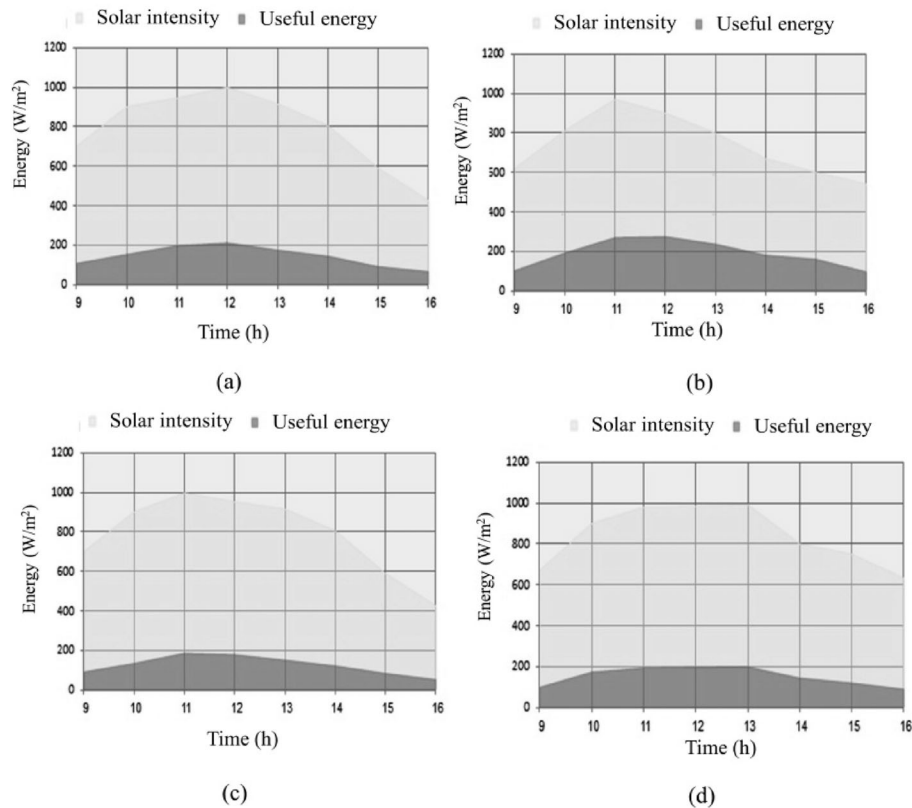


Fig. 9. Variation of Useful Heat Gain and Solar Intensity at mass flow rate of 0.0035 kg/s.

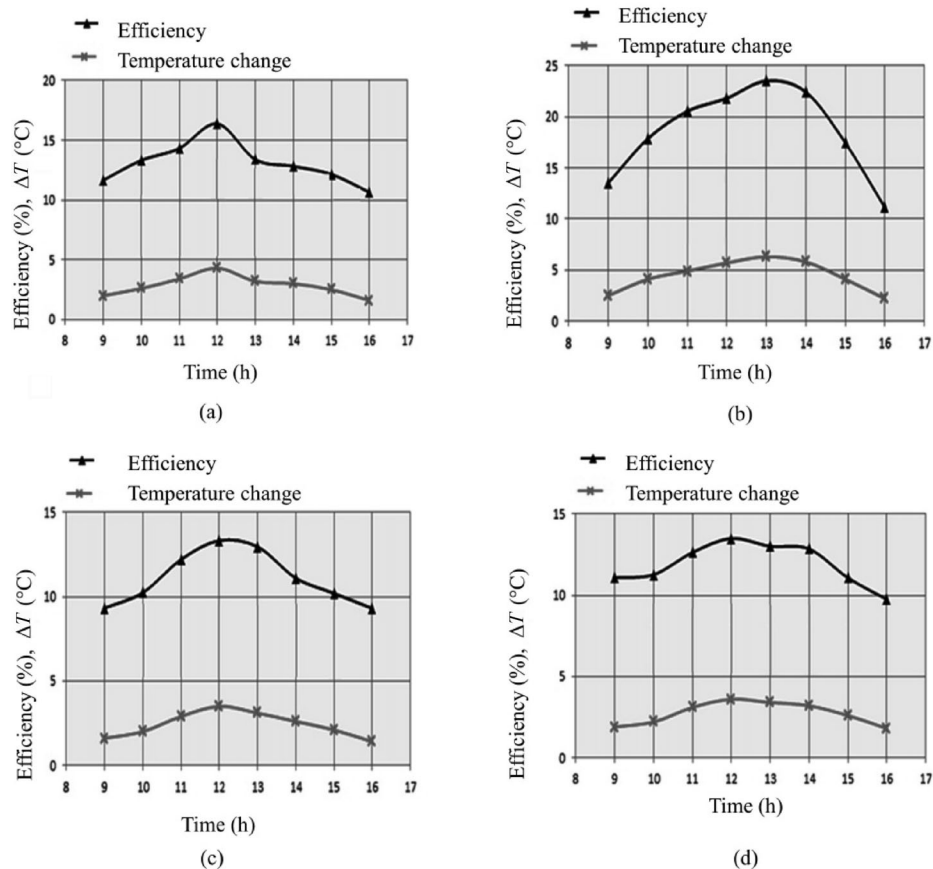


Fig. 10. Efficiency and temperature change at mass flow rate of 0.0087 kg/s.

efficiency was achieved with the copper tube because of the high conductivity of copper, which is considerably better than that of stainless steel.

Therefore, the temperature difference was higher with the copper tube. It can be observed that the performance of the collector increased with the glass cover tube. The glass cover tube reduced the heat losses and enhanced the performance of the parabolic trough solar collector system due to better greenhouse effect between the glass and tube. Figures 2, 3, 4, and 5 show the change in the inlet, outlet, and ambient temperatures in all cases recorded in this experimental investigation. The temperature increased with time until it reached a maximum value at around 1 to 2 p.m.

Figures 6, 7, 8, and 9 show all useful energy and solar radiation versus time. The amount of energy benefited from the solar intensity.

The system efficiency was estimated for various parameters. The efficiency was associated with the solar radiation and the temperature difference at the collector inlet and outlet. Figures 10, 11, 12, and 13 show the parameters versus time. It can be observed that when the mass flow rate was 0.0087 kg/s, the maximum value of the thermal efficiency was 23.54% with the glass covered copper tube, and the maximum amount of useful heat gain was 110.25 W. The thermal efficiency and useful heat gain for stainless steel were less than those for copper.

The thermal efficiency, which increased slowly with a mass flow rate of about 0.0067 kg/s, was 24.5%; the useful energy measured was 145.25 W. When the mass flow rate was 0.005 kg/s, the thermal performance of the collector was better than that at mass flow rates of 0.0087 kg/s and 0.0067 kg/s.

The maximum thermal efficiency and useful energy with the glass covered copper tube were 25.83% and 194.25 W, respectively. A mass flow rate of 0.0035 kg/s resulted in a better temperature difference across the absorber tube. The maximum efficiency and useful energy were 26.3% and 264.25 W, respectively.

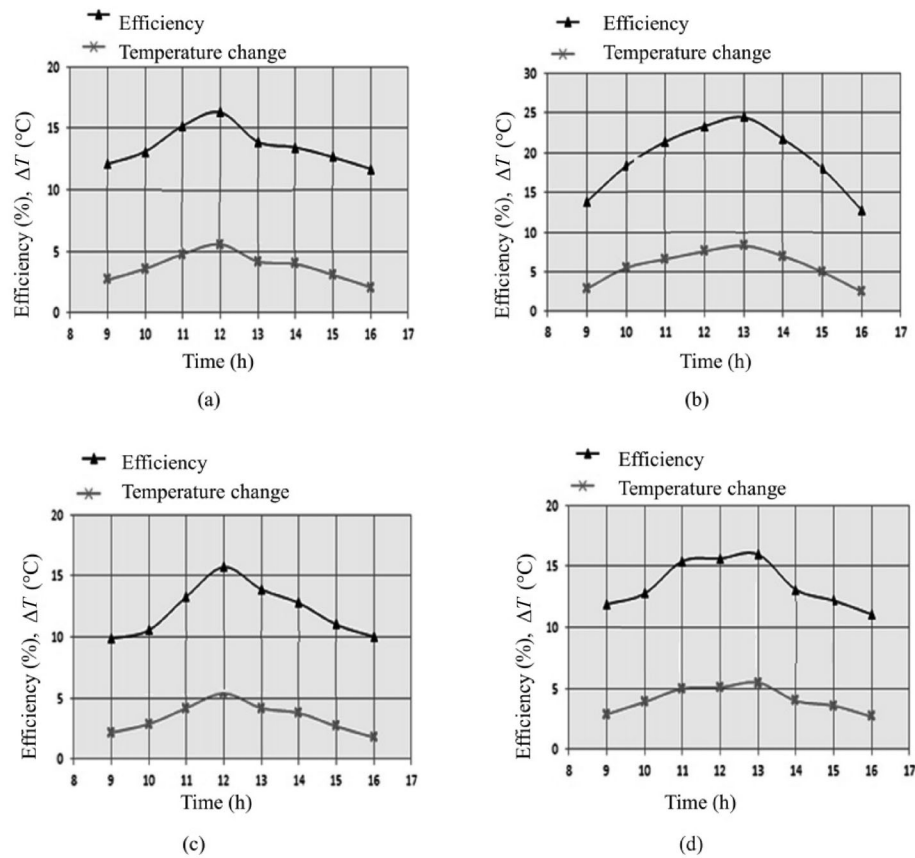


Fig. 11. Efficiency and temperature change at mass flow rate of 0.0067 kg/s.

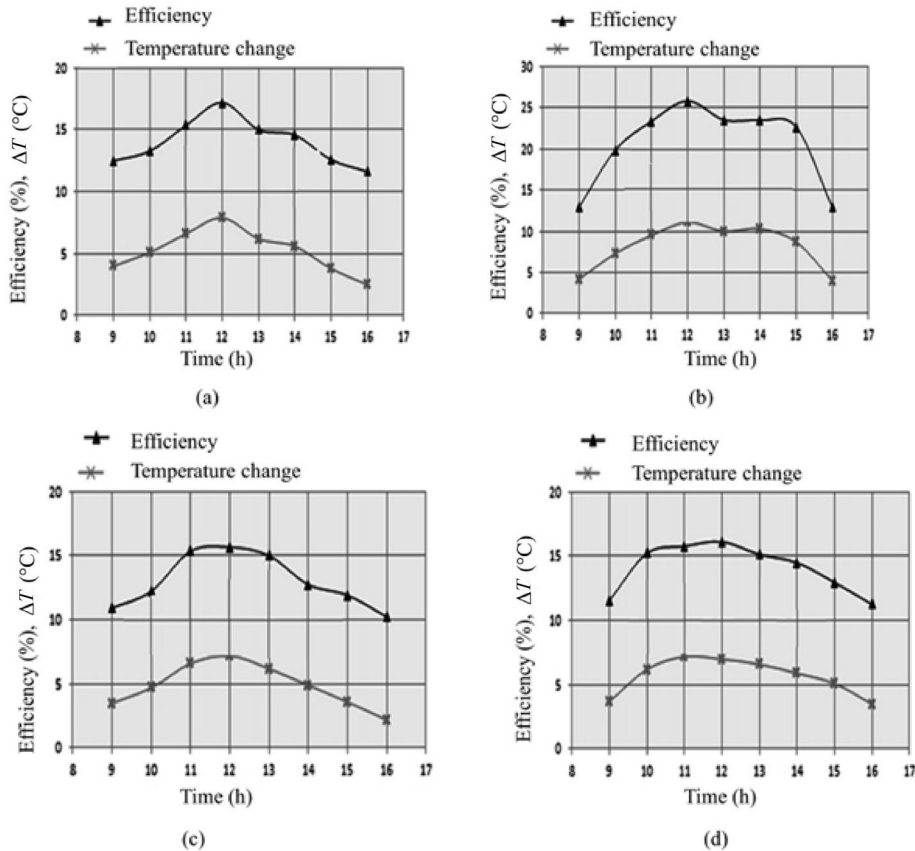


Fig. 12. Efficiency and temperature change at mass flow rate of 0.005 kg/s.

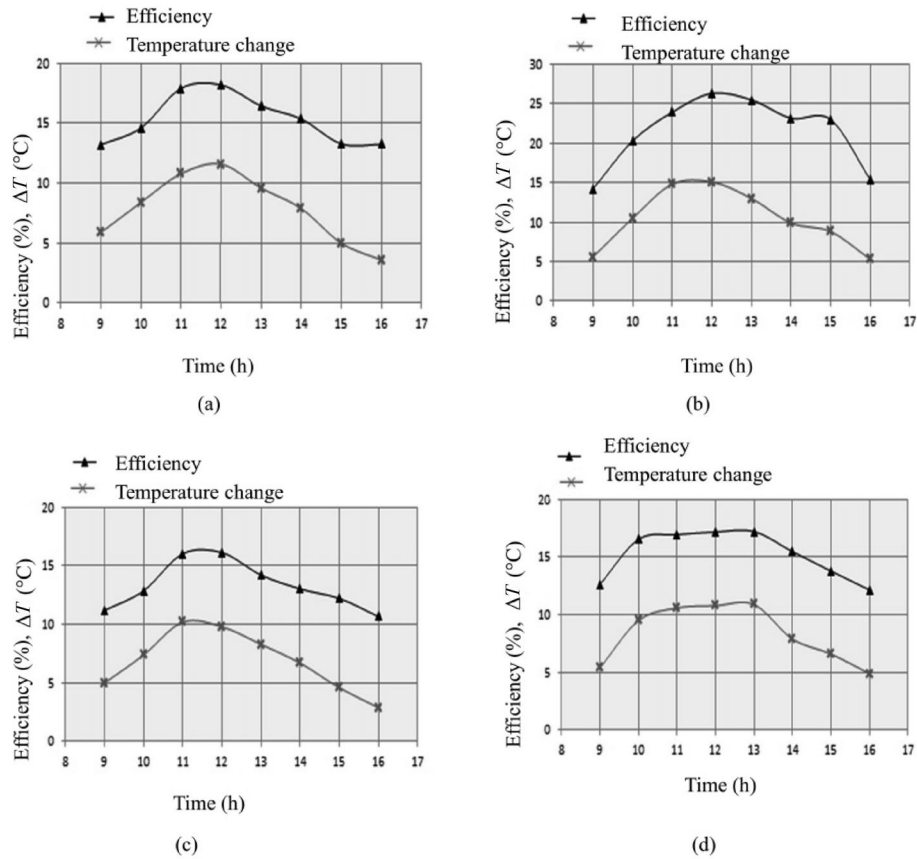


Fig. 13. Efficiency and temperature change at mass flow rate of 0.0035 kg/s.

It is better than in the other cases. The best results were obtained when the glass-covered copper tube was used as the absorber and the mass flow rate was 0.0035 kg/s. So, it is the best situation to get the best thermal performance. The efficiency of a real PTSC was higher than that measured in our system.

6. CONCLUSIONS

The parabolic trough solar collector is mainly used for power generation, the steam temperature got from high temperature. The PTSC system can find many applications, e.g., in air heating and generation of steam and hot water. In this case, the system is used for production of hot water.

Aluminum is used for the reflector surface because of its very high reflectivity. The absorber tube materials are copper and stainless steel. In this study, various parameters were measured for the absorber tube with and without glass tube. The solar radiation, system efficiency, and temperature at the inlet and outlet of the receiver tube were measured.

The system was east-west aligned and rotated through a required angle every 1 hour using manual tracking. In each case, the results obtained were the intensity of solar radiation, useful heat gain, and thermal efficiency. The performance of the PTSC system was measured based on the recorded parameters.

The conclusions of the present study are as follows.

- The performance of the PTSC system with the copper receiver tube at mass flow rates of 0.0087 kg/s, 0.0067 kg/s, 0.005 kg/s, and 0.0035 kg/s and the maximum efficiency obtained was 16.386%, 16.317%, 17.217%, and 18.2%, respectively.
- The performance of the PTSC system with the stainless steel receiver tube was worse than that with the copper tube.

- The glass cover tube reduced the heat losses and enhanced the system performance by improving the glass and tube greenhouse effect.
- The performance of the PTSC system with the glass covered copper receiver tube at mass flow rates of 0.0087 kg/s, 0.0067 kg/s, 0.005 kg/s, and 0.0035 kg/s and the maximum efficiency obtained was 23.54 %, 24.453 %, 25.83 %, and 26.4 %, respectively.
- The best results were obtained when the glass covered copper tube was used as the absorber and the mass flow rate was 0.0035 kg/s. So, it is the best situation to get the best thermal performance.

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