Original Research Article

Performance Assessment of Solar ParabolicTrough Collector with Varied Receiver Tube Materials

ABSTRACT

Renewable energy is the most promising energy-saving and environmentally friendly option. The concentrating type solar collector like parabolic trough collectorscan be utilized for solar thermal energy collection due to low cost and high-temperature output. The paper is an experimental study of a solar parabolic trough collector with manual sun tracking. A parabolic trough with an area of 2.5×1.75 m² was constructed for the present study. A highly polished aluminum sheet for concentrating the reflecting sunlight to the focal line contains the receiver tube. The parabolic trough was tracked at regular interval of one hour concerning the sun position and focused the sunlight into the receiver tube to ensure sound performance. Water is used as a working fluid inside the receiver tube, and experiments were done with three different mass flow rates of 0.0072,0.0112 and 0.0158 kg/s. Two heat-collecting elements, such as a stainless-steel receiver tube and a glass-coated copper receiver tube, were tested with a parabolic trough. The performance was analyzed based on the difference in the inlet and outlet temperature of the working fluid at the ends of the receiver tubes of the parabolic trough. The instantaneous efficiency of the parabolic trough with two different materials of receiver tube at three different flow rates were evaluated. The results showed that the glass coated copper tube surpassed in performance compared with stainless steel receiver tubes.The instantaneous efficiency of the glass coated copper tube is found to be 71.17% at a flow rate of 0.0158 kg/s which was significantly high when compared with that of the stainless-steel receiver tube. The glass coated copper tube prevents the convective heat transfer loss and thereby increases the efficiency. The experiment shows that the performance of the parabolic trough solar collector strongly depends upon solar light tracking and the focal line containing the receiver tube.

Keywords: Solar, Parabolic trough, Receiver tube

1. INTRODUCTION

For an energy-deficient nation, solar-assisted energy generation technology is a sustainable solution for energy saving and environmental protection instead of fossil fuels. Solar technology does not increase greenhouse gases but does not create polluted particles [1]. Among different solar thermal equipment, the parabolic trough collector is the most common and best-known type of solar collector with lower cost [2]. Most solar power plants employ parabolic trough solar technology for generating thermal power [3]. Solar irradiation from the sun is collected on the surface of the collector and reflected into the absorber tube. The solar intensity varies throughout the day, with the highest intensity typically occurring around noon. For maximum solar thermal energy harness, systems must tilt and turn solar parabolic troughs to follow the sun's path across the sky throughout the day. Generally, water is used as the working fluid inside the absorber tube. The concentrating solar irradiation into the absorber tube containing working fluid is heated. This converted heat energy is used for various purposes like drying agricultural products, building heating, industrial process heat, producing electric power, and industrial steam generation.

Among concentrating-type solar collectors, the parabolic trough collector is chosen for steam generation because it is stable in high-temperature applications with less area for heat loss. The direct steam generation parabolic trough is a promising technology for solar-assisted seawater desalination [4]. However, parabolic trough solar collectors are a popular topic in power generation and seawater desalination. One crucial component of solar parabolic trough systems is the receiver tube, which plays a pivotal role in capturing and transferring the concentrated solar energy. This comparative study aims to explore the feasibility of the diverse receiver tube materials and their impact on the overall performance of solar parabolic trough collectors.

2. MATERIAL AND METHODS

2.1 Working of the solar parabolic trough collector

The basics of a parabolic trough collector are based on the solar radiation from the sun collected over the area of the reflecting surface and reflecting sun rays concentrated into the focal line of the parabola. The parabolic trough consists of a long, curved, parabolic-shaped reflector (often made of polished metal or another highly reflective material) that focuses incoming sunlight onto a linear receiver tube positioned at the parabola's focal point. High temperatures can be reached by concentrating the radiation from a large area to a small point. The receiver tube contains fluid to be heated. The parabolic trough collector was tracked manually which follows the sun with respect to the sun's position for collecting solar radiation. The parabolic collector includes the receiver tube, the concentrator, the power transmission, and the collector structure [5].In the absorber tube, the conversion of concentrated solar energy to thermal energy occurs. The losses in collectors are classified as a) Conductive losses: Heat transfer occurs through adjacent surfaces by conduction; this can be minimized by placing insulating materials in place of good conductors of heat. b) Convective losses: Heat losses due to carrying heat by some medium, like air from the surface, can occur in these devices and be minimized by closing all the air gaps [6]. The conceptual diagram is shown in the Fig.1. [7].

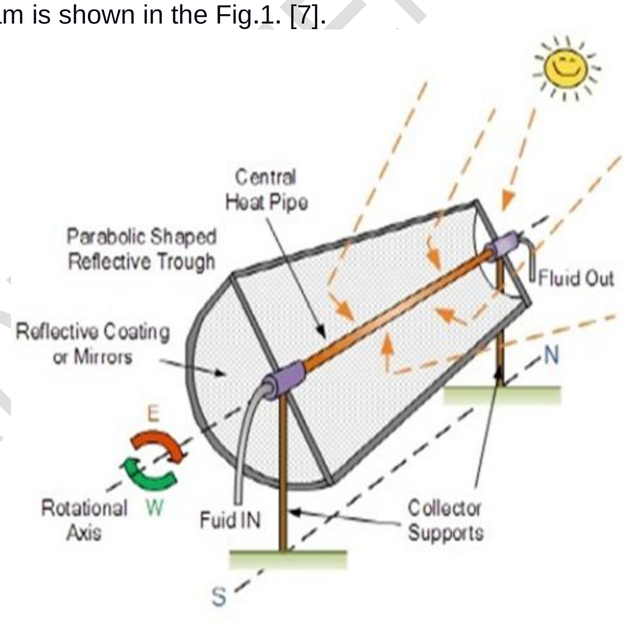

Fig.1. Parabolic Trough Collector [7]

2.2 Development of the solar parabolic trough collector

The experimental set up consisted of the following components

a) Parabolic trough with reflecting surface
b) Stainless steel absorber tube

c) Glass coated absorber tube
d) Resistance Temperature detector (RTD)
e) Flow meter
f) Pyranometer
g) Collecting tank
h) Motor

Table 1. Parameters of Solar Parabolic trough

Feature/parameters	Value
Collector dimension	2.5m x1.75 m
Collector area	4.375 m^2
Absorber tube diameter	25 mm
Glass tube diameter	40 mm
Length of receiver tube	2.5 m
Tilt factor	1
Specific heat of water	4180 J/kgK

The trough comprised high fiber weighing about 55 kg with a trough length of 2.5 m and a width of 1.75 m. It was covered with any of the reflecting material of polished aluminum sheet. The technical details of the solar parabolic trough are given in Table 1. The completed trough was mounted on the stands, with a height of about 2 m. The working fluid flows through the GI tubes above the trough. The receiving tube was coated with black paint. RTD was inserted at the inlet and outlet of the black-coated receiver tube to sense the inlet and outlet temperature of the working fluid. The end of RTD was connected to the virtual lab (lab view) monitor. From the arrangement, the temperature at each interval of time could be found. The flow meter was connected between the inlet and motor of the system to adjust or measure the flow rate of the working fluid using the virtual lab monitor through the lab view technique [8]. The liquid is then allowed to flow through the receiver tube with a centrifugal pump. The pipe connection was ended to a collecting tank. The collecting tank has a volume of 500 liters.

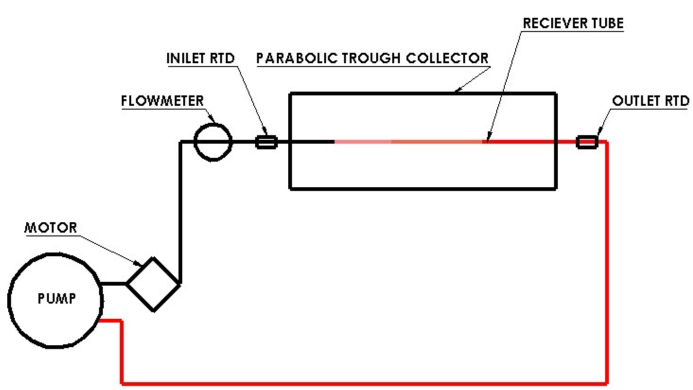

Fig.2 Schematic flow diagram of experimental set up.

The performance of the solar parabolic trough collector with a receiver tube of black color-coated stainless-steel pipe and glass-coated copper tube was assessed.

Fig.3 Experiment setup using stainless steel tube as receiver tube

In the first experiment setup with black colour coated stainless steel receiver tube, parabolic trough was oriented in north-south direction. The focal line of the parabolic trough black coated stainless-steel tube placed as receiver tube and the inlet and outlet connection was completed with GI pipes. For measuring the inlet and outlet temperature two RTDs were connected at the inlet and outlet section of the trough. In the second experiment, parabolic trough of same dimension with glass coated copper tube was used as the receiver tube (Fig.4). It had glass tube covering with 40 mm diameter. Using glass covering conventional heat loss due to wind could be reduced. Water was used as the working fluid for both experiments. The experiments were done with three different flow rates of 0.0072 kg/s, 0.0112 kg/s, 0.0158 kg/s, which were adjusted with a flow meter arranged at the inlet section of the trough. The temperatures of consecutive three days on hourly basis were measured with the inlet and outlet RTDs. The experimentswerecarried out on a sunny day of February and time was in between 9:00 am to 5:00 pm with a time interval of one hour. The intensity of irradiation measured using the pyranometer and solar irradiation intensity in the test location was 700 W/m^2. The performance of a solar heating panel strongly depends on the solar radiation received throughout a day [9]. The sun is tracked manually with its orientation.

Fig.4 Experimental setup using glass coated copper tube as receiver tube

The instantaneous efficiency of parabolic trough was calculated by using the following equation [7],

$$\text{Instantaneous efficiency}, \eta = \frac{Q}{A_c \times H_b \times R_b} \times 100$$

Where,
Q = Net useful heat gained by fluid (W)

$Q = m\ C_p\ (T_f - T_i)$
m = Mass flow rate of fluid (kg/s)
C_p = Specific heat of fluid (J/kgK) = 4180 J/kgK for water
T_f = Maximum temperature attained by fluid (°C)
T_i = Initial temperature of fluid (°C)
A_c= Area of collector (m^2) = 4.375m^2
H_b= Intensity of irradiation (W/m^2) = 700 W/m^2 in test location
R_b = Tilt factor for beam radiation = 1 (Assuming collector is always normal to incomingbeam radiations)

2.3 Statistical analysis

The statistical analysis was carried out to assess the effect of two different materials and three different flow rates on instantaneous efficiency of parabolic solar trough collector. Two factorials experiment was applied to study the effect.

3. RESULTS AND DISCUSSION

The instantaneous efficiency of the parabolic trough with different receiver tube at different flow rate were discussed in the following. Table 2. shows the inlet and outlet temperature of stainless-steel and glass coated copper receiver tube with flow rate of 0.0072 kg/s.

Table 2. Inlet and outlet temperature of stainless-steeland glass coated copper receiver tube with flow rate of 0.0072 kg/s

Sl.No	Time (24 Hours Format)	Stainless-steel receiver tube		Glass coated copper receiver tube	
		Inlet Temperature (°C)	Outlet Temperature (°C)	Inlet Temperature (°C)	Outlet Temperature (°C)
1	9	35	44	32	39
2	10	37	49	34.5	56
3	11	40.5	57	42	62
4	12	43	64	46	81
5	13	45	71.5	52	100
6	14	44	67	50	89
7	15	42.5	61	47	75
8	16	40	55.5	45	64
9	17	39	53	43	60

Heat, $Q = mC_p\ (T_f - T_i)$
T_f = Final temperature = 71.5 °C
T_i = Initial temperature = 45 °C
Q = 0.0072 X 4180 X (71.5 – 45)
= 795.33 W

$$\text{Instantaneous efficiency}, \eta\ = \frac{795.33}{4.375 \times 700 \times 1} \times 100\ = 25.97\ \%$$

For mass flow rate 0.0072 kg/s using receiver tube with stainless steel receiver tube, the maximum temperature obtained was 71.5°c and the efficiency of 25.97%.The calculated efficiency for mass flow rate of 0.0072 kg/s using glass coated copper tube as receiver tube as follows.

Heat, $Q = m\, C_p\, (T_f - T_i)$
T_f = Final temperature = 100 °C
T_i = Initial temperature = 52 °C
Q = 0.0072 X 4180 X (100 – 52)
= 1440.60 W

$$\text{Instantaneous efficiency}, \eta \ = \frac{1440.60}{4.375 \times 700 \times 1} \times 100 \ = 47.04\ \%$$

For glass coated copper tube as receiver tube, the maximum temperature obtained was 100°C and efficiency about 47.04%. The variation of temperature against time for a flow rate of 0.0072 kg/s with stainless steel and glass coated copper tube for a flow rate of 0.0072 kg/s is shown in Fig. 5.

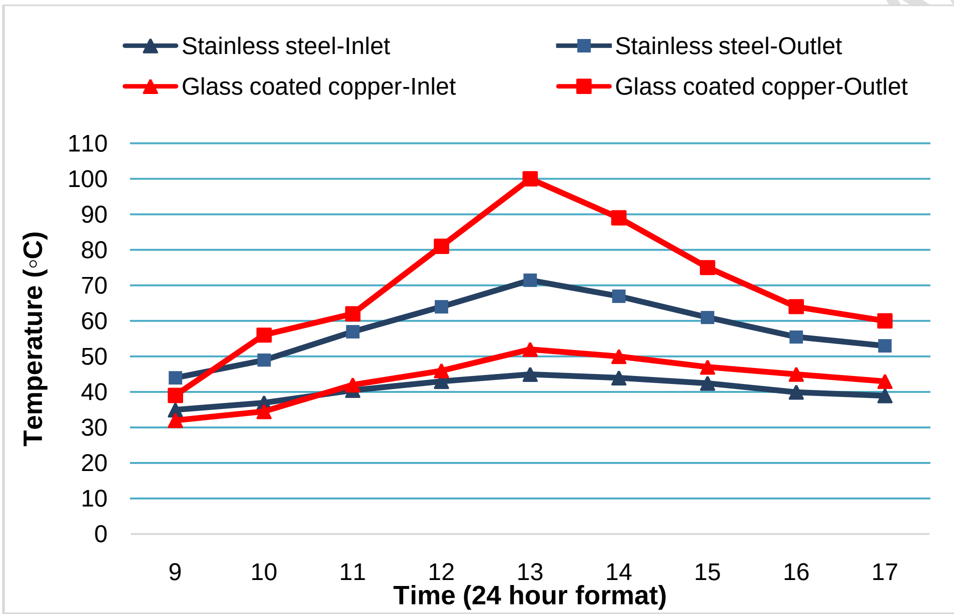

Fig.5 Variation of temperature against time for a flow rate of 0.0072kg/s using both absorber tube.

For a flowrate of 0.0112 kg/s, experiments were done using both absorption tubes. The inlet and outlet temperature of stainless-steel and glass coated copper receiver tube with flow rate of 0.0112 kg/s is shown in Table 3.

Table 3. Inlet and outlet temperature of stainless-steel and glass coated copper receiver tube with flow rate of 0.0112 kg/s.

Sl.No	Time (24 Hours Format)	Stainless-steel receiver tube		Glass coated copper receiver tube	
		Inlet Temperature (°C)	Outlet Temperature (°C)	Inlet Temperature (°C)	Outlet Temperature (°C)
1	9	35	41.5	34	40
2	10	37.5	45	38	59
3	11	38	51	41	65
4	12	40	56	43.5	77
5	13	43	65	46.5	88
6	14	42	62.5	45	70

7	15	40.5	57	43.7	69
8	16	38	54	43	60
9	17	37	50.5	34	40

The efficiencycalculation for a mass flow rate of 0.0112 kg/s using stainless steel receiver tube as follows

Heat, $Q = m\ C_p(T_f - T_i)$

T_f = Final temperature = 65°C

T_i = Initial temperature = 43 °C

Q = 0.0112 X 4180 X (65 – 43)

= 1029.95 W

$$\text{Instantaneous efficiency}, \eta \ = \frac{1029.95}{4.375 \times 700 \times 1} \times 100 \ = 33.63\ \%$$

The maximum temperature obtained in this case was 65 °C and with efficiency of 33.63%. The efficiency of the glass coated copper absorber tube with a flow rate of same mass flowrate of 0.0112 kg/s is calculated as follows.

Heat, $Q = m\ Cp\ (T_f - T_i)$

T_f = Final temperature = 88°C

T_i = Initial temperature = 34 °C

Q = 0.0112 X 4180 X (88 – 46.5)

= 1942.86 W

$$\text{Instantaneous efficiency}, \eta \ = \frac{1942.86}{4.375 \times 700 \times 1} \times 100 \ = 63.44\ \%$$

The maximum temperature obtained is 88 °C and efficiency is about of 63.44%. The variation of temperature against time for a flow rate of 0.0112 kg/s using both absorber tube is shown in Fig.6

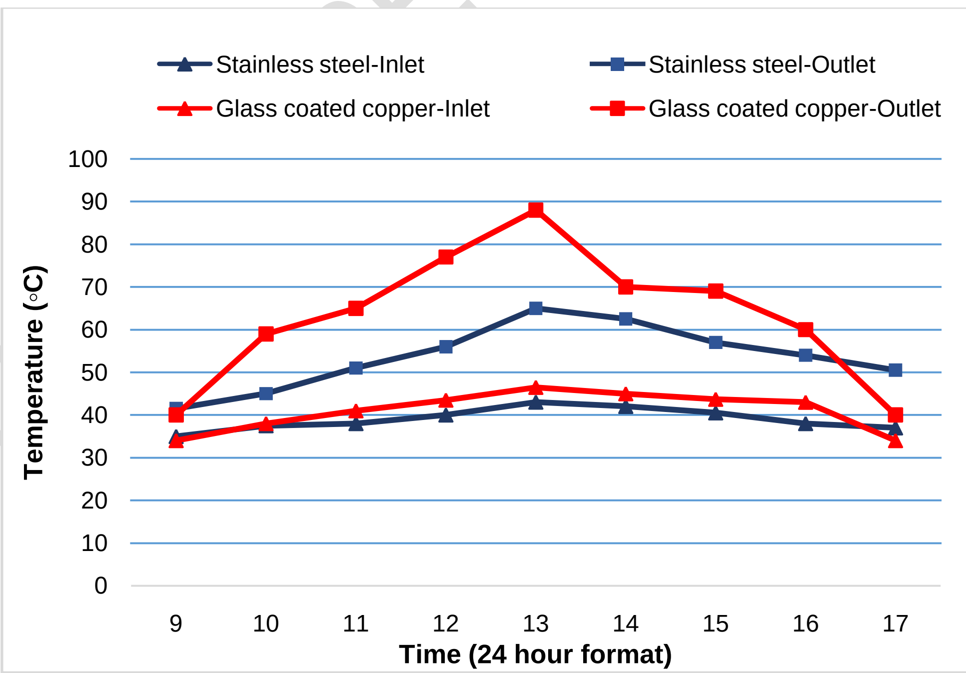

Fig.6 Variation of temperature against time for a flow rate of 0.0112 kg/s using both absorber tube

The experiments were conducted with both stainless steel and glass coated copper tube for a flow rate of 0.0158 kg/s. The inlet and outlet temperature of stainless-steel and glass coated copper receiver tube with flow rate of 0.0158 kg/s. is shown in Table 4.

Table 4. Inlet and outlet temperature of stainless-steel and glass coated copper receiver tube with flow rate of 0.0158 kg/s.

Sl.No	Time (24 Hours Format)	Stainless-steel receiver tube		Glass coated copper receiver tube	
		Inlet Temperature (°C)	Outlet Temperature (°C)	Inlet Temperature (°C)	Outlet Temperature (°C)
1	9	35	40	33	38
2	10	37	43	37	41.3
3	11	38.5	47.5	39.5	59
4	12	40	54.5	42	67
5	13	42	60.5	43	76
6	14	41.5	56	42.5	70.1
7	15	39	52	42	64
8	16	38	49	41.7	59.5
9	17	37	47.5	41	54

The efficiency of stainless-steel tube and glass coated copper tube at a mass flow rate of 0.0158 kg/s calculated as follows.

Heat, $Q = m\,C_p(T_f - T_i)$

T_f = Final temperature = 60.5 °C

T_i = Initial temperature = 42 °C

Q = 0.0158 X 4180 X (60.5 – 42) = 1221.81W

$$\text{Instantaneous efficiency}, \eta \ = \frac{1221.81}{4.375 \times 700 \times 1} \times 100 \ = 39.90\ \%$$

The maximum temperature obtained was found to be 60.5°C and the efficiency of 39.90 %. Similarly, the efficiency of the glass coated copper tube at the flow rate of 0.0158 kg/s was calculated as follows,

Heat, $Q = m\,C_p(T_f - T_i)$
T_f = Final temperature = 76°C
T_i= Initial temperature = 33 °C
Q = 0.0158 X 4180 X (76 – 43)
= 2179.45 W

$$\text{Instantaneous efficiency}, \eta \ = \frac{2179.45}{4.375 \times 700 \times 1} \times 100 \ = 71.17\ \%$$

The maximum temperature obtained using mass flowrate of 0.0158 kg/s is 76 °C and efficiency is about 71.17 %.The variation of temperature against time for a flow rate of 0.0158 kg/s using both absorber tube is shown in Fig.7

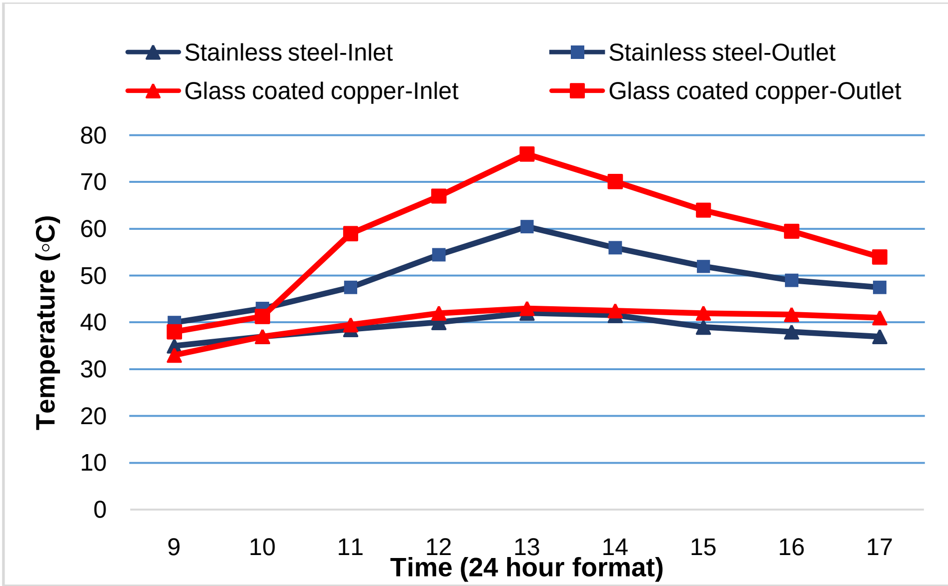

Fig.7 Variation of temperature against time for a flow rate of 0.0158 kg/s using both receiver tube

The maximum instantaneous efficiency of the two different receivertubes at three different flow rates of working fluid is shown in the Fig. 8. The maximum instantaneous efficiency obtained for glass coated copper tube was 71.17 % against 39.90% that of stainless-steel receiver tube at 0.0158 kg/s. The results shows that the instantaneous efficiency increased with the increase in flow rate.

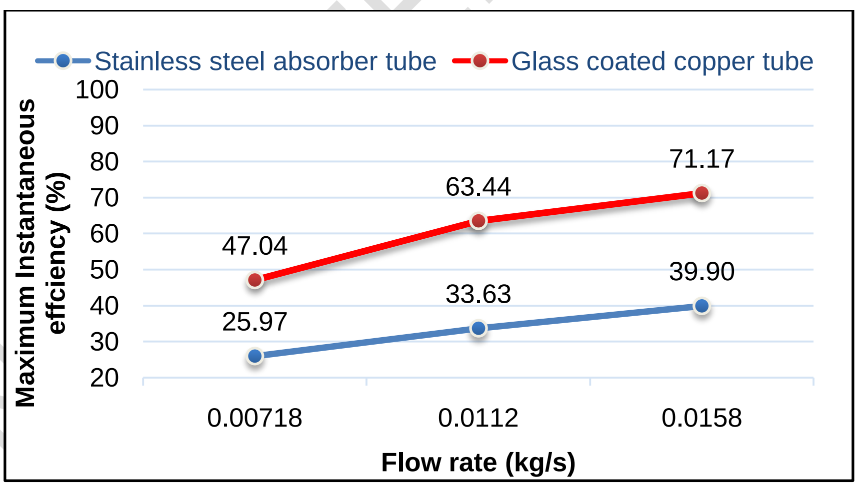

Fig.8 Variation of efficiency against mass flowrate

The effect of receiver tube material and flow rate on instantaneous efficiency of solar parabolic trough collector is shown in Table 5. The results showed that the model is statistically significant, as indicated by the p-value and the F-statistic (538.038) is also high for further supporting the overall significance of the model. The independent variables receiver tube material and flow rate are individually significant and the interaction between the variables shows high significance on dependent variable.

Table 5. Effect of receiver tube material and flow rate on instantaneous efficiency of solar parabolic trough collector

Dependent Variable: Efficiency

Source	Type III Sum of Squares	df	Mean Square	F	Sig.(*P*)
Corrected Model	4576.311[a]	5	915.262	538.038	<.001
Intercept	39517.976	1	39517.976	23230.685	<.001
Material	3372.942	1	3372.942	1982.788	<.001
Flowrate	1112.138	2	556.069	326.886	<.001
Material * Flowrate	91.231	2	45.616	26.815	<.001
Error	20.413	12	1.701		
Total	44114.700	18			
Corrected Total	4596.724	17			

a. R Squared = .996 (Adjusted R Squared = .994)

CONCLUSION

In the presented study the instantaneous efficiency of the solar parabolic trough with two different receiver tube material at three different flow rates of working fluid were determined. The maximum efficiency for stainless steel tube receiver is 39.90% and for glass coated copper tube receiver is 71.17%. For both receiver tube material maximum instantaneous efficiency was obtained for a mass flow rate of 0.0158 kg/s. The maximum temperature obtained for glass coated receiver tube used in the experiment was 100°C and that for stainless steel receiver tube was 71.5°C. From the experimental results it is concluded that the with same mass flow rate glass coated copper receiver tube is more efficient than stainless tube in converting water into steam in solar parabolic trough. The statistical analysis shows that the instantaneous efficiency of the glass-coated copper receiver tube is significantly higher than that of stainless steel.

REFERENCES

1. Kumar A, Lohit L. Improvements in efficiency of solar parabolic trough. IOSR Journal of Mechanical and Civil Engineering. 2013; 7(6): 63-75.
2. Zeroual B, Ahmed M. Design of parabolic trough collector solar field for future solar thermal power plants in Algeria.2[nd] International Symposium on Environment Friendly Energies and Applications. 2012: 168-172.
3. Hank P, Eckhard L, David K, Eduardo Z, Gilbert CRG, Rod M. Advances in Parabolic Trough Solar Power Technology. Journal of Solar Energy Engineering. 2002;124 (2):109-125.
4. Soteris K. Use of parabolic trough solar energy collectors for sea-water desalination. Applied Energy.1998; 60(2):65-88.
5. Robert O, Jens P. Dynamic modelling of a parabolic troughsolar power plant, Proceedings of the 10th International Modelica Conference: 2014: 1057-1066.
6. Pradeep KKV, Srinath T, Venkatesh R.Design, Fabrication and Experimental Testing of Solar Parabolic Trough Collectors with Automated Tracking Mechanism. International journal of research in Aeronautical and mechanical engineering. 2013;1(4): 37-55.

7. Rizwan M, Junaidi MAR, Suleman M, Hussain MA.Experimental Verification and Analysis of Solar Parabolic Collector for Water Distillation. International Journal of Engineering Research. 2014;3(10):588-593.
8. Brooks MJ, Mills I, Harms TM. Performance of a parabolic trough solar collector. Journal of Energy in Southern Africa. 2006; 17(3):71-80.
9. WengKY, Yin LL, Ji JF. Improvement of a solar heating panel's thermal efficiency: parabolic trough effect coupled with a porous packed bed. SEGi Review. 2011; 4(1):44-55.