

Thermal performance investigation of enhanced receiver tube for concentrated solar collector

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Abstract. This study presents an experimental investigation of conventional and enhanced receiver tube performance for the application of a concentrated parabolic trough collector (CPC). The CPC system is fabricated and tested for the conventional and enhanced receiver tubes. The experiments were performed on both tubes for the change of flow rates. The temperature rise of the tube surface, as well as working fluid, were monitored for varying flow rates. The results were compared and discussed in view of enhanced CPC system performance. The results exhibited that the temperature rise of the working fluid passing through the tube was more in the case of the enhanced tube compared to the conventional receiver tube under the same flow rates.

Keywords: enhanced receiver tube; parabolic trough collector; peripheral temperature variation; surface temperature; temperature rise

1. Introduction

The intensity of solar isolation in Oman is one of the highest in the world and it can fulfill a significant demand if explored successfully. It can be used for heating, electricity generation, process steam generation in the industry, and many other industrial and domestic applications. Solar radiation is a viable and sustainable alternative energy source to fossil fuel power generation, which is causing many environmental and health threats and global warming. The demand for power has raised significantly, which increases the consumption of fossil fuels and contributes to increasing the negative impact on the atmosphere (Epstein *et al.* 2011). Therefore, the application of solar energy is essential to be able to accommodate the continuous need for power generation. The CPC is one of the solar energy harvesting techniques and it mainly consists of a primary reflector, tube receiver, and a working fluid. This paper will focus on enhancing solar energy collection by enhancing the performance of the tube receiver.

Several improvements have been accomplished in the past for the receiver tube, and they can be classified into two general categories, geometric modifications, and material improvements. These enhancements use surface and geometrical modifications as well as modifying the flow channel of

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the tube by adding inserts or additional structures, which improves the heat transfer rate, however, the pressure loss also increases in the process (Sheikholeslami *et al.* 2015). The passive enhancements are widely adopted because of their capacity to increase the efficiency of the receiver tube. Torii *et al.* (2002) carried out an experimental study on inline and staggered arrangements of fins combined with vortex generators such as delta winglets, which is aimed to increase the heat transfer rate for a range of Reynolds number (350-2100). The results showed an increment in heat transfer by 10%-30%. Promvong (2008) conducted an experimental study on a conical ring insert and investigated its effect on the heat transfer performance and friction factor. The study tested different arrangements such as diverging conical ring, converging conical ring, and converging-diverging conical ring. The diverging conical ring yielded better heat transfer performance and the Nusselt number increase was about 333%. However, the results showed a considerable increase in the friction factor. Further, Promvong *et al.* (2010) examined experimentally the effect of combining ribs with winglets type vortex generators (WCGs) on the friction factor and forced convection heat transfer for turbulent flow. The experiments showed that the in-line arrangement was better than the staggered arrangement for friction factor and heat transfer.

Li *et al.* (2009) performed a numerical and experimental investigation to examine the double inclined ribs tube. The authors observed an increase in heat transfer in both investigations. Kumar and Reddy (2009) studied numerically the impact of a stainless-steel porous disk in the tube receiver and observed Nusselt number and pressure drop increase by 64% and 457 Pa, respectively. Eiamsaard and Promvong (2011) investigated the behavior of the heat transfer and the pressure drop in a tube with double-sided delta wings in a tape insert and observed an increase in Nusselt number by 165% with an enhancement in friction factor by 14.8 times. Reddy and Satyanarayana (2008) performed an experimentally investigated the effect of porous inserts of various designs such as square, triangle, trapezoidal and circular. The inserts were examined for different characteristic dimensions. The results showed that the trapezoidal shape gives the optimum heat transfer enhancement of 13.8% with a pressure drop of 1.7 kPa. Mwesigye *et al.* (2014) conducted a numerical analysis to study the effect of centrally placed perforated plate in a receiver tube at a range of Reynolds number. The Nusselt number is enhanced by 8%-133%, however, the friction factor is enhanced by 1.40-95 times. The overall improvement in the receiver tube efficiency was within 1.2%-8%.

Jaramillo *et al.* (2016) carried out an experimental investigation to investigate the effect of using a twisted tape inside the receiver tube. The results showed about a 1% improvement in thermal efficiency, although using twisted tape was not worth it. Fuqiang *et al.* (2016) introduced an outwardly convex corrugated and asymmetric tube to be utilized as a receiver tube. The author observed the maximum Nusselt number enhancement of 59% at Reynolds number of 67120. Chang *et al.* (2017) carried out a simulation study to investigate the effect of using a concentric and eccentric pipe insert in the receiver tube and observed a significant heat transfer. Huang *et al.* (2017) investigated the performance of a receiver tube with an inner dimpled surface. The Nusselt number is improved by 1.0-28%, however the friction factor is increased by 1.0-18%. Bellos *et al.* (2017) investigated the impact of the longitudinal rectangular fins in a receiver tube. The study was carried out for different length and thicknesses of longitudinal fins. For optimum case, the increase in Nusselt number was 65.8% with an enhancement of friction factor by 99.4%.

Bitam *et al.* (2018) numerically compared the thermal performance of a sinusoidal receiver tube with a conventional straight receiver tube and found an increase in both friction factor and Nusselt number by 45% and 40%, respectively. Loni *et al.* (2020) investigated a rectangular cavity receiver for varying cavity angle, position, and aperture angle. The authors found an increase in thermal

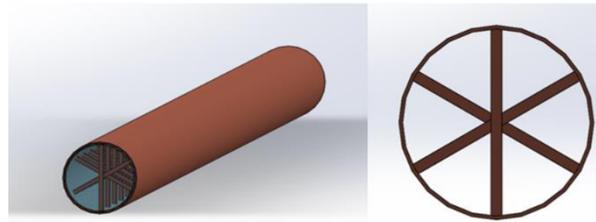


Fig. 1 Enhanced receiver tube with inside wire structures

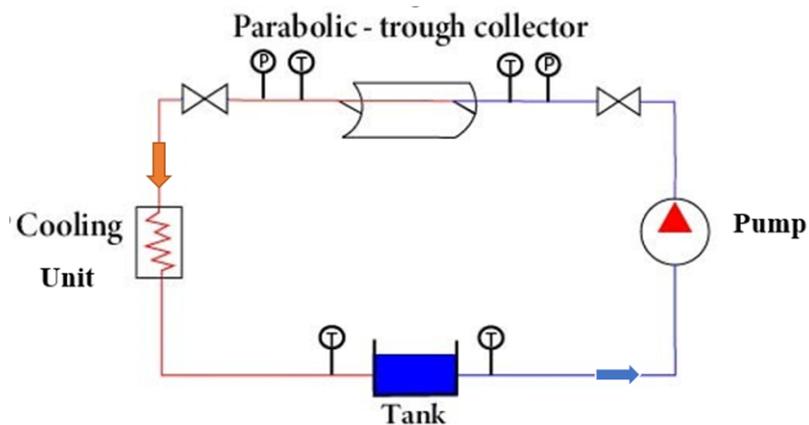


Fig. 2 Schematic of experimental setup with its components, and sensors

performance and power absorbance. In the present study, a wired structure is used inside the receiver tube to create flow deflection and separation of boundary layer. The protrusions are designed inside the receiver tube to create flow chaos and enhance flow mixing.

2. Design details and experimental setup

Fig. 1 shows the enhanced receiver tube structure with wired inner structure. The receiver tube is a 1.2 m long with a 20.7 mm inner diameter and 0.4 mm wall thickness. The receiver tube and passive wired structures are made of copper. The wires are spread to touch inner surfaces. The parabolic reflector is made of polished aluminum sheet, with a 1 m aperture width, 90° aperture angle, 266 mm focal length and 1.1478 m distance between rims making a total aperture area of 1.2 m².

The system used for conducting the experiment consists of several components, which are special purpose parts and standard parts. The enhanced receiver tube, the primary reflector, and supporting structure are designed and fabricated in-house. On the other hand, the pump, the valves, and the connecting pipes are standard purpose parts and selected from the shelf. Fig. 2 shows a schematic for the main components. K-type thermocouples are used to collect temperature distribution at the receiver tube surface, and to measure the inlet and outlet water temperatures with a data logger. Further, a flow meter for measuring the flow rate, a Pyranometer for measuring the solar incident flux are used to complete the setup.

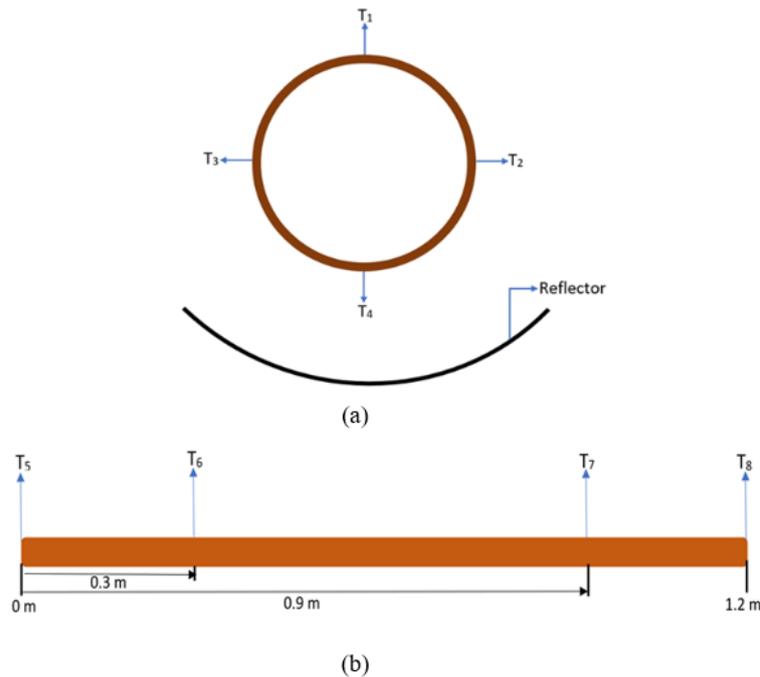


Fig. 3 The placement of thermocouples for surface temperature measurements (a) along the circumference, (b) along the length

The distribution of temperature on tube receiver surface is monitored with the help of thermocouples placed at the tube outer surface and a data logger. The placement of thermocouples is shown in Fig. 3.

The experiment was conducted for conventional as well as enhanced receiver tubes and the data were collected for analysis under different flow conditions and overtime at different heat flux conditions. The trough was inclined to receive the normal radiation and the rotation of the trough was controlled manually.

The heat energy received by water can be calculated as

$$Q = \dot{m}C_p\Delta T$$

The water temperature rise can be defined as

$$\Delta T = T_{out} - T_{in}$$

Where T_{in} and T_{out} are fluid inlet and outlet temperatures, respectively. The \dot{m} and C_p are the mass flow rate and specific heat of water, respectively.

3. Results and discusion

Figs. 4 and 5 show the variation of the receiver tube surface temperature along the length with the change of flow rate for the conventional and enhanced tube receiver, respectively. The

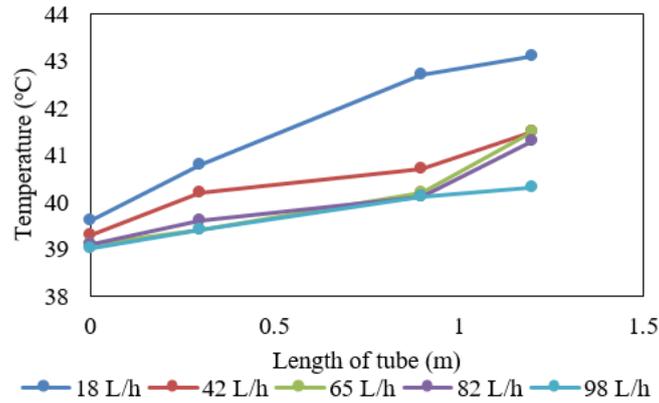


Fig. 4 The Temperature variation of the conventional receiver tube surface along the length with the variation of flow rate.

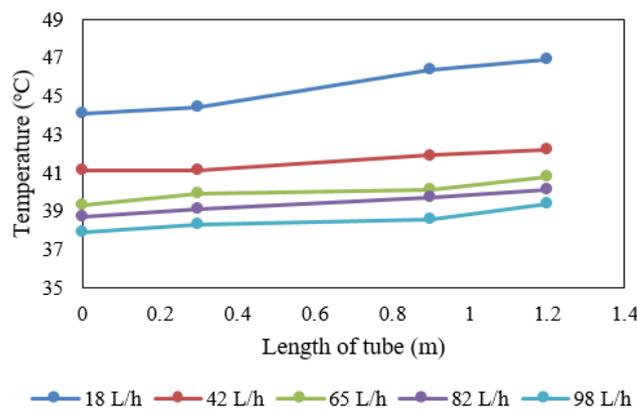


Fig. 5 The Temperature variation of the enhanced receiver tube surface along the length with the variation of flow rate

temperature of the tube receiver increases along the length in both cases. The fluid temperature increases as the fluid moves in the tube due to the increase in resident time of the fluid. The increased bulk fluid temperature reduces the rate of heat transfer as the fluid moves in the tube. This reduction in heat transfer increases the tube surface temperature in the flow direction. There is a monotonous increase in surface temperature with the decrease in flow rate. At low flow rate the fluid resident time in the tube increases and as a result, it receives more amount of heat energy while passing through the tube. The surface temperature increases at a higher rate at low rates compared to higher flow rates for both the tubes.

The temperature distribution along the periphery is shown in Figs. 6 and 7 for conventional and enhanced receiver tubes, respectively. The temperature is measured at four locations along the periphery as shown in Fig. 3(a). The temperature is the highest at a point (T_4), which is facing the reflector and receiving highest intensity of the concentrated radiation from reflector, and the lowest at the point (T_1), which is away from the reflector and no radiation is reaching to that point from reflector. The temperature at the points, which are laterally at an equal distance from the reflector

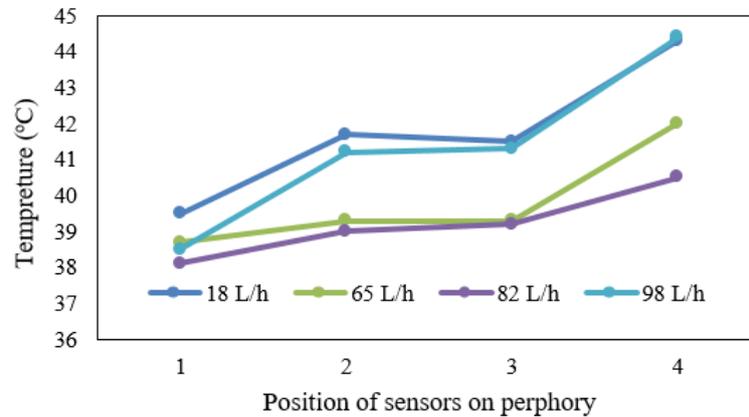


Fig. 6 The Temperature variation of the conventional receiver tube surface along the periphery with the variation of flow rate.

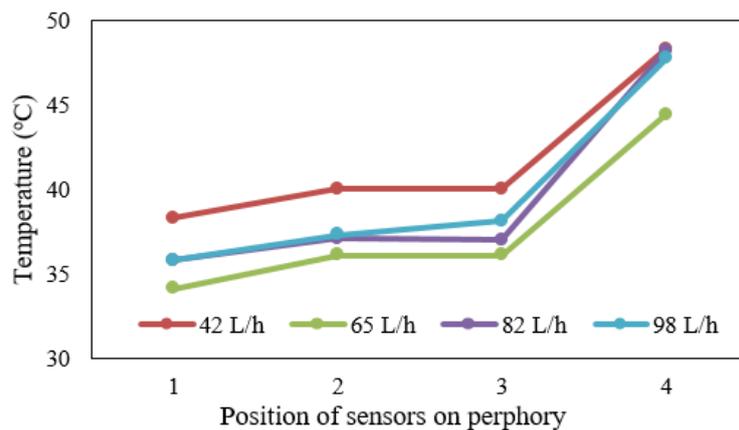


Fig. 7 The Temperature variation of the enhanced receiver tube surface along the periphery with the variation of flow rate

(i.e., points T_2 and T_3) is the same, which are receiving marginal radiations. The temperature variations are found to be the same for both conventional and enhanced receiver tubes; however, they are different in magnitudes.

Further, the temperature rise of the working fluid is measured with the change of flow rates for both conventional and enhanced receiver tubes as shown in Fig. 8. The inlet fluid temperature was kept almost constant and the rise in fluid temperature was monitored with the help of thermocouples and data logger. The resident time of the fluid increases with the increase in length and the fluid receives more amount of heat with the increase in length of the collector. However, the rise in temperature reduces with the increase in flow rate as the fluid residence time is reduced. The capacity of the fluid increases, which reduces the temperature monotonously in both conventional and enhanced receiver tubes with increase in flow rates. The enhanced tube showed almost 1°C higher temperature rise for almost all flow rates investigated in this study for a CPC of 1 m length and 1.2 m^2 aperture area.

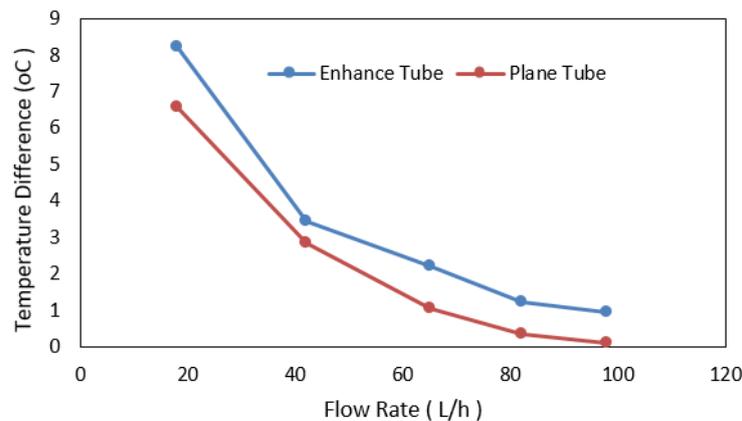


Fig. 8 The Temperature rise of the working fluid in conventional and enhanced receiver tubes

5. Conclusions

The current study investigates thermal performance of the CPC. The experiment is setup and an enhanced receiver tube is designed, fabricated and tested for the application of solar collector receiver. The thermal performance of the proposed enhanced receiver tube is investigated and compared with the conventional receiver tube. Generally, the temperature of the receiver tube surface increases along the length of the collector. The higher temperature was observed at the surface facing the tube and the lowest surface temperature was observed at the back of the tube. The enhanced tube shows better thermal performance and higher temperature rise of the working fluid at various flow rates investigated in this study compared to conventional receiver tube.

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