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Enhanced heat transfer in a parabolic trough solar receiver by inserting rods and using molten salt as heat transfer fluid☆

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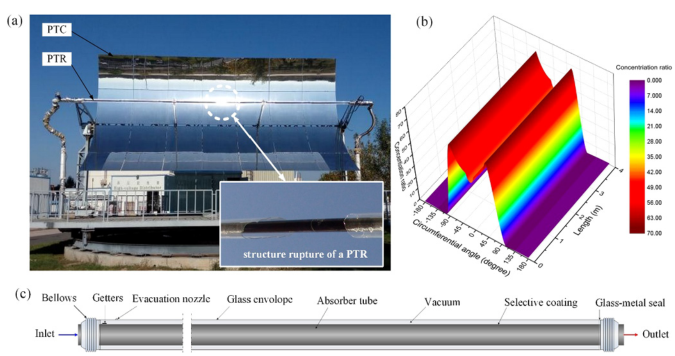
HIGHLIGHTS

- A three-dimensional model for a parabolic trough receiver with rod insert is developed.
- Effects of the rod insert key parameters are investigated.
- A comprehensive integrated performance factor is introduced and examined.
- The mechanism of molten salt heat transfer enhancement is revealed.
- Optimum rod parameters are recommended.

GRAPHICAL ABSTRACT

A typical parabolic trough solar collector system with damaged receiver tubes, the calculated non-uniform heat flux distribution, and the schematic structure of a parabolic trough receiver.



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ABSTRACT

With the aim to enhance the reliability and overall heat transfer performance of a parabolic trough receiver, concentric rod and eccentric rod are introduced as turbulators, and the flow and convective heat transfer characteristics of molten salt in a parabolic trough receiver are analyzed. A three-dimensional model was developed and has been validated with experimental results and empirical equations. Highly non-uniform heat flux was provided by a novel parabolic trough collector. The result shows that both concentric rod insert and eccentric rod insert can enhance the heat transfer performance effectively. For a parabolic trough receiver with a concentric rod insert, with the increasing of dimensionless diameter *B*, the normalized Nusselt number is about 1.10 to 7.42 times over a plain parabolic trough receiver. The performance evaluation criteria can't reasonably evaluate the effect of *B* growth on the comprehensive heat transfer performance. By introducing integrated performance factor, it can give a reasonable solution, and it shows that the integrated performance factor has a significance decreases with the increase of Reynolds number when *B* is larger than 0.8. With *B* increasing, the integrated performance factor of parabolic trough receiver with concentric rod insert decreasing under a certain Reynolds number. For an eccentric rod insert, the performance evaluation criteria and the integrated performance factor decrease with the increasing of Reynolds number under a certain dimensionless eccentricity *H*. The

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performance evaluation criteria decreases from about 1.84 to 1.68 times over a plain parabolic trough receiver when *H* is 0.8. Moreover, the temperature distribution can be uniformed and the maximum temperature on the absorber tube also can be remarkably reduced with the increasing of *B* and *H* under a certain Reynolds number, which helps to reduce the thermal deflection and increase the reliability for a parabolic trough receiver.

1. Introduction

Energy utilization and ecological environment are the hot issues in the current global social development [1–3], and almost 90% of the global energy budget centering around thermal energy conversion and storage [4–6]. Solar energy has been regarded as a promising inexhaustible source of clean energy due to its abundance and easy accessibility [7,8]. As a kind of sustainable and compatible electric generating technology, concentrated solar power (CSP) can solve the mismatch between energy generating supplies and user demand [9–12]. The International Energy Agency (IEA) predicts that CSP could meet up to 12% of the global electricity demand by 2050 [13]. Among the various CSP collection technologies, parabolic trough collector (PTC) is the most mature and widely used technology in the past decades [14–19]. However, due to the maximum operating temperature of heat transfer oil is less than 666 K, the further improvement of power generation efficiency has encountered bottlenecks. Increasing the concentration ratio (more than 100) and operating temperature (more than 700 K) are the key approaches to further improve the efficiency of PTC system. Heat transfer oil cannot work safely over 673 K to avoid decomposition [20]. Molten salt (MS) [21] has gained a lot of research and application due to its advantages of high working temperature (higher than 830 K), large specific heat, high thermal stability, low vapor pressure and low cost, etc. PTC with MS technology received special attention in recent years for its high performance and low-cost aspects [22]. A typical PTC system consists of an array of parabolic shaped mirrors to track the sun and concentrate the direct normal irradiance (DNI) onto parabolic trough receiver (PTR) tubes which are fixed at the PTC's focal line, as shown in Fig. 1a. The heat flux distributed on the PTR surface is extremely high and non-uniform, as presented in Fig. 1b. The PTR plays a vital role in absorbing solar energy and convert it into high-temperature heat, the principle structure of a PTR is illustrated in Fig. 1c. The overheating of the receiver tube and heat transfer fluid (HTF) and the induce structure rupture due to excessive thermal deformation are most likely to happen when the system works at high-temperature [23–25]. PRT typically account for 30% of the cost of a solar field. In order to avoid these damages, the issues of convective heat transfer and fluid flow of MS in PTR with extremely high and non-uniform heat flux are widely concerned [26,27]. Liu et al. [28] and Wu et al. [29] experimentally studied the MS convective heat transfer in a circular tube and obtained serval heat transfer correlations with circumferentially uniform heat flux. However, the non-uniform heat flux thermal boundary of the PTR was neglect in these studies. Wu et al. [30] also experimentally investigated the heat loss of a PTC with a new developed low-melting-point MS. The convective heat transfer correlations were calculated with Reynolds number between 10,000 and 21,000, and Prandtl number between 9.5 and 12.2. Results show that the heat transfer coefficients with low melting point MS demonstrate good agreement with Gnielinski equation and Sieder-Tate equation. Xiong et al. [31] numerically investigated the thermal performance of heat loss of a PTR under steady state. The results show that annular pressure and selective coatings make greater influence to heat loss than wind speed. Cheng et al. [32] developed a 3D optical model to study the thermal performance of a PTC, the results show that the method and model are reliable to simulate PTC concentrating solar collectors. Wang et al. [33] numerically investigated the performance of a PTR using molten salt as HTF by a coupled three-dimensional simulation and found that the circumferential temperature difference (CTD) of the PTR increases with the rising of the DNI. However, the absorber tube in these approaches is ideal smooth plain tube and cannot be used effectively to resolve the issues of overheating and structure rupture in a PTR working with high temperature MS.

To enhance the convective heat transfer in PTR, much research focuses on various techniques for the heat transfer enhancement in PTR with wavy or rough surfaces, usage of molten salt or nanofluids and installation of turbulator or swirl flow device inside the absorber tube [34,35]. Waghole et al. [36] made an investigation on the heat transfer and friction factor of silver nanofluid in PTR with twisted tape inserts by the experimental method. The experiments show that friction factor, Nusselt number, and enhancement efficiency of enhanced PTR are found to be 1.0–1.75 times, 1.25–2.10 times and 135–205%, respectively, over plain PTR. Reddy et al. [37,38] presented the experimental investigation of heat transfer of a PTR with porous disc enhanced according to ASHRAE 93-1986 test procedure. Six different receiver configurations are investigated. The results show that the porous disc enhanced receiver improves the performance of the PTR significantly. Xiao et al. [39] developed a novel double tube helical heat exchanger using MS as HTF and the heat transfer enhancement in a helical annular duct was achieved. The heat transfer enhancement ratio was found to be enlarged by smaller inner-outer-pipe diameter ratio and lower molten salt temperature. Wang et al. [40] numerically studied the effect of inserting metal foams in PTR on heat transfer. The result shows that for constant layout and porosity, the geometrical parameter affects on the thermal performance greatly. While for constant layout and geometrical parameter, the porosity affects on the thermal performance slightly. Wang et al. [41] numerically investigated heat transfer enhancement of PTR with a symmetric outward corrugated tube. The effective heat transfer coefficient can be enhanced up to 8.4% and maximum thermal strain can be decreased up to 13.1%. Huang et al. [42] numerically studied the fully developed turbulent convective heat transfer in dimpled tubes of PTR. The results indicate that Nusselt number and the average friction factor in dimpled receiver tubes under non-uniform heat flux are larger than those under uniform heat flux and the deep dimples are far superior to the shallow dimples for the same Grashof number. Lu et al. [43–45] experimentally investigated the convective heat transfer of ternary nitrate salt in a transversely grooved tube and spirally grooved tube with uniform heat flux. Results show that Nusselt number of transversely grooved and spirally grooved tube is remarkably higher than that of the plain tube, and molten salt should avoid worsening phenomena for high-temperature difference and low heat transfer coefficient. Chen et al. [46] experimentally investigated the enhanced heat transfer of mixed MS in a transversally corrugated tube with three different sets of parameters and found the drag coefficient for transversally corrugated tubes is larger than that of a smooth tube. In these studies, although the enhanced heat transfer methods such as metal foam and porous disc can achieve higher heat transfer intensification, they all cannot meet the operation of MS draining when MS is used as HTF, MS will freeze in PTR if it is not completely drained. Moreover, due to the limitation of industrial processing and manufacturing costs, the structure and the processing technology of the PTR should not be too complex. Therefore, there is little possibility that the enhanced heat transfer methods such as a corrugated tube, a spiral tube or an internal finned tube can be easily used in a PTR. To make matters worse, the corrugated tube, spiral tube will aggravate the thermal bending deformation damage of the PTR with extreme non-uniform heat flux.

The concentric rod and eccentric rod inserts are simple and feasible