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Optimization of Porous Insert Configuration in a central Receiver Tube for Heat Transfer Enhancement

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Abstract

In this paper, the heat transfer enhancement for convection heat transfer of turbulent flow in a central receiver tube filled with porous medium under non-uniform circumferential heat flux was numerically investigated. The effects of some parameters of porous medium (layout, thermal conductivity and porosity) and the Reynolds number (*Re*) on the thermal and thermo-hydraulic performance were discussed. The results showed that the enhanced receiver tube (ERT) with down-filling porous inserts and in-filling porous inserts have good thermal performance when the ratio of thermal conductivity of porous medium to working fluid (λ_s/λ_f) is less than 1,000. The ERT with out-filling porous inserts and up-filling porous inserts have good thermo-hydraulic performance when $\lambda_s/\lambda_f > 100$. The porosity ($\varepsilon$) and *Re* also affect the thermal and thermo-hydraulic performance, the Nusselt number (*Nu*) and performance evaluation criteria (PEC) of heat transfer enhancement under constant pumping power of most kinds of ERTs decrease with the increase of ε, but the PEC of the ERT with in-filling porous inserts increases with the increase of ε. The *Nu* of all kinds of ERTs increases with the increase of *Re*, but the PEC decreases with the increase of *Re*.

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Keywords: Central receiver tube; Heat transfer enhancement; Porous medium; Configuration; Numerical simulation

1. Introduction

Solar power tower system (SPTS) is a primal concentrating solar power, which has many obvious advantages including low average cost and large-scale power generation [1]. The receiver is the key component of the SPTS. There are two main kinds of receivers used to SPTS: volumetric receiver and tubular receiver. The tubular receiver can well bear pressure and high temperature, and is applicable to various heat transfer fluid (HTF), such as water/steam, liquid metal, and molten salt.

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The solar flux distribution on the receiver is non-uniform resulting from the concentrating mirror optics. The non-uniform solar flux distribution exists not only in the whole receiver, but also in the single tube. The non-uniform heat flux distribution can cause the un-homogeneity of the temperature field in the receiver tube and flow region. The un-homogeneity of the temperature field may result in a lot of problems including the increase of the local heat loss, plastic deformation, and decomposition of HTF [2]. The heat transfer enhancement is one way to solve the above problems due to its ability to decrease the irreversibility of heat convection [3]. Porous material can effectively enhance the heat convection through rebuilding the velocity field and increasing the effective thermal conductivity of fluid; it has been studied as a great deal for possible use in solar receivers. For example, Reddy et al. [4] investigated the heat transfer enhancement of a parabolic trough receiver tube with porous disc numerically. Wang et al. [5] numerically analyzed the enhancement of forced convective heat transfer in a parabolic trough receiver tube with metal foams under non-uniform heat flux condition. Mwesigye et al. [6] studied the thermal and thermodynamic performance of a parabolic trough receiver tube with centrally placed porous insert under non-uniform heat flux condition.

In this paper, the heat transfer enhancement in a central receiver tube filled with porous medium under non-uniform circumferential heat flux was numerically investigated. The optimal one-dimensional (1D) porous insert configurations were analyzed. Also the sensitivity analysis of some parameters of porous medium (filling volume, thermal conductivity and porosity) and the Reynolds number was discussed.

2. Physical model

A typical external tubular receiver using mixed nitrate molten salt (60 wt. % $NaNO_3$ and 40 wt. % KNO_3) as HTF is considered, and its schematic diagrams are shown in Fig. 1. It can be seen that only the sunward sections ($-90° \leq \theta \leq 90°$) of the receiver tubes absorb the sunlight. Therefore, the circumferential heat flux distribution of receiver tube is non-uniform, and a cosine distribution is assumed in this paper [7]. The heat transfer enhancement in one single enhanced receiver tube (ERT) filled with porous medium is investigated. The receiver tube is made of the Alloy 800H with thermal conductivity of 18.41 W/m^2 K, and its inside and outside diameters (D_i and D_o) are 18.6 mm and 21 mm, respectively [7]. The length of ERT is 0.5 m, and an auxiliary segment with a length of 1.5 m is placed before the inlet of ERT to make sure that the fluid is fully developed in the ERT. As shown in Fig. 2, four kinds of ERT with porous inserts are considered, and the geometrical parameter of porous medium is defined by the dimensionless height $H=h'/D_i$. The porous inserts will be installed in the ERT by soldering.

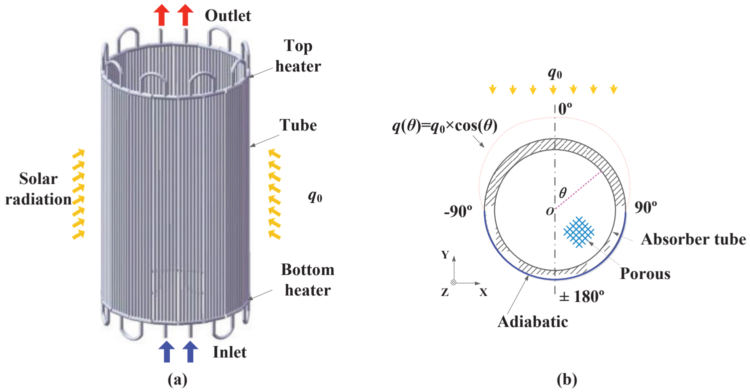

Fig. 1. (a) Schematic of the external tubular receiver and (b) cross-section of single receiver tube filled with porous medium.

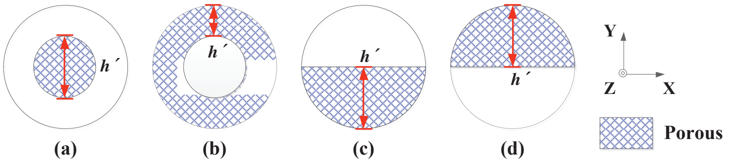

Fig. 2. (a) ERT with in-filling porous insert (ERT-IFPI), (b) ERT with out-filling porous insert (ERT-OFPI), (c) ERT with down-filling porous insert (ERT-DFPI) and (d) ERT with up-filling porous insert (ERT-UFPI).

3. Mathematical formulation and numerical procedure

Governing equations: the governing equations include the continuity, momentum, k-ε, and energy [5]. To simplify the analysis, some assumptions in the simulation are listed as follows: (1) the heat loss at the outer wall of receiver tube is ignored; (2) only the un-homogeneous of circumferential heat flux distribution is considered, the axial heat flux distribution is regarded as uniformity; (3) the porous medium is made of metal foam, and is regarded as homogeneous and isotropic; (4) the Brinkman-Forchheimer model is adopted to describe the flow in the porous region, the porosity (ε), permeability (K) and inertia coefficient (F) are from the experiment data of Calmidi et al [8], shown in Table 1; (5) the liquid phase and the solid phase in porous medium exists in a state of local thermal equilibrium, and the effective thermal conductivity (λ_e) is calculated by the mathematical model of Calmidi et al [8].

Table 1. Properties of metal foam.

#	Porosity (ε)	PPI	K ($\times 10^7$ m^2)	F
Case1	0.9726	5	2.7	0.097
Case2	0.9546	20	1.3	0.093
Case3	0.9486	10	1.2	0.097
Case4	0.9272	40	0.61	0.089

Boundary conditions: the fluid region in the receiver tube and the receiver tube wall are considered as the simulation domain, the boundary conditions can be expressed as follows: (1) inlet boundary: constant velocity and temperature condition; (2) outlet boundary: fully-developed condition; (3) the ends of receiver tube: Adiabatic condition; (4) the inner surface of the receiver tube: non-slip velocity and temperature coupled condition; (5) the outer surface of the receiver tube: heat flux boundary condition.

Numerical methods: the CFD commercial code FLUENT 6.3 is used to simulate the flow and heat transfer processes in the receiver. The governing equations are discretized by the finite volume method. The convective terms in energy and momentum equations are discretized with the second upwind scheme. The coupling between velocity and pressure is based on SIMPLE algorithm. The convergence criterions for the normalized residuals of all solved variables are restricted to be less than 10^{-8}. During computation, the thermo-physical properties of molten salt under a temperature of 673.15 K are selected [9].

Parameter definitions: in order to analyze the thermal-hydraulic characteristics of the ERT, some parameters are defined. The Reynolds number, Nusselt number, and friction factor is defined as:

$$Re = \frac{\rho u D_{\mathrm{i}}}{\mu}, \quad Nu = \frac{h D_{\mathrm{i}}}{\lambda_f}, \quad f = \frac{\Delta p}{L}\frac{D_{\mathrm{i}}}{(1/2)\rho u^2} \tag{1}$$

The performance evaluation criterion (PEC) of heat transfer enhancement under constant pumping power is defined as [10]:

$$\mathrm{PEC} = \frac{Nu/Nu_{\mathrm{c}}}{\left(f/f_{\mathrm{c}}\right)^{1/3}} \tag{2}$$

Where, the subscript "c" represents clear receiver tube without porous medium.

Code checking: to ensure that the calculation results are reliable, the grid independence test is made. The thermal-hydraulic characteristics for fully developed flow in the receiver tube without filled porous medium are investigated. Four different grid systems are tested namely 20 (radial) × 24 (circumferential) × 333 (axial), 31 × 41 × 571, 41 × 58 × 800, 50 × 73 × 1000. The difference of *Nu* and *f* between the fourth and fifth grid system are less than 0.6% and 0.15%, respectively. So the fourth grid system is chosen in making a trade-off between the CPU time and the accuracy.

Models validation: Fig. 3 shows the *Nu* and *f* for a turbulent flow in the receiver tube without porous medium. It can be seen that the *Nu* predicted by this paper is between the two values calculated by Sieder-Tate correlation and Gnielinski correlation. Also the maximum error of *f* predicted by this paper is less than 0.9% compare to the value calculated by Filonenko correlation. Fig. 4 shows the *Nu* and *f* for a turbulent flow in a circular tube partially filled with porous medium are validated with the experiment of Huang et al. [11]. The porous medium made from copper is cylindrical shape placed at the core of the tube. The maximum error of *Nu* and *f* between the predicted by this study and the experimental data of Huang et al are less than 6.1% and 12.5%, respectively.

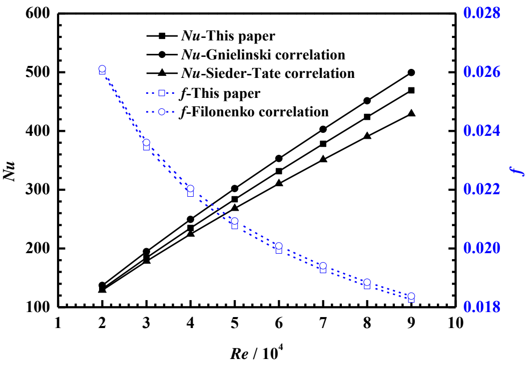

Fig. 3. Comparison of *Nu* and *f* predicted by this paper with classical correlations for the clear receiver tube.

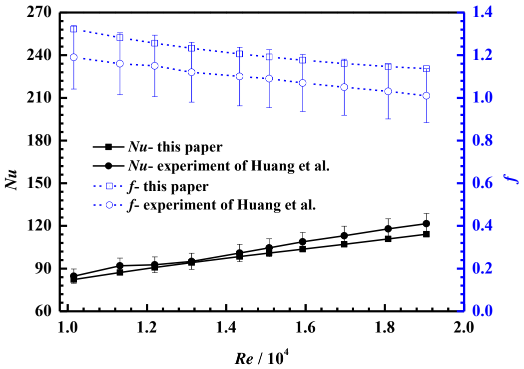

Fig. 4. Comparison of *Nu* and *f* predicted by this paper and Huang et al. [11] for tube partially filled with porous medium.

4. Result and Discussion

In order to apply the porous insert to the performance enhancement of the receiver tube, the thermal and thermo-hydraulic performance of the ERT should be studied. The optical-to-thermal energy conversion efficiency and security can be improved by increasing the thermal performance. However, the thermal performance is increased at the sacrifice of pump power. Therefore, the thermo-hydraulic performance should also be discussed. Below, the sensitivity analysis of some parameters of porous medium and the Reynolds number (*Re*) is discussed.

First, the effects of some parameters of porous medium on the thermal and thermo-hydraulic performance are studied. Fig. 5 shows the *Nu* and PEC for different geometrical parameters (*H*) when the ratio of thermal conductivity of porous medium to working fluid (λ_s/λ_f) equals 1.0, ε=0.9726 and *Re*=90,000. It can be seen that the ERT-DFPIs and ERT-IFPIs have the highest *Nu* and PEC. This is because that the ERT-DFPIs and ERT-IFPIs can make the fluid mostly flows through the gap between porous insert and the upper-wall of ERT, and the velocity gradient near the tube wall is increased. Fig. 6 shows the *Nu* and PEC of some ERT with good porous inserts for different λ_s/λ_f when ε=0.9726 and *Re*=90,000. It can be seen that the *Nu* and PEC increase with the increase of λ_s/λ_f except the ERT-IFPIs. It also can be seen that the PEC of ERT-OFPIs and ERT-UFPIs can be greater than 1.0 only when $\lambda_s/\lambda_f \geq 100$. Fig. 7 shows the *Nu* and PEC of some ERT with good porous inserts for different ε when λ_s/λ_f=1,000 and *Re*=90,000. It can be seen that the *Nu* of all ERTs decreases with the increase of ε. This is because the ability of the velocity field rebuilding and the effective thermal conductivity both decrease with the increase of ε. It also can be seen that the PEC decreases with the increase of ε except the ERT-IFPIs.

Also, the effects of *Re* on the thermal and thermo-hydraulic performance are studied. Fig. 8 shows the *Nu* and PEC of some ERT with good porous inserts for different *Re* when ε=0.9726 and λ_s/λ_f=1,000. It can be seen that the *Nu* increases with the increase of *Re*, but the PEC decreases with the increase of *Re*. It also can be seen from Figs. 6-8 that the λ_s/λ_f, ε and *Re* affect the optimal layout of porous insert.

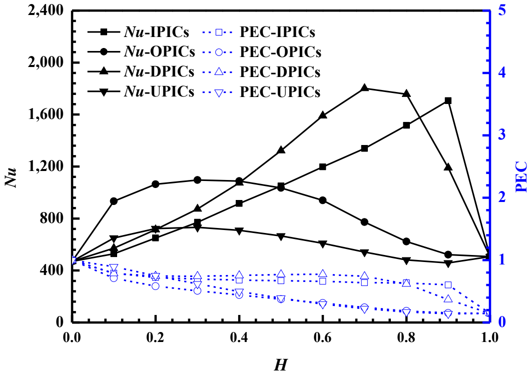

Fig. 5. *Nu* and PEC as functions of *H* for different kinds of ERTs when λ_s/λ_f=1.0, ε=0.9726 and *Re*=90,000.

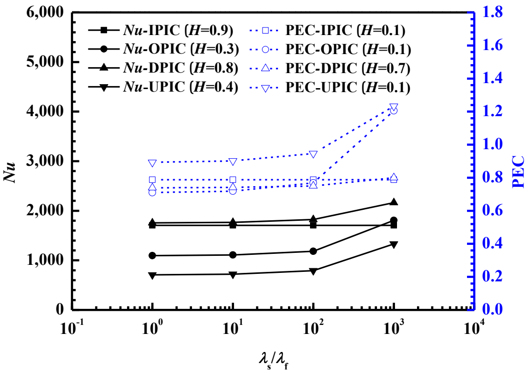

Fig. 6. *Nu* and PEC as functions of λ_s/λ_f for different kinds of ERTs when ε=0.9726 and *Re*=90,000.

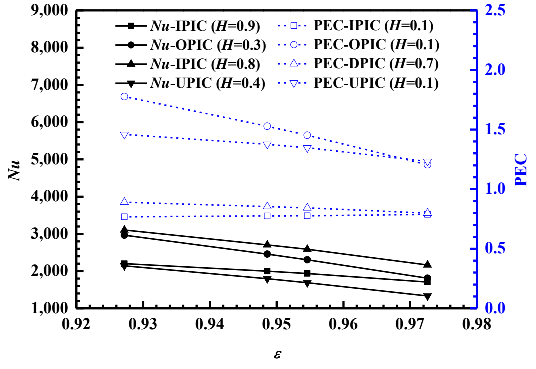

Fig. 7. *Nu* and PEC as functions of ε for different kinds of ERTs when λ_s/λ_f=1,000 and *Re*=90,000.

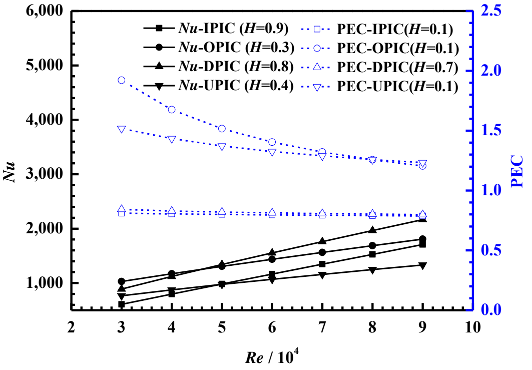

Fig. 8. *Nu* and PEC as functions of *Re* for different kinds of ERTs when λ_s/λ_f=1,000 and ε=0.9726.

5. Conclusion

In this paper, a numerical investigation was carried to study the heat transfer enhancement in a central receiver tube partially or completely filled with porous medium. The effects of some parameters of porous medium (H, λ_s, ε) and the Re on the thermal and thermo-hydraulic performance were also discussed. The following conclusions can be made.

The ERT-DFPIs and ERT-IFPIs have good thermal performance when $\lambda_s/\lambda_f<1{,}000$. The ERT-OFPIs and ERT-UFPIs have good thermo-hydraulic performance when $\lambda_s/\lambda_f>100$. The ε and Re also affect the thermal and thermo-hydraulic performance, the Nu and PEC of most kinds of ERTs decrease with the increase of ε, but the PEC of ERT-IFPIs increases with the increase of ε. The Nu of all kinds of ERTs increases with the increase of Re, but the PEC decreases with the increase of Re. Besides, the λ_s/λ_f, ε and Re affect the optimal layout of porous insert.

Acknowledgements

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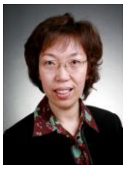

Biography

Ya-Ling He is currently a professor of Xi'an Jiaotong University, and director of the Key Laboratory of Thermo-Fluid Science & Engineering of MOE. She is an Associate Editor of Applied Thermal Engineering and Heat Transfer Research. She is also International Institute of Refrigeration-Vice President of Commission B1, and Members of the Scientific Council of ICHMT.