Heat transfer enhancement by filling metal porous medium in central area of tubes

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Given that the fluid within the tubes of some industrial heat exchangers is under a state of fully developed laminar flow with a constant Nu number, increasing the surface area for heat transfer will significantly increase the flow resistance. In this paper, we filled metal porous medium with high thermal conductivity, high porosity and high filling radius in the central area of fully developed laminar flow within the tube, and established corresponding numerical models for fluid flow and heat transfer. Numerical simulation results indicate that after filling the tube with metal porous medium, the temperature profiles within the porous medium area are very uniform, and the temperature difference between the tube wall and the fluid decreases significantly which correspondingly results in a notable increase of Nu number; meanwhile, the characteristic of flow field redistribution occurs within the enhanced tube, but the total flow resistance composed of the Darcy resistance and inertial resistance of the porous medium area and the shear stress caused by velocity gradient and fluid viscosity of the non-porous medium area near the wall increase; correspondingly, the performance evaluation criteria (PEC) value is thus applied to evaluate the effect of the heat tranfer enhancement method. For a tube of 9 mm in radius, the PEC values are all above 1 when the filling radius of the metal porous medium is larger than 7 mm.

Keywords: Heat transfer enhancement, Porous medium, Performance evaluation criteria

Introduction

Heat exchangers have extensive application in the fields of energy, electrical power, metallurgy and chemical industry. Enhancing convection heat transfer and reducing the flow resistance are two effective ways to improve the performance of heat exchangers. For single phase convection heat transfer within a tube, the most frequently applied methods for heat transfer enhancement at present include the reduction of boundary layer thickness, the increase in surface area for heat transfer of the tube wall by installing fins of all kinds and the increase in fluid velocity from laminar flow to turbulent flow.[1] Heat transfer enhancement techniques corresponding to the methods mentioned above include internally finned tube,[2] spirally corrugated tube,[3] horizontal tube with helical rib,[4] microfinned tub[5] and many other kinds of tube for heat transfer enhancement.[6] Since the aim of these techniques is mainly to directly decrease the thickness of the velocity boundary layer by changing the shape and area of the tube wall or changing the fluid flow direction and thus decrease the thermal boundary layer, they can be classified as boundary flow heat transfer enhancement.

For fluid flow over a flat plate, one of the heat transfer enhancement methods is to increase the velocity of the fluid so as to form a rather larger velocity gradient and a rather larger temperature gradient near the wall, and hence, heat transfer enhancement is finally realised. For inner tube flow, however, as the increase in the fluid velocity generates considerable shear stress but the Nu number remains constant, the increase in the continuous expansion surface area generates considerable friction loss which causes considerable momentum dissipation. As a result, when the methods of boundary flow heat transfer enhancement are applied, the flow resistance will experience a considerable increase; if this increase is excessive, it will even actually limit the application scope of this kind of heat exchangers.

Currently, heat transfer enhancement techniques for fully developed laminar tube flow have not been extensively reported. In order to improve the flow and heat transfer characteristics in this situation, some researchers have tried taking measures focusing on the tube centre. Through filling porous medium, Mohamad and Pavel[7,8] carried out numerical simulation and experimental verification on the heat transfer and flow of the inner tube fully developed laminar flow, the results of which revealed that the heat transfer was considerably enhanced. Wang *et al.*[9] carried out numerical simulation and experimental research on the characteristics of heat transfer and resistance by filing metallic filament insert in the centre of a rectangular channel. Bejan and Kraus divided the flow at the entrance of the tube into

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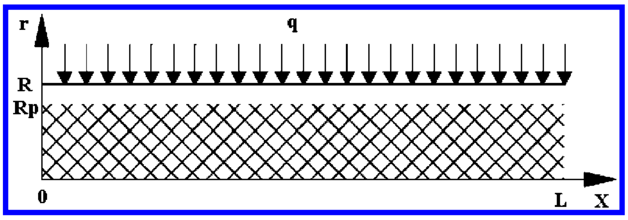


1 Model of tube filled with metal porous medium in central area

boundary flow and core flow.[10] Boundary flow has relatively higher velocity and temperature gradients, while core flow has more homogeneous velocity and temperature profiles. Based upon this, Liu *et al.*[11] proposed a concept of inner tube core flow heat transfer enhancement aiming at improving the integrated performance of heat transfer and flow of fully developed laminar tube flow. The numerical simulation results indicated that some methods used in the central area might be useful to the integrated performance of heat transfer and flow of the enhanced tube.

Filling metal porous medium with high thermal conductivity, high porosity and high filling ratio in the central area of fully developed laminar flow within the tube might be quite effectivce in improving the performance of the enhanced tube. This is because filling porous medium with high thermal conductivity in the central area can homogenise the temperature profile of the central area, and filling porous medium with high porosity can avoid both excessive Darcy resistance and the forming of excessively large velocity gradient within the boundary flow near the tube wall. Focusing on this, after the filling of metal porous medium in the central area of a tube when the inlet fluid flow is in fully developed laminar state, the influences of different packing radii and Re numbers on the velocity and temperature profiles and the performance evaluation criteria (PEC) value of the enhanced tube are studied in this paper.

Mathematic and physical models

Within a tube with a radius of 9 mm, air is considered as the fluid media to study the fluid flow and heat transfer characteristics of the fully developed laminar flow. As shown in Fig. 1, the material for the porous medium the authors use to fill the central area of the tube is aluminium with particle diameter and porosity being 0·8 mm and 0·95 respectively. No porous medium is filled in the annular space between the tube wall and the outer diameter of the porous medium area. Through alternating, the packing radius R_p, we will analyse the heat transfer and flow characteristics of the enhanced tube under different packing radii. In order to make sure that the fluid has been fully developed for flow and heat transfer before entering the enhanced tube, an auxiliary heating segment with a length of 1500 mm is placed right before the inlet of the enhanced tube which is 500 mm in length, and a wake flow segment with a length of 100 mm is connected to its outlet, aiming at eliminating the influence of the outlet boundaries on the computation results of the enhanced tube. The auxiliary heat segment and the heat transfer enhancing segment are both heated with constant heat flux, and the wall of the wake flow segment is adiabatic because the boundary condition of this segment has no effect on the results of the enhanced tube. During computation, assumptions are made as follows:

(i) porous medium is homogeneous and isotropic
(ii) local heat equilibrium is achieved between the porous medium matrix and the fluid
(iii) the inlet of the enhanced tube has reached the state of fully developed laminar
(iv) computational model is two-dimensional axisymmetric.

For areas with no porous medium filled, the mass, momentum and energy equations of two-dimension are as follows:

$$\frac{\partial u}{\partial x}+\frac{1}{r}\frac{\partial (rv)}{\partial r}=0 \tag{1}$$

$$\frac{\partial (uu)}{\partial x}+\frac{1}{r}\frac{\partial (rvu)}{\partial r}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+v\frac{\partial^2 u}{\partial x^2}+\frac{v}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right) \tag{2}$$

$$\frac{\partial (uv)}{\partial x}+\frac{1}{r}\frac{\partial (rvv)}{\partial r}=-\frac{1}{\rho}\frac{\partial p}{\partial r}+v\frac{\partial}{\partial x}\left(\frac{\partial v}{\partial r}\right)+\frac{v}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v}{\partial r}\right) \tag{3}$$

$$\frac{\partial (uT)}{\partial x}+\frac{1}{r}\frac{\partial (rvT)}{\partial r}=a\frac{\partial^2 T}{\partial x^2}+a\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) \tag{4}$$

where u and v represent the velocity in x and r directions respectively, ρ represents the air density, p represents the fluid pressure, T represents the thermodynamic temperature of the fluid, and c_p and λ represent the isobaric specific heat capacity and the heat conductivity respectively.

For the area with porous medium filled, the related mass, momentum and energy equations of two-dimension are as follows

$$\frac{\partial u}{\partial x}+\frac{1}{r}\frac{\partial (rv)}{\partial r}=0 \tag{5}$$

$$\frac{\rho}{\varepsilon}\frac{\partial u}{\partial t}+\frac{\rho}{\varepsilon^2}\left[\frac{\partial (uu)}{\partial x}+\frac{1}{r}\frac{\partial (rvu)}{\partial r}\right]= -\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial u}{\partial r}\right)-\frac{\mu u}{K}- \frac{\rho F}{(K)^{1/2}}\left(u^2+v^2\right)^{1/2}u \tag{6}$$

$$\frac{\rho}{\varepsilon}\frac{\partial v}{\partial t}+\frac{\rho}{\varepsilon^2}\left[\frac{\partial (uv)}{\partial x}+\frac{1}{r}\frac{\partial (rvv)}{\partial r}\right]= \frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial v}{\partial r}\right)-\mu\frac{v}{r^2}- \frac{\mu u}{K}-\frac{\rho F}{(K)^{1/2}}\left(u^2+v^2\right)^{1/2}v \tag{7}$$

$$\rho_m c_{p,m}\left[\frac{\partial T}{\partial t}+\frac{\partial (uT)}{\partial x}+\frac{1}{r}\frac{\partial (rvT)}{\partial r}\right]= \frac{\partial}{\partial z}\left(\lambda_m\frac{\partial T}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_m\frac{\partial T}{\partial r}\right) \tag{8}$$

where ε represents the porosity of the porous medium, K represents the permeability of the porous medium, F represents the inertial coefficient, the subscript s means parameters for the porous medium matrix, the subscript *a* means parameters for the fluid and the subscript *m* means apparent parameters or average parameters of the whole zone filled with porous medium.

Flow and heat transfer characteristics

In order to analyse the flow and heat transfer characteristics of the enhanced tube, the flow resistance coefficient f is defined as follows

$$\Delta P = f \frac{L}{d} \frac{\rho V_m^2}{2} \tag{9}$$

where ΔP is the pressure drop between the inlet and the outlet of the enhanced tube filled with porous medium, and the convection heat transfer coefficient h and the dimensionless number Nu are defined as follows

$$h = \frac{q}{\pi (T_w - T_f)} \tag{10}$$

$$\mathrm{Nu} = \frac{hd}{\lambda} \tag{11}$$

where d, L and q are the inner diameter, length of the tube and heat flux from the wall to the fluid respectively. The integrated PEC for the enhanced tube, which takes both the heat transfer enhancement and flow resistance increase into consideration, is defined as follows[12]

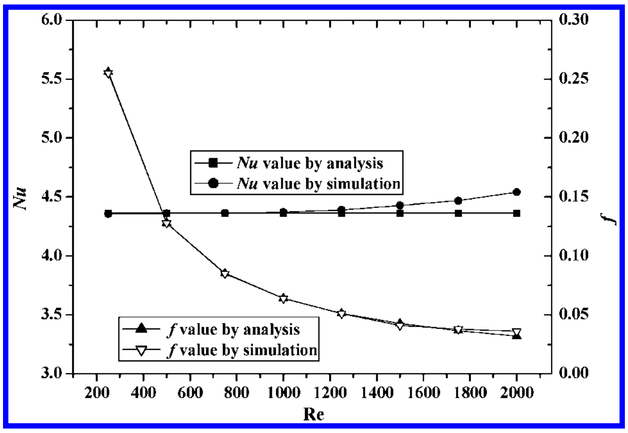
$$\mathrm{PEC} = \frac{\mathrm{Nu}/\mathrm{Nu}_0}{(f/f_0)^{1/3}} \tag{12}$$

The boundary conditions for the model are set as follows: the inlet of the auxiliary segment is provided with homogeneous temperature and velocity condition. The outlet of the auxiliary segment is imposed with pressure outlet, a constant convection heat flux of 100 W m^{-2} is imposed on the tube wall, and the wall of the wake flow segment is adiabatic. A control volume, finite difference approach is used to solve the model equations with the boundary conditions specified above. Laminar model is applied during numerical computation, the SIMPLE scheme is applied for the coupling of pressure and velocity, second order upwind scheme is applied for the discretisation of the momentum and energy equations; meanwhile, the mesh independence of the computation results is also taken into consideration. During computation, property parameters of air under a temperature of 293 K are uniformly selected as the inlet property parameters. In concrete, values of property parameters are as follows: $\rho = 1{\cdot}025$ kg m^{-3}, $C_p =$ 1005 J $kg^{-1}K^{-1}$, $\lambda = 0{\cdot}0259$ W $m^{-1}K^{-1}$ and $\nu = 1{\cdot}506 \times 10^{-5}$ m^2s^{-1}. The variation scope of the Re number for the air flow inside the tube is 250–2000, with a interval of 250 during numerical simulation.

Computation results and analysis

Computation verification

In order to insure that the results are grid size independent, different meshes are tested, namely, 1050×50, 1050×100, 2100×100 and 2100×150. The simulated results are compared with the Nu number and the flow resistance coefficient f in a smooth tube where the analytical result of Nu number is 4·364 and that of f is 64/Re for laminar flow, and the computation verification was carried out for different Re numbers. The

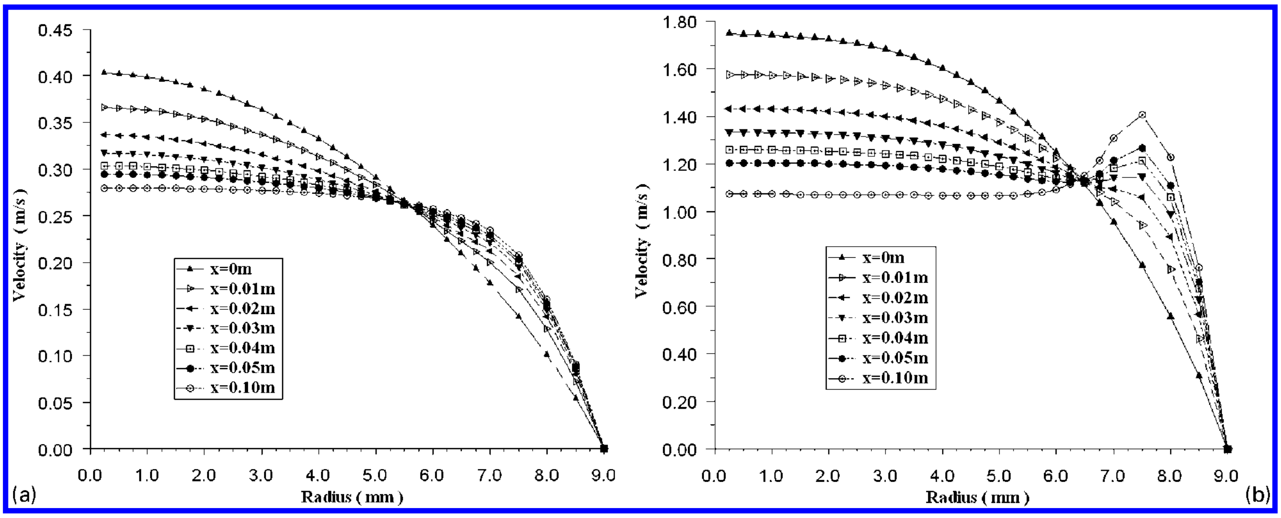


2 Error analysis for computation results

comparisons of the numerical simulation results, when the meshes of the model are 2100×100, with the analytical solutions are shown in Fig. 2. It can be seen from this figure that the numerical simulation results of both f and Nu accord with the analytical values pretty well, sufficiently illustrating the feasibility and accuracy of the numerical simulation carried out in this paper. The maximum errors of the numerical simulation for f and Nu number in the scope of Re from 250 to 2000 are acceptable. In addition, when the meshes of the model are 2100×100 and 2100×150 respectively, the differences of the same parameters between these two mesh models are very slight. Thereby, the meshes of the computation model are all selected as 2100×100.

Velocity and temperature profiles

Figure 3 shows the velocity profiles within the enhanced tube when the filling radius R_p of the metal porous medium is 7·0 mm. As indicated in Fig. 3*a*, the variation of velocity along the radial direction no longer meets parabolic function when Re is 250 and x is constant; instead, the fluid velocity at the centre of the tube decreases and the velocity of the fluid near the wall increases. Besides, the fluid velocity at the centre of the tube keeps decreasing and the velocity of fluid near the wall keeps increasing along the flow direction, illustrating that the flow of the fluid makes the flow velocity profiles at the centre more homogeneous after filling porous medium in the centre of the tube, and a new velocity profile within the tube is established, which remarkably differs from the parabolic function of fully developed laminar flow; thus, the phenomenon of new velocity profiles of the enhanced tube filled with porous medium can be called as redistribution of flow field,[7] which can easily be seen in a smooth tube from the entrance region to the fully developed flow. This phenomenon of flow field redistribution becomes more remarkable when Re number with large values is imposed, just as shown in Fig. 3*b*. While comparing Fig. 3*a* and *b*, it is obvious that at the same cross-section, the larger the Re number, the smaller and more homogeneous the velocity profiles at the tube centre will be, but the larger the fluid velocity gradient in the region near the wall without metal porous medium will be. Numerical simulation results indicate that when x is larger than 0·1 mm, namely, after entering the inlet of the segment with porous medium filled farther than 0·1 mm, the velocity profiles along the radial direction keep unchanged and remain homogeneous within the



a Re=250; *b* Re=1250

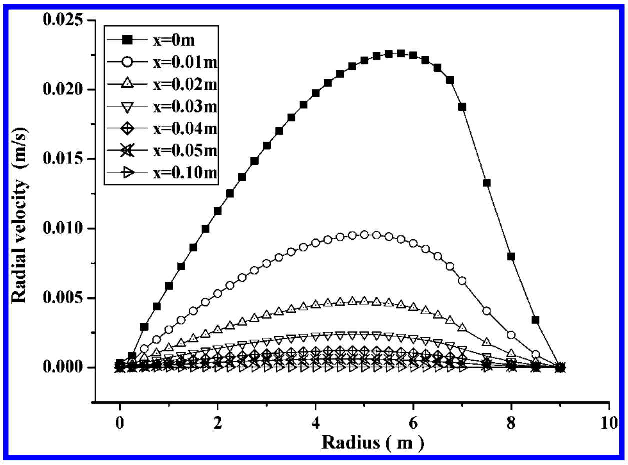
3 Velocity profiles when R_p is 7 mm

porous zone; however, relatively large velocity gradient exists within the boundary flow area.

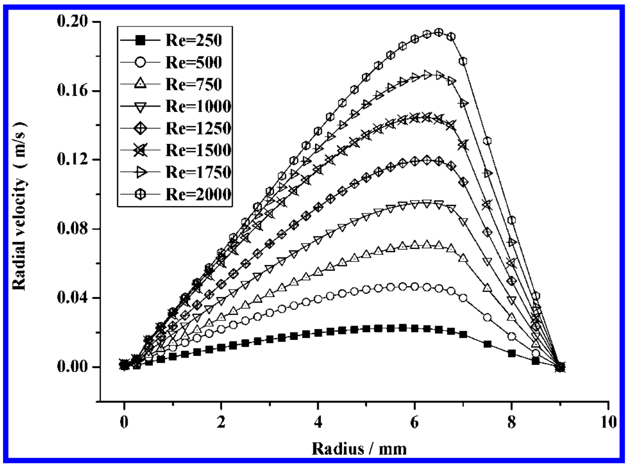
To manifest the phenomenon of flow field redistribution more vividly, Fig. 4 shows the radial velocity profiles of each cross-section along the flow direction when R_p and Re number are 7·0 mm and 250 respectively. Obviously indicated in this figure, since the filling of porous medium at the centre of the enhanced tube greatly changes the inner tube flow profiles and causes the phenomenon of radial flow along the wall, which directly causes a velocity decrease in the tube centre and a velocity increase for the fluid near the wall. Heat transfer will occur once the temperature of the wall differs from that of the fluid, and the mentioned two phenomena will notably strengthen the convection heat transfer between the fluid and the wall. Besides, the closer to the inlet of the enhanced tube, the larger the radial velocity at any cross-section will be. The reason for this is that the fluid converts from parabolic function of fully developed laminar into a new flow field within the enhanced tube, and the effect of flow field redistribution is quite notable at the inlet of the enhanced tube; when it is far from the inlet, the redistribution of flow field is completed and a new stable flow field is formed; thus, the radial velocity of the flow decreases to zero. As shown in this figure, when the enhanced tube is 9 mm in radius with R_p being 7 mm, the redistribution of flow field mainly emerges before an entry distance of 0·1 mm within the enhanced tube; beyond that distance, the radial velocities at different cross-sections all become close to zero, which illustrates that the flow is quickly driven to steady state after the fluid enters the enhanced tube packed with porous medium.

Figure 5 shows the inlet radial velocity profiles under different Re numbers when R_p is 7 mm. It is found that the radial velocities of different radii at the inlet section of the enhanced tube all increase as the Re number increases. It should also be noted that radial velocities under different Re numbers at the inlet section of the enhanced tube all reach their peak values when the radius is 6·5 mm. The maximal radial velocity at the inlet section of the enhanced tube corresponding to Re number of 750 is $\sim$0·07 m s^{-1}; as for a Re number of 2000, the corresponding maximal radial velocity at the inlet of the enhanced tube is close to 0·2 m s^{-1}. This indicates that Re number has significant effect on the radial velocity profiles of the enhanced tube: the larger the Re number, the larger the maximum radial velocity of each cross-section of the enhanced tube will be.

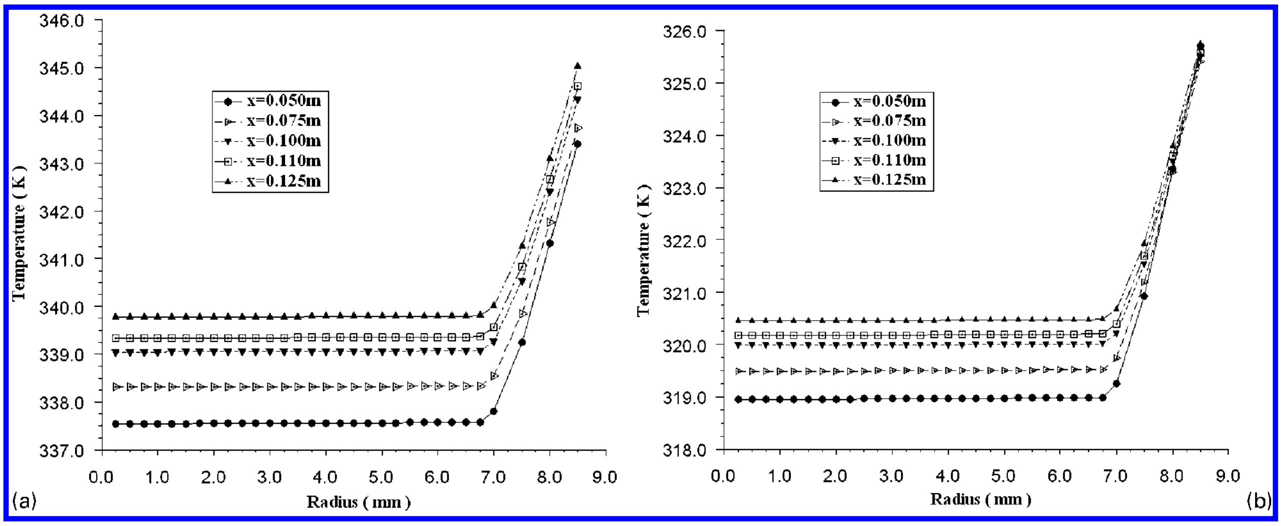
Figure 6 shows the radial temperature profiles of different cross-sections within the enhanced tube under different Re numbers when R_p is 7 mm. As shown in this



4 Radial velocity profiles when R_p is 7 mm and Re number is 250



5 Inlet radial velocity profiles under different Re numbers when R_p is 7 mm



a Re=250; *b* Re=1250

6 Temperature profiles within enhanced tube when R_p is 7 mm

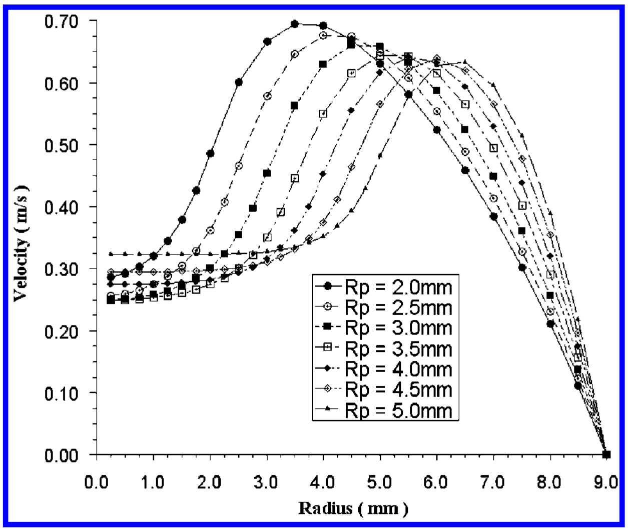
figure, the temperature profiles are quite homogeneous in the core of the enhanced tube where porous medium is filled, while in zones with no porous medium filled near the wall, the temperature gradient is pretty large. The porous medium within the enhanced tube is made of aluminium whose heat conductivity is far bigger than that of air; therefore, the metal porous medium makes the fluid temperature in this area homogenise quickly when fluid flows through the porous zone. In the view of heat transfer, the existence of porous medium actually has two advantages: temperature homogenising, which makes the temperature profiles in the central area of the enhanced tube more homogeneous, and reducing the temperature difference between the wall and the fluid. Since the areas near the wall is not filled with porous medium, temperature of this area shown in the figure appears as linear variation and indicates pretty high temperature gradient. As a matter of fact, although filling porous medium at the centre of the enhanced tube is somewhat effective in raising the temperature gradient near the wall, the uppermost function of filling metal porous medium at the centre of the enhanced tube is that it reduces the temperature difference between the wall and the fluid; when heat flux is constant, the heat convection coefficient is significantly increased according to the Newton's law of cooling.

It should be noticed from Fig. 6*b* that when Re number is a little larger, the temperature gradient near the wall is different for different cross-sections vertical to the axial flow direction: the closer to the inlet of the enhanced tube, the higher the temperature gradient and the convection heat transfer coefficient will be. The main reason for this is that the radial velocity is larger due to the redistribution effect of the fluid flow when it gets closer to the inlet of the enhanced tube, thus causing a relatively higher temperature gradient.

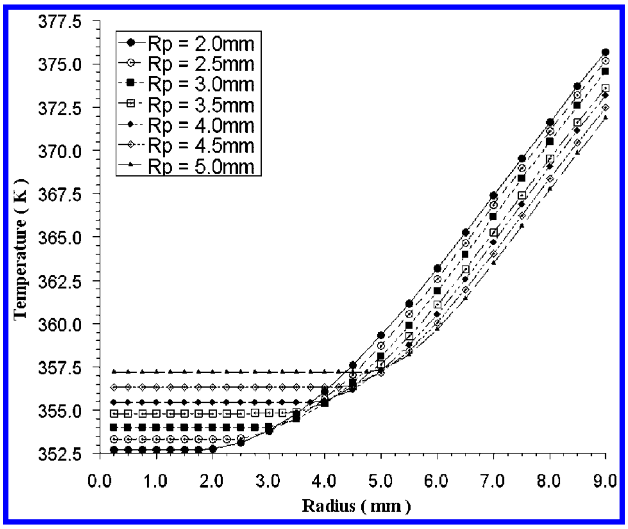
Apparently, filling porous medium in the central area of the enhanced tube does not increase the surface area for heat transfer of the tube wall, which is totally different from the conventional heat transfer enhancement method through increasing the surface area for heat transfer but attempting to improve the temperature uniformity at the tube centre and reduce the temperature difference between the fluid and the wall. As suggested by the simulation results, when the fully developed laminar flow enters the enhanced tube with porous medium filled in the central area, new entrance flow segment and steady flow segment for flow and heat transfer are formed in the tube, both of which are different from the entrance flow segment and steady flow segment for the laminar flow within a smooth tube without filling with porous medium. As for the smooth tube, even the fluid flows in with homogeneous velocity, the flow of fluid will also cause the redistribution of the flow field, and the radial fluid flow is towards the centre of the tube, resulting in a decrease in fluid flow near the wall of the smooth tube; thus, the heat transfer coefficient decreases. As for enhanced tube with porous medium filled in the central area, the radial fluid flow is towards the wall, resulting in an increase in fluid flow near the wall of the enhanced tube; thus, the heat transfer coefficient increases. On the other hand, both the temperature and the velocity profiles of the fully developed laminar flow in smooth tube are parabolic, while those in the steady segment of the enhanced tube both remain homogeneous, which causes significant difference in convection heat transfer coefficient between the smooth tube and the enhanced one.

Therefore, the heat transfer enhancement mechanism through filling porous medium at the tube centre can be externalised in following four aspects:

(i) fluid velocity at the tube centre is decreased while the velocity near the wall is increased
(ii) as the fluid flow is redistributed due to the filling of porous medium in the tube centre, velocity towards the wall along the radial direction is generated and hence the heat transfer is enhanced
(iii) the temperature profiles in the porous zone at the tube centre are homogeneous, which reduces the temperature difference between the fluid and the wall
(iv) filling porous medium at the central area of the enhanced tube actually forms new entrance and stable flow segments, whose flow and heat transfer characteristics are both notably different from the entrance flow segment and the fully developed laminar flow segment of smooth tube.



7 Influence of porous medium packing radius on inner tube velocity profiles



8 Influence of porous medium packing radius on inner tube temperature profiles

Velocity and temperature profiles under different packing radii

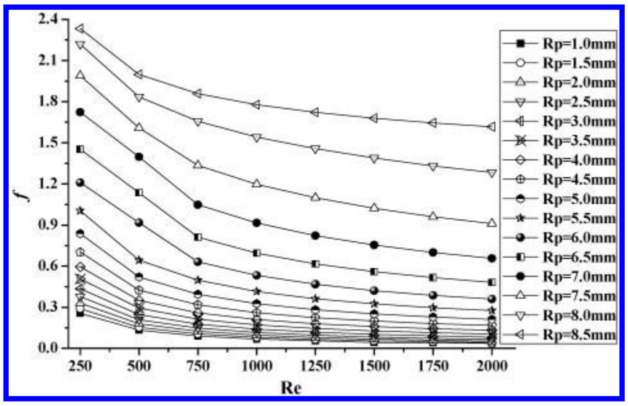
Figure 7 shows the influence of porous medium packing radius on the inner tube velocity profiles at the cross-section where x is 0·05 m when Re number is kept constant as 500. Apparently, the flow resistance inside the tube will experience a notable increase after filling porous medium. In the porous zone, the flow resistance is composed of Darcy resistance and inertial resistance: the smaller the porosity, the larger the Darcy resistance will be; on the other hand, the faster the flow speed, the larger the inertial resistance will be. Since porous medium with high porosity is applied in this paper, research on the influence of the porosity on the Darcy resistance will be carried out in the next step. In the non-porous zone, the flow resistance is mainly the shear stress caused by fluid viscosity. As shown in the figure, the flow resistance both in the central area and near the wall apparently increases after the filling of porous medium. However, there is still another phenomenon that is worth attention: when the porous medium packing radius R_p is small, the flow velocity in the porous zone is relatively small, while in the non-porous zone, a considerable peak value of velocity is observed, and the fore and after velocity gradients of the peak value are both relatively high, which definitely increases the flow resistance. While increasing Rp value of the porous medium, the peak value of the velocity in non-porous zone keeps moving towards the wall and gradually decreases, but the fluid velocity in porous zone first decreases and then increases, and reaches a valley value when the R_p value is 3·5 mm.

Through continuously increasing the R_p value, it is found from the computation results that the fluid velocity in the porous zone keeps increasing and remains homogeneous all the time, while the peak value of the fluid velocity in the non-porous zone keeps decreasing and vanishes at the end. Its velocity profiles are similar to the curve of velocity profiles in Fig. 3*a* when x exceeds 0·10 m, which reduces the shear stress caused by the velocity gradient; however, the Darcy resistance and the inertial resistance both increase remarkably because of the expansion of the porous zone, causing the increase in the total flow resistance of the enhanced tube.

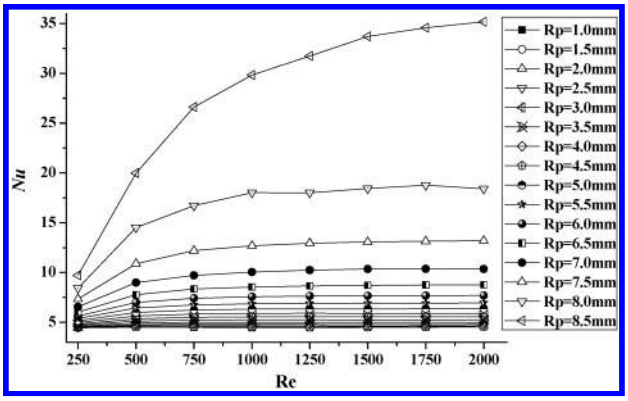
Figure 8 shows the influence of porous medium packing radius on the inner tube temperature profiles at the cross-section of x=0·05 m when Re number also is kept at 500. As shown in this figure, the temperature profiles in the porous zone display good uniformity; besides, the temperature homogeneous area expands as the porous medium packing radius increases. On the other hand, the fluid temperature in the central area increases as the porous medium packing radius increases. Through further observation, it is found that the temperature profiles under different packing radii in the non-porous zone are almost parallel to each other, which further illustrates that the increase in the packing radius is not able to remarkably enlarge the temperature gradient of the fluid near the wall. However, as the packing radius increases, the fluid temperature in the porous zone increases, while the temperature of the wall decreases as the temperature of the fluid near it decreases; thus, the outcome is that the temperature difference between the wall and the fluid is reduced. According to the above results, it can be concluded that the ultimate outcome of filling porous medium in the central of the tube is that the temperature profiles at the tube centre are more homogeneous and the fluid temperature of the tube centre increases, while the wall temperature reduces; thus, the temperature difference between the wall and the fluid reduces and the enhancement of heat transfer is realised.

Integrated performance evaluation of heat transfer and fluid flow

Figures 9 and 10 show the influences of the porous medium packing radius and Re number on the flow resistance and heat transfer characteristics. As shown in these figures, the flow resistance factor f and the Nu number both increase as the porous medium packing radius increases when Re number is kept constant. When the porous medium packing radius is smaller than 5 mm, the increase amplitude of both f and Nu of the enhanced tube is slight, while when the packing radius exceeds 5 mm, the amplitude increase of both f and Nu become more and more remarkable. It can thus be seen that the flow resistance as well as the heat transfer after



9 Influence of porous medium packing radius and Re number on resistance coefficient *f*



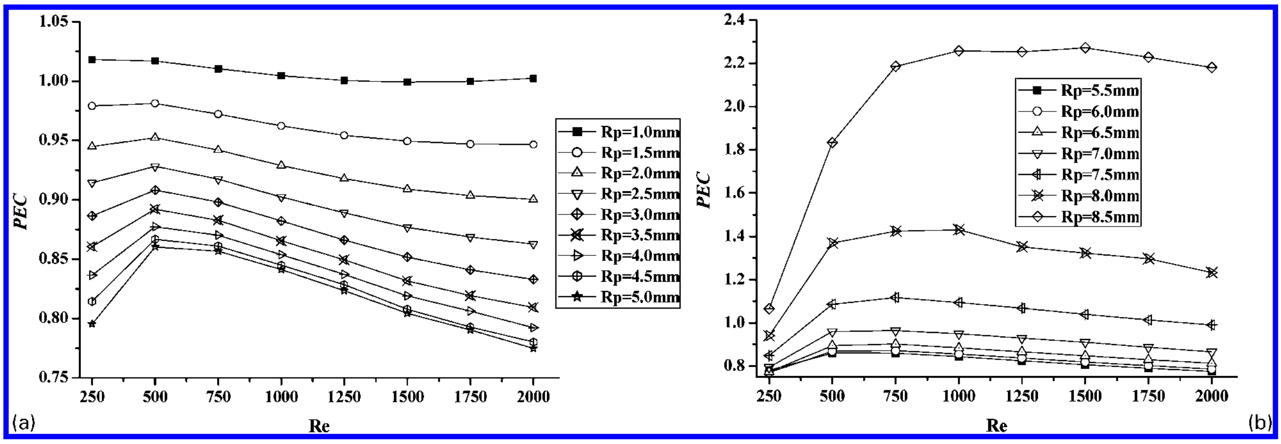
10 Influence of porous medium packing radius and Re number on Nu number

filling porous medium in the enhanced tube, is also remarkably increased.

Based on the integrated performance of heat transfer and flow resistance, one of the key criteria of evaluating the feasibility of engineering application of the tube with porous medium filled in the central area is that whether its PEC value is higher than 1. If the PEC value of the enhanced tube is higher than 1, it means that when compared with smooth tube, the amplitude increase of Nu number is higher than that of flow resistance factor *f* after filling porous medium in the central area, which means that the enhanced tube is of high application value; otherwise, if the PEC value of the enhanced tube is lower than 1, it means that the amplitude increase of Nu number is lower than that of *f*, and the application is restricted due to its excessive power consumption.

Figure 11 shows the influences of porous medium packing radius and Re number on the PEC values of the enhanced tube filled with porous medium in the central area. As indicated in the figure, the influences of porous medium packing radius and Re number on the PEC value are actually quite complicated. When the Re number remains constant, the packing radius R_p of 5·0 mm serves as a boundary for the variation of PEC value of the enhanced tube: when R_p is smaller than 5·0 mm, the PEC value of the enhanced tube keeps decreasing as R_p increases; when R_p is bigger than 5·0 mm, the PEC value of the enhanced tube keeps increasing as R_p increases. This illustrates that when R_p is within a range of small values, increasing R_p mainly changes the velocity profiles of the flow field and causes remarkable increase in the Darcy resistance and inertial resistance in the central area. The increase in velocity generates two notable velocity gradient near the wall of non-porous zone (Fig. 7), which brings about significant increase in resistance of the whole enhanced tube; therefore, the amplitude increase of resistance coefficient *f* is higher than that of Nu number, and the enhanced tube under this state has lower application value. In contrast, when R_p is bigger than 5·0 mm, the increase in R_p prominently enlarges the temperature homogeneous area of the radial cross-section, mainly changes the temperature profiles of the whole enhanced tube and prominently reducing the temperature difference between the wall and the fluid. Although the Darcy resistance and inertial resistance in the central area are also increased significantly, the velocity gradient near the wall of the non-porous zone decreases. Moreover, the amplitude increase of Nu number of the enhanced tube is higher than that of *f*. When R_p exceeds 7·0 mm, the enhanced tube is of higher application value. When porous medium packing radius reaches 8·5 mm and Re number is above 750, the PEC values shown in Fig. 11*b* of the enhanced tube are all above 2·0.

As shown in Fig. 11*a*, when Re number is near 500, all PEC values under different packing radii all reach peak values. The reason for this is that when Re is small, the influence of the increase in Re number on the Nu number is quite remarkable, while its influence on the Darcy resistance and inertial resistance within the porous zone and the influence on the shear stress of the non-porous zone are comparably slight; thus, the



a 1·0 mm ≤ R_p ≤ 5·0 mm; *b* 5·5 mm ≤ R_p ≤ 8·5 mm

11 Influences of porous medium packing radius and Re number on PEC value

overall effect is the increase in the PEC values. In contrast, when Re number is large, as the Re number increases, the outcome is totally reversed, and the overall effect is the decrease in the PEC values.

Apparently, the total flow resistance can be affected by the Darcy resistance and the inertial resistance of the porous zone, and the shear stress caused by velocity gradient and fluid viscosity of the non-porous medium area near the wall; filling porous medium in the central area obviously aggrandises the above three types of resistance, and the total flow resistance increases as the packing radius increases. Future work, such as finding the optimal porosity or giving the more concrete relationship between R_p, Re and PEC value, will be carried out to make the study more meaningful for the industrial application of such kinds of heat exchangers by filling metal porous medium in the core flow of tubes.

Conclusions

After filling porous medium filled in the central area of the fully developed laminar tube flow, numerical simulations on the flow and heat transfer characteristics are carried out in this paper, and detailed analyses on the influences of porous medium packing radius and Re number on the velocity and temperature profiles, flow resistance coefficient f, Nu number and PEC value are made. Corresponding conclusions the authors obtained are as follows:

1. Filling porous medium with high thermal conductivity and high porosity in the central area of fully developed laminar tube flow makes the temperature profiles in the porous medium area more homogeneous and reduces the temperature difference between the wall and the fluid, and thus heat transfer is significantly enhanced.

2. The influence of packing radius R_p and Re number on the PEC value of the enhanced tube is quite complicated. Only when the packing radius R_p has relatively large value can the enhanced tube show an ideal value of PEC.

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