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Study on Heat Transfer characteristics of Fluid-solid Two-phase Flow in a spiral slice inserted Tube

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Abstract. The heat transfer performance of the liquid-solid two-phase flow in the heat transfer tube with spiral slices insert was analyzed. The influence of the pitch of the spiral piece, the height of the spiral piece and the volume concentration of the solid particles on the heat transfer and the resistance of the tube was simulated by Fluent software. The results show that the heat transfer performance of the tube in which the spiral piece is inserted and passed into the solid particles is superior to that of the smooth tube. And the heat transfer enhancement is up to 55.48% compared with the smooth tube. The heat transfer tube enhances heat transfer accompanied by an increase in resistance. The values of the comprehensive evaluation indicators are all greater than 1. The comprehensive heat transfer performance of the tube is significantly enhanced.

1. Introduction

Heat exchangers are widely used in petroleum, chemical, energy and pharmaceutical industries. Increasing the heat transfer efficiency of the heat exchanger and preventing the dirt deposit on the heat transfer surface are important measures to improve the heat transfer efficiency. The interpolated spiral slices and the liquid-solid two-phase flow enhance the heat transfer of the wall. At the same time, dirt deposition on the heat transfer surface is prevented and on-line cleaning is achieved. Domestic and foreign scholars have carried out a lot of research on the heat transfer enhancement performance of heat exchange tubes with built-in spiral devices^[1-6]. However, there is little research on the complex technique in which the spiral slice is inserted into the tube and the solid particles are introduced. A reasonable mathematical model was established in the paper for numerical simulation. The effects of different parameters on the heat transfer and resistance of the tubes were investigated. The comprehensive performance of the pipe was studied by analyzing the value of the comprehensive evaluation index.

2. Model

2.1 Physical model

The physical model is built in conjunction with structural parameters in actual engineering applications. The heat exchange tube with the specification of $\Phi 32 \times 3.5$ mm is the research object of this paper. The length of the tube is 1.5m. The spacing of the inserted spiral slices is 350mm. The density of the solid particles was 1100 Kg/m³. The working fluid in the tube is water. The fluid flows sufficiently at the inlet and outlet. The structural of the tube inserting spiral slice is shown in 'figure 1'.



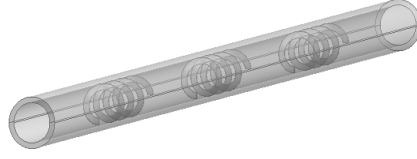


Figure 1. Structure of the tube inserting spiral slice

2.2 Mathematical model

The flow of fluid within the tube with inserting spiral slices follows basic conservation laws. The mathematical descriptions of conservation laws are the mass conservation equation, the momentum conservation equation and the energy conservation equation^[7]. These governing equations are expressed as follows.

2.2.1 Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (1)$$

2.2.2 Momentum conservation equation

$$\begin{cases} \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = \frac{\partial}{\partial x}(\mu \frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(\mu \frac{\partial u}{\partial y}) + \frac{\partial}{\partial z}(\mu \frac{\partial u}{\partial z}) - \frac{\partial p}{\partial x} + F_x \\ \frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho vu)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = \frac{\partial}{\partial x}(\mu \frac{\partial v}{\partial x}) + \frac{\partial}{\partial y}(\mu \frac{\partial v}{\partial y}) + \frac{\partial}{\partial z}(\mu \frac{\partial v}{\partial z}) - \frac{\partial p}{\partial y} + F_y \\ \frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho wu)}{\partial x} + \frac{\partial(\rho wv)}{\partial y} + \frac{\partial(\rho ww)}{\partial z} = \frac{\partial}{\partial x}(\mu \frac{\partial w}{\partial x}) + \frac{\partial}{\partial y}(\mu \frac{\partial w}{\partial y}) + \frac{\partial}{\partial z}(\mu \frac{\partial w}{\partial z}) - \frac{\partial p}{\partial z} + F_z \end{cases} \quad (2)$$

2.2.3 Energy conservation equation

$$\frac{\partial(\rho T)}{\partial t} + \frac{\partial(\rho u T)}{\partial x} + \frac{\partial(\rho v T)}{\partial y} + \frac{\partial(\rho w T)}{\partial z} = \frac{\partial}{\partial x}(\frac{k}{c_p} \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\frac{k}{c_p} \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\frac{k}{c_p} \frac{\partial T}{\partial z}) + S_r \quad (3)$$

Where, ρ is the density of the fluid. t is the time. u, v, w are the components of the velocity vector in x, y, z directions, respectively. c_p is the specific heat capacity. T is the temperature. k is the heat transfer coefficient of fluid. p is the pressure on the fluid micro-body. F_x, F_y, F_z are the physical forces on the micro-body. μ is the dynamic viscosity. S_r is a viscous dissipation term.

3. Numerical simulation

3.1 Meshing

The tubes with spiral slices inserted are divided by an unstructured grid due to irregular structure. Considering the influence of the boundary layer of the wall, the boundary layer is meshed. The wall boundary layer is divided into five layers. The thickness of the first layer is 0.05 mm. The meshing of the computational domain is shown in 'figure 2'.

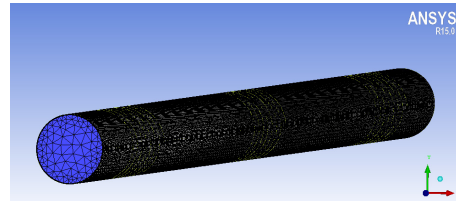


Figure 2. Meshing of the computational domain

3.2 Boundary conditions

According to the conditions and characteristics of the fluid flow in the heat exchange tube, the boundary conditions of the calculation area are respectively set as follows.

3.2.1 Boundary condition of inlet. The boundary condition of inlet is velocity inlet. The temperature of the fluid at the inlet is 310K. The flow rate is 1 m/s. The temperature and velocity at which the solid particles enter the flow field are the same as those of the fluid.

3.2.2 Boundary condition of outlet. The boundary condition of outlet is outflow.

3.2.3 Boundary condition of the wall. The wall is fixed and meets the no-slip wall boundary conditions. The temperature of the wall is uniform and constant at 330K.

3.3 Parameter setting

3.3.1 Heat transfer coefficient

$$E(K) = \left(\frac{k}{k_0} - 1 \right) \times 100\% \quad (4)$$

Where, k is the heat transfer coefficient of the tube in which the spiral slices are inserted and passed into the particles. k_0 is the heat transfer coefficient of the smooth tube.

3.3.2 Resistance coefficient

$$E(f) = \left(\frac{f}{f_0} - 1 \right) \times 100\% \quad (5)$$

Where, f is the resistance coefficient of the tube in which the spiral slices are inserted and passed into the particles. f_0 is the resistance coefficient of the smooth tube.

3.3.3 Comprehensive evaluation index. According to the comparison of the three working effects proposed by Lin Zonghu^[8]. Define a comprehensive evaluation index that considers both heat transfer and flow resistance of the heat transfer tube:

$$E = \left(\frac{k}{k_0} \right)^{3.5} - \frac{f}{f_0} \quad (6)$$

When the value of the comprehensive evaluation index is greater than 0, it indicates that the overall performance of the tube with spiral slices inserted and particles added is better than that of the smooth tube. And the value of comprehensive evaluation index is larger, the comprehensive performance of the tube is better.

4. Simulation results analysis

4.1 Effect of pitch of the spiral slice on heat transfer and resistance

According to the setting of structural parameters in an actual engineering application, the research range of the pitch of the spiral slice indicated by s is from 20mm to 100mm. They are divided into five groups for testing. The parameters such as the height of the spiral slice indicated by h , the concentration of the solid particles indicated by c , and the particle diameter indicated by d are set to a fixed value. That is, $h=4\text{mm}$, $c=3\%$, and $d=1\text{mm}$.

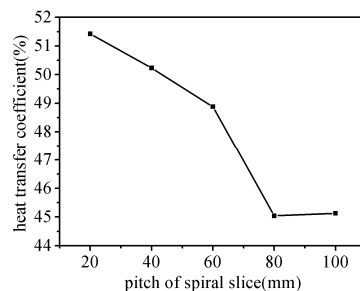


Figure3. Diagram of pitch of spiral slice and enhanced heat transfer coefficient.

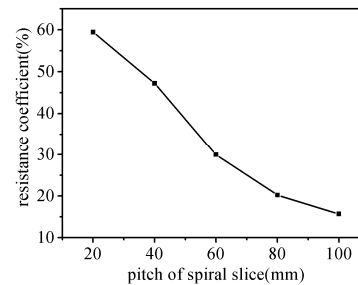


Figure4. Diagram of pitch of spiral slice and resistance coefficient.

'figure 3' and 'figure 4' are graphs showing the relationship between the pitch of spiral slice and the enhanced heat transfer coefficient and the resistance enhancement coefficient, respectively. It can be seen that the enhanced heat transfer coefficient and the resistance enhancement coefficient are significantly reduced as the pitch increases. When the pitch reaches 80mm, the increase of the pitch of spiral slice has little effect on the heat transfer coefficient of the tube.

4.2 Effect of height of the spiral slice on heat transfer and resistance

The range of the height of the spiral slice is from 2mm to 10mm, and is equally divided into five groups. The other three parameters are fixed values, which are $s=40\text{mm}$, $c=3\%$, and $d=1\text{mm}$.

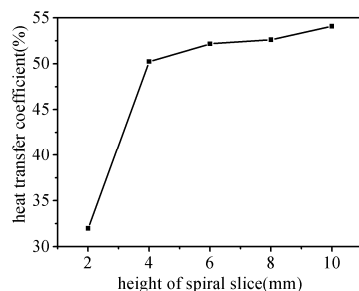


Figure5. Diagram of height of spiral slice and enhanced heat transfer coefficient.

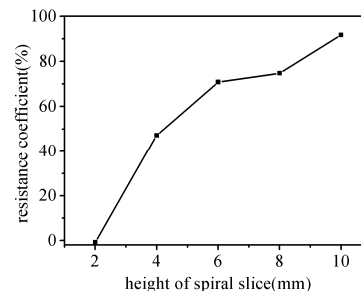


Figure6. Diagram of height of spiral slice and resistance coefficient.

In 'figure 5', it can be seen that the heat transfer coefficient increases remarkably as the height increases when the height of spiral slice is in the range of 2 mm to 4 mm. In the range of 4mm to 10mm, the increase of the heat transfer coefficient is slowed down. As can be seen from 'figure 6', the resistance enhancement coefficient increases as the height increases. When the height of the spiral slice is in the range of 6mm to 8mm, the change trend of the enhanced heat transfer coefficient and the resistance enhancement coefficient is gentle.

4.3 Effect of concentration of the solid particles on heat transfer and resistance

The concentration of solid particles was studied in the range of 1% to 9%, and was divided into five groups. The remaining parameters are set to fixed values, which are $s=40\text{mm}$, $h=4\text{mm}$, and $d=0.4\text{mm}$.

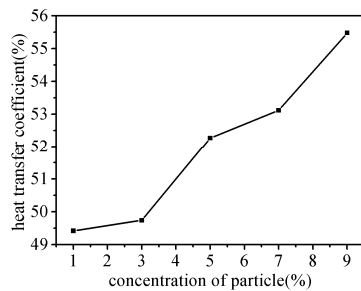


Figure7. Diagram of particle concentration and enhanced heat transfer coefficient.

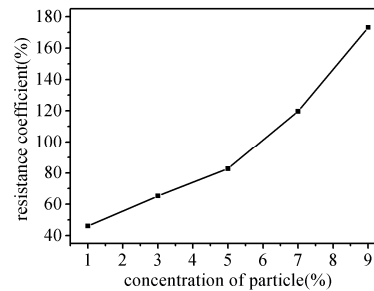


Figure8. Diagram of particle concentration and resistance coefficient.

In 'figure 7', the enhanced heat transfer coefficient increases as the particle concentration increases. The relationship between the resistance enhancement coefficient and the particle concentration is shown in 'figure 8'. The resistance enhancement coefficient is significantly enhanced as the particle concentration increases. When the particle concentration is 9%, the drag coefficient is nearly 1.7 times that of the smooth tube.

4.4 Effect of pitch of the spiral slice, height of the spiral slice and concentration of the solid particles on the comprehensive performance

The corresponding parameters are set to simulate the influence of the pitch of spiral slice, the height of the spiral slice and the particle concentration on the overall performance. The numerical calculation results of the comprehensive evaluation index are shown in the following figures.

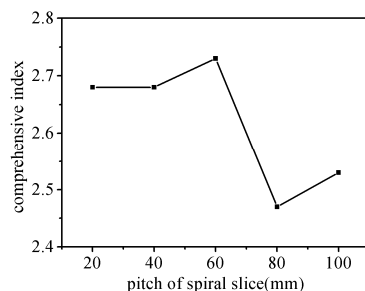


Figure9. Diagram of pitch of spiral slice and comprehensive index.

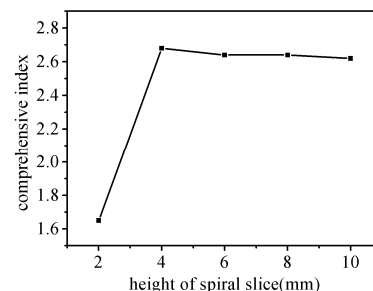


Figure 10. Diagram of height of spiral slice and comprehensive index.

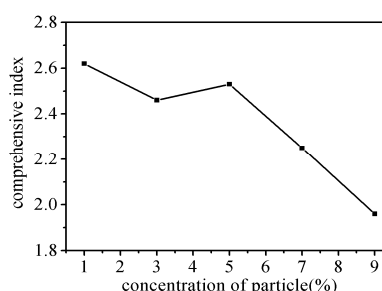


Figure11. Diagram of particle concentration and comprehensive index.

In 'figure 9', the overall performance of the heat exchange tubes increases first and then decreases as the pitch of spiral slice increases. The comprehensive performance of the tube is the best when the pitch is 60mm. As can be seen from 'figure 10', the values of the comprehensive evaluation indexes all reach 2.6 or more when the height of spiral slice reaches 4 mm. The overall heat transfer performance is significantly enhanced. The relationship between the comprehensive evaluation index and the particle concentration is shown in 'figure 11'. As can be seen from the figure, the value of the comprehensive evaluation index decreases as the particle concentration increases.

5. Conclusion

- The results show that the insertion of the spiral slice and the introduction of solid particles significantly enhance the heat transfer performance of the tube.
- The combination of the spiral slice and the liquid-solid two-phase flow enhances the heat transfer performance and causes the resistance of the tube to increase significantly.
- The influence of various parameters on the heat transfer performance of the tube in which the spiral slice is inserted and passed into the particle was simulated. The complex technique can significantly improve the comprehensive performance of the tube.

Acknowledgment

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