Study on turbulent flow in <1-2> wave wall tube heat exchanger

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Abstract: The traditional straight wall tube heat exchanger has low heat exchange efficiency, in order to solve this problem, the turbulent flow in wave wall tube heat exchanger was studied by numerical simulation. It is found that the unique corrugated structure of the heat exchange tube in the wave wall tube heat exchanger can improve the flow state of the fluid in the heat exchanger. The average pressure drop of heat exchanger gradually increases with the increase of Reynolds number $Re$. Under the same conditions, the average pressure drop of wave wall tube heat exchanger is lower than that of straight wall tube heat exchanger. The improvement of heat exchange performance of heat exchanger can not be realized only by increasing the inlet flow of heat exchanger. The wave wall tube heat exchanger can strengthen the heat exchange of the fluid in the heat exchanger.

1. Introduction

Nowadays, the problem of energy shortage is becoming more and more serious. How to make rational use of energy has become the core issue of industrial development in various countries. In order to alleviate the problem of energy shortage, all countries are looking for new energy or energy-saving methods, and heat exchangers play an important role in energy transfer [1]. The part directly involved in heat exchange in the heat exchanger is the heat exchange tube, and its heat exchange efficiency can often directly affect the efficiency of the heat exchanger. The traditional smooth circular tube has low heat exchange efficiency. Many scholars change the pipe type to change the flow state of the fluid in the pipe, so as to achieve the effect of strengthening heat exchange [2-3]. As a new and efficient heat exchange tube, wave wall tube has the advantages of simple structure and easy flow separation, which has attracted extensive research by scholars at home and abroad. Wu Jinxing et al. [4] carried out simulation and Experimental Research on sine wave wall tube. The results show that the periodic structure of sine wave wall tube can induce secondary flow; under the same conditions, the comprehensive heat transfer performance of sine wave wall tube is stronger than that of smooth circular tube. Zeng Min et al. [5] pointed out that there is a critical Reynolds number. When $Re$ is greater than this critical value, the heat transfer performance of wave wall tube is better than that of circular tube under the same conditions. Nishimura et al. [6] pointed out that under the same power, the optimal heat and mass transfer of fluid in wave wall tube occurs in the range of medium Reynolds number. Zhang Liang et al. [7] pointed out that the convective heat transfer coefficient of bellows heat exchanger can be increased by 45.2% ~ 51.1% compared with straight wall heat exchanger. Considering the heat transfer characteristics and resistance characteristics, it is found that the comprehensive heat transfer performance of bellows heat exchanger is better than that of straight wall heat exchanger. Deng Xianhe et al. [8] pointed out that the hollow ring shell and tube heat exchanger can promote interfacial turbulence and strengthen convective heat transfer for the gas on both sides of...
the tube. The total heat transfer coefficient of the heat exchanger can reach up to 30W / (m². K), which can save 40% ~ 50% of the heat transfer area compared with the traditional heat exchanger. Wei Lifeng et al. [9] pointed out that there is secondary flow in the spiral elliptical tube, resulting in uneven radial distribution of temperature gradient and velocity gradient in the cross section of the spiral elliptical tube. At the same time, it is found that with the increase of fluid inlet angle $\theta$ the Nusselt number $Nu$ increases, the friction coefficient $f$ increases and the comprehensive heat transfer performance increases. Cong Xiaochun et al. [10] studied the heat transfer and resistance characteristics on the air side of the flat fin heat exchanger and found that the smaller the fin spacing is, the larger the Reynolds number $Re$ is, which is more favorable to improve the Nusselt number $Nu$ and reduce the resistance factor of the flat fin heat exchanger. Wu Zengfa et al. [11] conducted numerical simulation research on the wound tube heat exchanger. The results show that the outer diameter, layer spacing, tube spacing and winding angle of the wound tube have a significant impact on the heat transfer performance of the heat exchanger. With the increase of the outer diameter of the tube and the decrease of layer spacing, tube spacing and winding angle, the Nusselt number $Nu$ of the shell side of the wound tube heat exchanger gradually increases.

To sum up, although predecessors have done a lot of research on the heat transfer and flow characteristics of a single wave wall tube, and the research on the application of special-shaped tubes in heat exchangers is also very rich, no one has systematically studied the flow and heat transfer characteristics of wave wall tube heat exchangers when wave wall tubes are applied to shell and tube heat exchangers. Therefore, this paper studies the turbulent flow of <1-2> wave wall tube heat exchanger by numerical simulation, which can provide an important reference for the application of wave wall tube heat exchanger in engineering.

2. Geometric model
In this paper, the turbulent flow of <1-2> wave wall tube heat exchanger is studied. The structure of wave wall tube is shown in Figure 1. The maximum diameter of wave wall tube $D_{\text{max}} = 12$ mm, the minimum diameter $D_{\text{min}} = 5$ mm, wavelength $\lambda = 25$ mm, wave amplitude $A = 3.5$ mm, and the total length of tube $L = 510$ mm. Each wave wall tube in wave wall tube heat exchanger has 18 wave bands, and 30 mm straight tube walls are reserved at both ends of the tube. The three-dimensional model diagram of wave wall tube heat exchanger is shown in Figure 2. There are two fluid flows in wave wall tube, one cold fluid and one hot fluid. The overall structure is <1-2>, 1 represents one shell side, 2 represents two tube sides, and the baffle is single bow; the main structural parameters are shown in Table 1.

![Fig. 1 Structural diagram of wave wall tube](image-url)
3. Grid division and boundary condition setting

Due to the large curvature of the heat exchange tube in the wave wall tube heat exchanger, the non-structural grid with stronger adaptability is adopted. In the grid division process, the shell side, tube side and shell need to be meshed respectively. Finally, considering the calculation cycle, calculation equipment, accuracy and other factors, the number of grids of the wave wall tube heat exchanger is determined to be about 3.7 million.

Boundary condition setting: the fluid flowing in the wave wall tube heat exchanger is cold and hot water. The inlet of cold and hot fluid adopts velocity inlet. The cold fluid flows in the shell side; the inlet temperature is 20 °C; the hot fluid flows in the tube side; the inlet temperature is 90 °C; the outlet is set as pressure outlet; and the outlet pressure is set as 0 Pa. The implicit solver based on pressure is used in the solution process, the coupling of pressure and velocity adopts the couple algorithm, and the turbulence model adopts RNG K-ε model [12]. The following assumptions are made in the process of model establishment and simulation: (1) the gap between baffle and heat exchange tube is ignored, (2) The physical parameters of cold and hot fluid remain unchanged in the flow process.

4. Analysis of calculation results

4.1 Velocity analysis

Figure 3 shows the flow trajectory of the fluid in the heat exchanger. It can be clearly seen from the figure that the fluid on the shell side of the straight wall tubular heat exchanger forms a large reflux zone near the baffle, that is, the flow dead zone. The fluid makes vortex movement, while the fluid on the shell side of the wave wall tubular heat exchanger has a better overall flow state during the flow process. There is no obvious flow dead zone near the baffle. This is because the heat exchange tube of the wave wall tube heat exchanger is a wave wall tube. The wave wall tube has a unique periodic corrugated structure. It can not only improve the flow state of the fluid in the wave wall tube, but also...
improve the flow state of the fluid on the shell side of the tube, and reduce the backflow caused by the collision between the shell side fluid and the baffle.

In order to more intuitively analyze the velocity change of fluid in wave wall tube heat exchanger and straight wall tube heat exchanger, figure 4 shows the velocity cloud diagram of fluid in the heat exchanger at section z = 0. It can be seen from the figure that the inlet velocity and outlet velocity of the two heat exchangers are the same, ensuring that the mass flow of fluid entering the heat exchanger is the same as that exiting the heat exchanger in unit time. In the heat exchange area of the heat exchanger, due to the corrugated structure of the wave wall tube, the velocity of the fluid on the tube side of the wave wall tube heat exchanger is higher than that in the straight wall tube heat exchanger.

4.2 Pressure analysis

Figure 5 shows the pressure distribution of Z = 0 section straight wall tubular heat exchanger. Since the outlet is set as the pressure outlet and the pressure is set as 0Pa in the simulation calculation process, in order to make the fluid flow smoothly from the outlet of the heat exchanger, the inlet pressure of the heat exchanger is greater than 0. As can be seen from Figure 5, the pressure decreases gradually with the flow of fluid, and the most obvious decrease is at the baffle. There is an obvious pressure drop on both sides of the baffle. Therefore, when designing the heat exchanger, it is necessary to design the thickness of the baffle thicker to ensure that the baffle has sufficient strength.

Figure 6 shows the change of the average pressure drop at the inlet and outlet of the shell side fluid of the heat exchanger with the Reynolds number $Re$. It can be seen from Fig. 6 that the average pressure drop of the shell side fluid of the two heat exchangers gradually increases with the increase of the Reynolds number $Re$. At the same time, it can be seen that under the same Reynolds number $Re$, the shell side pressure drop of wave wall tube heat exchanger is lower than that of straight wall tube heat exchanger, because wave wall tube can improve the flow state of fluid in the heat exchanger and reduce the flow resistance of fluid.
4.3 Temperature analysis

Figure 7 shows the temperature distribution of the fluid in the heat exchanger. It can be seen from the figure that the temperature of the two heat exchangers at the inlet is the same, while the outlet temperature of the tube side of the wave wall tube heat exchanger is lower than that of the straight wall tube heat exchanger, and the hot fluid flows in the tube side, indicating that the hot fluid in the tube side of the wave wall tube heat exchanger can be cooled to a lower temperature faster under the same conditions. Therefore, compared with the straight wall tube heat exchanger, the wave wall tube heat exchanger strengthens the heat exchange of cold and hot fluids.

Figure 8 shows the change of the outlet temperature of the heat exchanger with the Reynolds number $Re$. It can be seen from Fig. 8 (a) and Fig. 8 (b) that the outlet temperature of the shell side of the wave wall tube heat exchanger first increases and then decreases with the increase of the Reynolds number $Re$. The outlet temperature of the tube side first decreases and then increases with the increase of Reynolds number $Re$. As can be seen from figure 8 (b) and figure (c), under the same Reynolds number, the outlet temperature of the tube side of the wave wall tube heat exchanger is lower than that of the straight wall tube heat exchanger. Because the tube side of the heat exchanger flows hot fluid, the wave wall tube heat exchanger can cool down the temperature faster than the straight wall tube heat exchanger during the flow and heat exchange of the heat exchanger, that is, the wave wall tube heat exchanger has stronger heat exchange capacity. At the same time, it is found that there is a peak in the three diagrams, and the improvement of heat exchange performance of heat exchanger can not be realized only by increasing the inlet flow of heat exchanger.
5. Conclusion

(1) The unique corrugated structure of the heat exchange tube in the wave wall tube heat exchanger can improve the flow state of the fluid in the heat exchanger and reduce the flow dead zone.

(2) The average pressure drop on the shell side of the heat exchanger increases gradually with the increase of Reynolds number $Re$, and under the same Reynolds number $Re$, the average pressure drop of wave wall tube heat exchanger is less than that of straight wall tube heat exchanger.

(3) Under the same conditions, the outlet temperature of the tube side of the wave wall tube heat exchanger is lower, that is, the wave wall tube heat exchanger can cool the hot fluid to a lower temperature faster, and the wave wall tube heat exchanger can strengthen the heat exchange of the fluid in the heat exchanger.

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