Simulation on Heat Transfer Enhancement Characteristics of Inserted Multi-helical Spring

Ma Yuxiang, Liu Yongqi, Sun Peng

Abstract—**In order to enhance the heat exchange effect of spring heat exchange tube, based on the traditional helical spring heat exchange tube, a new type of helical spring heat exchange tube was developed by changing the spring section into a square and contacting the spring with the inner wall of the heat exchange tube. The helical spring heat exchange tube was simulated by Fluent software, the influence of several springs inserted into the tube on the heat exchange effect was analyzed. The results show that: with the increase of the number of springs inserted into the tube, the velocity of the fluid in the spring heat exchange tube gradually decreases, and the pressure drop also gradually decreases, the velocity field gradually presents a symmetrical distribution along the central axis, the flow state of the fluid gradually tends to be stable, and the distribution of pressure field and temperature field in the tube is gradually uniform. When the Reynolds number was 20000, the heat transfer coefficient of the four-helical spring heat exchange tube was increased by 11.45W·m^2·K^{-1} and pressure drop was decreased by 40.31Pa compared with that of single-helical spring heat exchange tube; when the Reynolds number was 40000, the heat transfer coefficient of the four-helical spring heat exchange tube was increased by 3.94W·m^2·K^{-1} and pressure drop was decreased by 157.88Pa compared with that of single-helical spring heat exchange tube.**

Index Terms—**enhanced heat transfer, heat exchange tube, numerical analysis, spring number**

I. INTRODUCTION

As a kind of heat exchange process equipment, heat exchangers are widely used in chemical industry, petroleum, power, food and many other industrial production, with the rising cost of energy and raw materials today, enhanced heat transfer technology for improving the heat transfer efficiency of heat exchangers has been a research hotspot[1]-[2]. The main methods used by heat exchangers to enhance heat transfer include surface treatment of heat transfer tubes, grooving the inner and outer wall surfaces of heat transfer tubes, internal insert, change of support and so on[3]. The heat transfer enhancement method can be divided into active enhancement heat transfer technology and passive enhancement heat transfer technology, the former requires additional mechanical power or electromagnetic force to enhance heat transfer, the latter is usually enhanced by changing the shape of the heat transfer surface and adding reinforcement elements, in addition to pump power, this method does not require any additional power[4]-[5]. Heat transfer enhancement can improve heat transfer efficiency, reduce the volume of heat exchanger, reduce equipment cost and save energy, so it is of great significance to the research of heat transfer enhancement.

Interpolated helical spring is a typical passive heat transfer enhancement technology, which has been widely concerned because of its advantages such as convenient processing and installation, free change of spring pitch and wide application range, many scholars at home and abroad have studied the flow and heat transfer characteristics in the heat exchanger tube with inserted helical spring through experimental research and numerical simulation. Xu jianmin [6]-[7] used Particle Imaging Velocimetry (PIV) to observe and analyze the flow field of al2o3-distilled water nanofluids and distilled water with different mass fractions in the inner spiral spring tube, velocity and vorticity diagrams of nanofluids with different mass fractions under different Reynolds coefficients were obtained, and the effects of coil spring pitch, wire diameter and middle diameter on the flow field in the tube were analyzed, Through experiments, the best way to enhance the degree of turbulence was determined. Shyy Woei Chang[8] proposed a new convenient passive heat transfer enhancement method by using segmental spiral springs to induce axial vortices, and proposed correlations for each enhanced tubular flow. Liu Lifang[9]-[10] studied the heat transfer characteristics in the core flow region of spiral spring heat exchange tubes with different coil diameters inserted by numerical simulation and experiment, analyzed the influence of the diameter of the inserted coil on the velocity field, temperature field and heat transfer enhancement effect of the core flow. Smith Eiamsa-ard[11] studied the influence of sectional spiral springs in square tubes on heat transfer and turbulent pressure drop performance under the condition of uniform heat flux through self-built experimental platform.

Shandong University of Technology designed a new type of spiral spring heat exchange tube, the spring uses a square cross section and contacts the spring with the inner wall of the heat exchange tube to further enhance heat exchange. Compared with the traditional circular spring, the square spring can better enhance the heat transfer, but the pressure drop is slightly higher. On the basis of the preliminary study, the double-helical, triple-helical and four-helical square section springs are inserted into the heat exchange tube to analyze the changes of fluid velocity, temperature and pressure in the tube, in order to explain the heat transfer mechanism of multi-helical spring heat exchange tube and promote the development of new efficient heat transfer element.

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II. PHYSICAL MODEL AND MATHEMATICAL DESCRIPTION

The distribution of the springs in the spring heat exchange tube is shown in figure 1, when the number of springs increases by one, the pitch of each spring increases by twice as much as that of the single helical spring, so as to ensure that when multiple springs are inserted into the tube, the pitch under the joint action of multiple springs is the same. The equivalent diameter of the spring is 6mm, the pitch is 33.5mm, the length of the heat exchange tube is 500mm, the wall temperature is 500K, and the inlet air temperature is 310K.

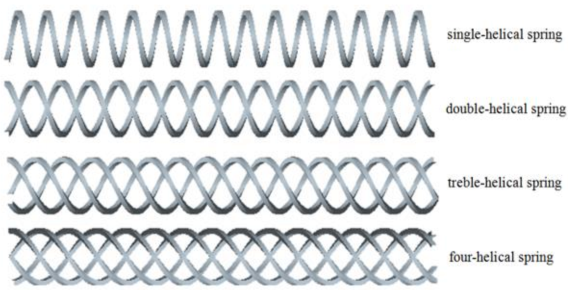

Fig.1 Schematic diagram of spring distribution

The mesh is divided by ICEM, as shown in Fig.2, Fig.3 shows the grid quality detection, it can be seen from the figure that the grid quality divided is above 0.3, which can ensure the calculation accuracy.

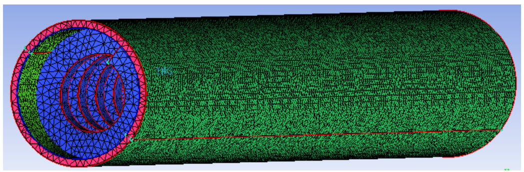

Fig.2 Diagram of grid division

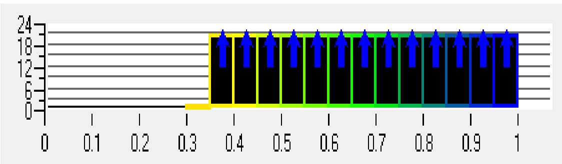

Fig.3 Grid quality detection

In this paper, the flow field parameters in the tube do not change with time, so it can be regarded as single-phase steady state flow. Ignoring the influence of gravity, the continuity equation, momentum equation and energy equation are shown as follows:

Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

Momentum equation:

$$\begin{aligned}
&\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)\\
&\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)\\
&\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\mu}{\rho}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)
\end{aligned} \tag{2}$$

Energy equation:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=a\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{3}$$

where, u,v,w represent the velocity of the fluid in x,y and z directions respectively; μ is the dynamic viscosity of air; ρ is the density of air; a represents the thermal diffusivity of the air; T is temperature; P is pressure.

The outer surface of the pipe is a constant wall temperature surface with a heating temperature of 500K, the wall surfaces at both ends of the tube are adiabatic, spring surface and gas contact surface, tube inner surface and gas contact surface are set as gas/solid coupling surface, while spring and tube inner surface contact surface is set as solid/solid coupling surface. The gas inlet is set as the velocity inlet, the inlet velocity is 5~10m/s, and the inlet temperature is 310K; the gas outlet is the pressure outlet. The simulated gas is air, the heat exchange tube and the spring are made of 304 stainless steel.

III. RESULT

Fig. 4 shows the velocity vectors of the inlet air with a velocity of 7.5m/s and the single-helical, double-helical, treble-helical and four-helical spring heat exchange tubes at x=0mm and y=100~200mm sections. It can be seen from the figure that, with the increase of the number of inserted springs, the flow rate of the fluid in the core area of the heat exchange tube gradually decreases and changes greatly, but the flow rate of the fluid near the tube wall and the spring does not decrease significantly, the maximum fluid velocity in the single-helical spring heat exchange tube is 18m/s, while the maximum fluid velocity in the four-helical spring heat exchange tube is 14m/s, this is because as the number of inserted springs increases, the mutual constraints of the springs on changing the flow direction of the fluid increase, enabling the fluid to flow smoothly in the tube. At the same time, it can be seen from the figure that, due to the internal structure of the spring heat exchange tube, jet effect is formed at the wall far away from the spring due to the increased cross section of the flow passage, at the wall near the spring, because the passage narrows suddenly, throttle effect is formed, these two effects lead to a number of small eddies near the wall and the spring, and the fluid presents axial and radial flow modes, however, near the center of the tube, the fluid flow is mainly axial, and tangential flow and radial flow are almost absent.

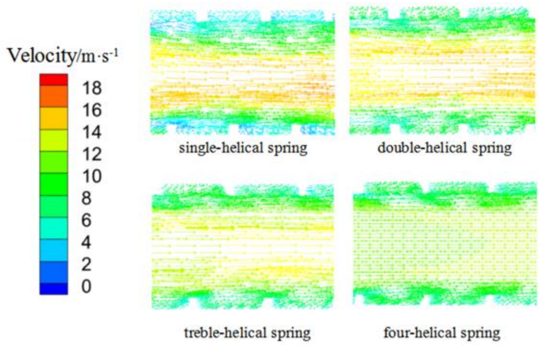

Fig.4 Velocity vector distribution of axial section at x=0mm, y=100~200mm

Fig. 5 shows the velocity vectors of the inlet air with a velocity of 7.5m/s and the single-helical, double-helical, treble-helical and four-helical spring heat exchange tubes at y=480mm sections(near the exit). It can be seen from the figure that after the spring is inserted, the fluid velocity boundary layer in the tube is thinned, the velocity gradient at the wall surface is increased, and the flow near the spring is complicated, resulting in backflow and vortex, due to the guiding effect of the spring, the fluid rotates in the tube, instead of a single axial flow, tangential flow and radial flow occur at the same time. The centrifugal force generated by the tangential velocity component produces a significant centrifugal convection effect, which causes the fluid in the central area of the heat exchange tube to be mixed with the fluid near the wall surface, enhances the heat transfer effect. At the same time, the tangential rotation of the fluid in the single coil spring heat exchange tube is obvious, the fluid velocity in the tube is large, and the vortex is obvious at the section away from the spring, But with the increase of the number of springs, the flow form of the fluid in the tube changes, the fluid velocity gradually decreases, and the whirlpool decreases.

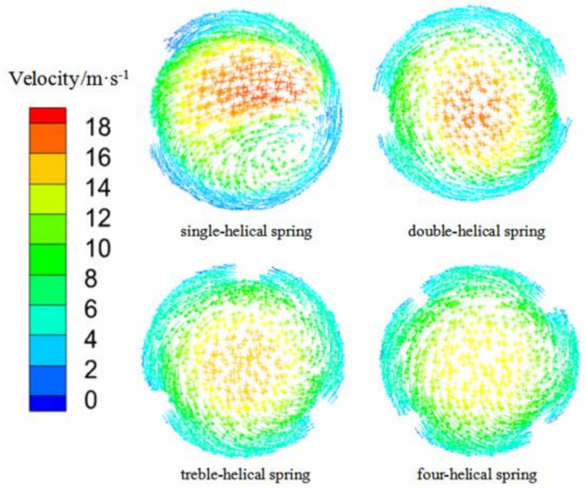

Fig.5 Velocity vector distribution of radial section at y=480mm

Fig.6 shows the temperature contour of the single-helical, double-helical, treble-helical and four-helical spring heat exchange tubes at x=0mm section with the inlet air velocity of 7.5m/s. As can be seen from the figure, when the temperature of the tube wall is the same, the temperature gradient of the four kinds of spring heat exchange tubes varies greatly in the vertical direction, and the heat transfer situation is obvious, this is because the existence of the spring destroys the fluid flow state near the wall, while the heat transfer area increases, making the heat exchange tube not only has a large temperature gradient near the wall, but also affects the temperature gradient in the vertical direction of the core flow area. Compared with the double -helical, treble-helical and four-helical spring heat exchange tubes, the temperature field of the single helix spring heat exchange tubes in the latter half is not symmetrical along the axis, but slightly off the center axis, with an eccentric distribution, this is because the diversion effect of the coil spring changes the direction of fluid flow in the tube, so that the fluid rotates in the tube, and it is no longer a single axial flow, the flow state of the fluid will have a certain influence on the heat transfer effect, resulting in the unbalanced distribution of the temperature field. The double-helical, treble-helical and four-helical springs are symmetrical in the center, and the combined action of several springs balances the influence of the single helical spring on the eccentric flow of the fluid, so that the fluid can rotate along the central axis, the fluid flow in the tube is more steady, and the temperature field is symmetrically distributed relative to the center. And the steady flow of the fluid in the tube has a certain effect on reducing the pressure drop in the tube.

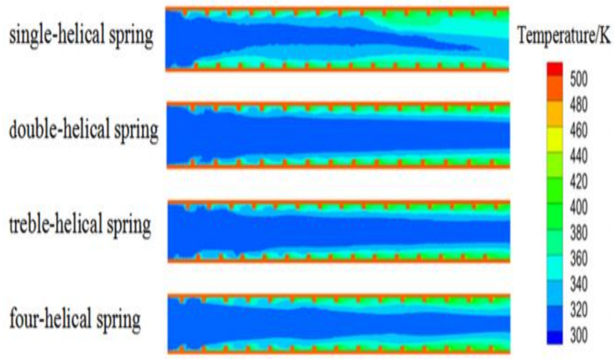

Fig.6 Temperature contour plot of axial section at x=0mm

Fig.7 shows the temperature contour of the single-helical, double-helical, treble-helical and four-helical spring heat exchange tubes at y=480mm(near the exit) section with the inlet air velocity of 7.5m/s. As can be seen from the figure, the four kinds of spring heat exchange tubes all have relatively high temperature near the spring and near the wall, the inserted spring increases the contact area between the heat exchange tube and the fluid, and the heat exchange area also increases, so that the heat of the tube wall can be better transferred to the fluid; however, the core flow area near the center is less affected by the spring, and the spring has a small guiding effect on the fluid flow state, making the fluid flow stable, and the core fluid has a small displacement effect on the heat, resulting in a lower temperature. Compared with double-helical, treble-helical and four-helical spring heat exchange tubes, the temperature field distribution of single-helical spring heat exchange tubes is not uniform at the section, this is because the fluid flow in the heat exchanger tube with single coil spring is affected by only one spring, and the turbulence of the single spring causes the fluid flow direction in the tube to deviate from the center axis, under the influence of fluid eccentric flow, the heat transfer between the inner wall of heat exchange pipe and the fluid is not uniform, which makes the temperature field distribution and fluid velocity field distribution more similar; the double-helical, treble -helical and four-helical springs arranged in a symmetrical manner in the center of the spring balance the eccentric flow of the fluid in the tube, the fluid can rotate along the central axis, the fluid flow state is stable, and the distribution of velocity field and temperature field is symmetrical.

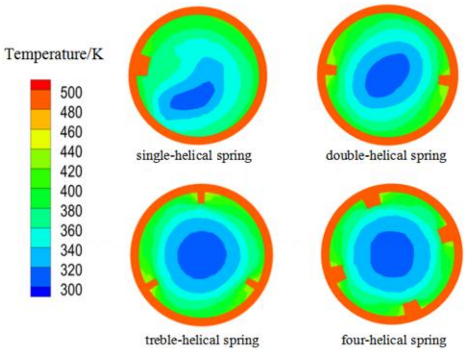

Fig.7 Temperature contour plot of radial section at y=480mm

Fig.8 shows the pressure contour of the single-helical, double-helical, treble-helical and four-helical spring heat exchange tubes at x=0mm section with the inlet air velocity of 7.5m/s. As can be seen from the figure, the pressure field in the four kinds of spring heat exchange tubes presents a segmented distribution state, the pressure decreases gradually from the air inlet to the outlet, and the pressure drop changes in the same length of pipe is similar. The pressure drop of the heat exchange tube with single-helical spring is the largest, and the pressure at the inlet can reach about 160Pa, with the increase of the number of springs in the tube, the pressure drop gradually decreases. The four kinds of spring heat exchange tubes all produce great pressure near the windward side of the spring. The resistance of the spring to the fluid causes the pressure near the windward side of the spring to increase suddenly, but the pressure is lower on the leeward side of the spring, especially near the air inlet. With the increase of the number of springs, the pressure near the windward side of the spring decreases gradually, this is due to the joint action of multiple springs to make the fluid flow state becomes stable, the fluid flow rate decreases, so that the pressure inside the tube decreases.

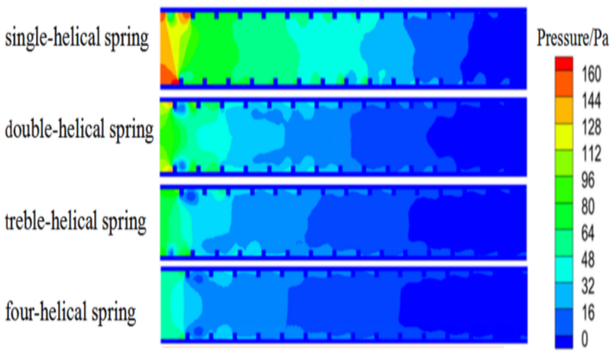

Fig.8 Pressure contour plot of axial section at x=0mm

Fig.9 shows the pressure contour of the single-helical, double-helical, treble-helical and four-helical spring heat exchange tubes at y=250mm(half the length) section with the inlet air velocity of 7.5m/s. As can be seen from the figure, when the fluid flows through the middle part of the heat exchange tube, the pressure inside the heat exchange tube with single-helical spring is still relatively high, with the increase of the number of springs in the tube, the pressure in the heat exchange tube gradually decreases, and the pressure in the heat exchange tube with four-helical springs has almost decreased to the lowest value, there are relatively high pressure fields near the windward surface of the single-helical and double-helical springs, while the pressure fields near the windward surface of the treble-helical and four-helical springs hardly change. The pressure field distribution at the cross section of the single helical spring is uneven and asymmetrical, this is because the single-helical spring guides the fluid too strongly, and the fluid changes in the direction of flow, with the increase of the number of springs, the guiding effect of each spring on the fluid is balanced, so that the fluid flow becomes more stable and the velocity of flow decreases correspondingly.

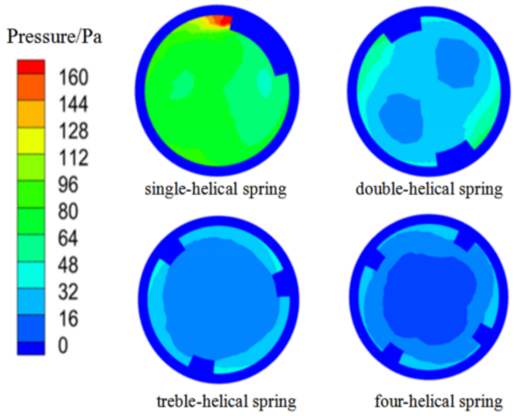

Fig.9 Pressure contour plot of radial section at y=250mm

Fig. 10 shows the comparison of outlet temperatures of single-helical, double-helical, treble-helical and four-helical spring heat exchange tubes with Reynolds number when the spring pitch p is fixed at 33.5mm and the equivalent diameter is 6mm. It can be seen from the figure that the outlet temperature of the four kinds of spring heat exchange tubes decreases with the increase of Reynolds number, which is because the fluid flow rate in the tube increases with the increase of Reynolds number, resulting in the increase of flow rate, at the same time, the heating time of the tube wall to the fluid is shortened, resulting in less heat exchange and lower outlet temperature. It can also be seen from the figure that the outlet temperature of the four-helical spring heat exchange tube is the highest, followed by the treble-helical tube, and the single-helical tube is the lowest, when the Reynolds number is 20000, the outlet temperature of the four-helical spring heat exchange tube increased by 8.14℃ compared with that of the single-helical spring heat exchange tube; when the Reynolds number is 40000, the outlet temperature of the four-helical spring heat exchange tube increased by 5.77℃ compared with that of the single-helical spring heat exchange tube. This is because compared with the single helical spring, the four-helical spring has a stronger guiding effect on the fluid, so that the heat exchange between the fluid in the central area and the wall surface is more sufficient, resulting in a significant increase in the outlet temperature of the fluid. However, with the gradual increase of the number of springs inserted into the tube, the temperature rise of the outlet decreases gradually, indicating that when the number of springs inserted into the tube is too much, the improvement of the heat transfer capacity of the heat exchange tube is relatively small, and the subsequent increase in the difficulty of processing.

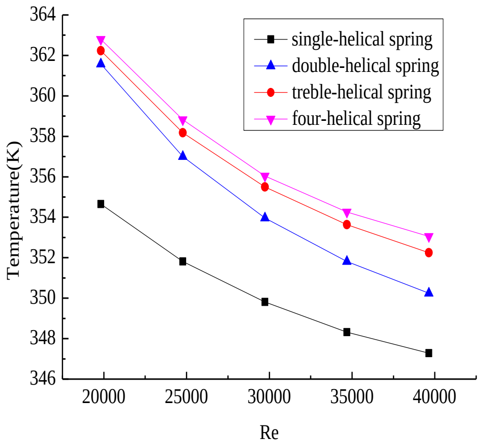

Fig.10 Comparison of heat exchange tube outlet temperature

Fig. 11 shows the comparison of pressure drop of single-helical, double-helical, treble-helical and four-helical spring heat exchange tubes with Reynolds number when the spring pitch p is fixed at 33.5mm and the equivalent diameter is 6mm. As can be seen from the figure, the pressure drop in the tube of the four kinds of spring heat exchange tubes increases with the increase of Reynolds, because when Reynolds number increases, the flow velocity in the tube increases, resulting in the increase of the resistance of the spring to the fluid and the increase of the pressure drop. It can also be seen from the figure that the pressure drop of the single-helical spring heat exchange tube is the highest, followed by the double-helical tube, and the four-helical tube is the lowest. When the Reynolds number is 20000, the pressure drop in the four-helical spring heat exchange tube is 40.31Pa lower than that in the single-helical spring heat exchange tube. When the Reynolds number was 40,000, the pressure drop in the four-helical spring heat exchange tube was 157.88Pa lower than that in the single-helical spring heat exchange tube, this is because with the increase of the number of springs in the tube, the guiding effect on the fluid is enhanced, so that the fluid flow state is more stable, the pressure drop decreases.

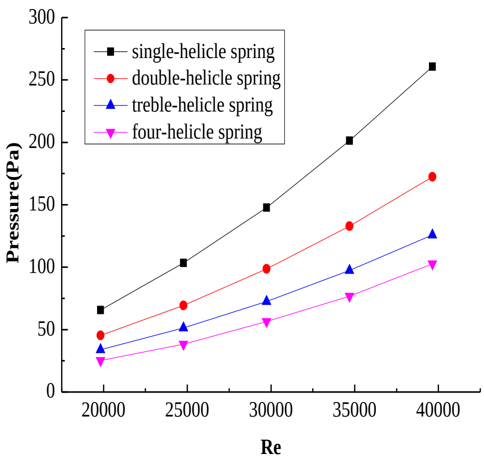

Fig.11 Comparison of heat exchange tube pressure drop

Fig. 12 shows the comparison of heat transfer coefficient of single-helical, double-helical, treble-helical and four-helical spring heat exchange tubes with Reynolds number when the spring pitch p is fixed at 33.5mm and the equivalent diameter is 6mm. As can be seen from the figure, the heat transfer coefficient of the four kinds of spring heat exchange tubes all increase with the increase of Reynolds, and the heat transfer coefficient of the four-helical spring heat exchange tubes is the highest, followed by the three-helical heat exchange tubes, and the single-helical heat exchange tube is the lowest. When the Reynolds number is 20000, the heat transfer coefficient of the four-helical spring heat exchange tube is 11.45W • m2 • K-1 higher than that of the single-helical spring heat exchange tube, when the Reynolds number is 40000, the heat transfer coefficient of the four-helical spring heat exchange tube is 3.94W • m2 • K-1 higher than that of the single-helical spring heat exchange tube. This is because the spring has a great influence on the flow state of the fluid at the boundary layer, so that the thickness of the bottom layer of the laminar flow of the boundary layer decreases, the thermal resistance of the wall decreases, and thus the enhanced heat transfer coefficient increases.

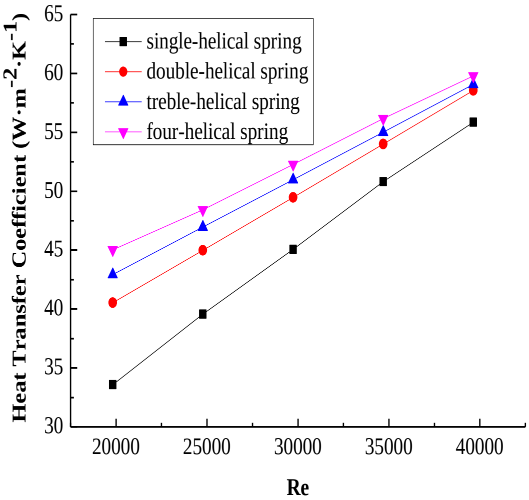

Fig.12 Comparison of heat exchange tube heat transfer coefficient

IV. Conclusion

With the increase of the number of springs inserted into the tube, the flow rate of the fluid in the spring heat exchange tube gradually decreases, and the pressure drop gradually decreases, the velocity field gradually presents a symmetrical distribution along the central axis, the fluid flow state gradually tends to be stable, and the distribution of temperature field and pressure field in the tube gradually becomes uniform

The outlet temperature and heat transfer coefficient of the helical spring heat exchange tube increased with the increase of the number of springs in the tube. Compared with the single-helical spring heat exchange tube, the outlet temperature of the four-helical spring heat exchange tube increased by 5.77–8.14℃, and the heat transfer coefficient increased by 3.94–11.45W·m^2·K^{-1}.

The pressure drop of the helical spring heat exchange tube decreased with the increase of the number of springs in the tube. Compared with the single-helical spring heat exchange tube, the pressure drop of the four-helical spring heat exchange tube decreased by 40.31–157.88Pa.

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