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Simulation on Heat Transfer Enhancement Characteristics of Inserted Spiral Spring Fins

Yuxiang Ma[a], Yongqi Liu[b, *], Peng Sun[c], Min Lu[d] and Yuqiu Zhang[e]

School of Transportation and Vehicle Engineering, Shandong University of Technology, 255049, China

[a]1421440559@qq.com, [b]liuyq65@163.com, [c]1035111367@qq.com, [d]704319072@qq.com, [e]704152897@qq.com

*Corresponding author: liuyq65@163.com

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Abstract: In order to enhance the heat exchange effect of spring heat exchange tube, based on the traditional spiral spring heat exchange tube, a new type of spiral 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 spiral spring heat exchange tube was simulated by Fluent software, and compared with the circular section spring heat exchange tube, the influence of equivalent diameter, pitch and section shape on the heat exchange effect was analyzed. The results show that: the heat transfer effect of square section spring heat exchange tube is improved than that of circular section spring heat exchange tube; when the Reynolds number of inlet is 20000~40000 and the pitch is 33.5mm, the heat transfer coefficient and tube pressure drop of spiral spring heat exchange tube increase with the increase of spring equivalent diameter, compared with the smooth tube, the heat transfer coefficient increase by 109%~164%, while the pressure drop increase by 5~18 times; when the equivalent diameter is 6mm, the heat transfer coefficient and tube pressure drop increase with the decrease of spring pitch, compared with the smooth tube, the heat transfer coefficient increase by 109%~158%, while the pressure drop increase by 8~16 times.

1. Introduction

The energy crisis has now become a major problem facing human development. Although China's energy resources are still relatively abundant, the per capita share is very low. Coal, oil, and natural gas account for only 56%, 11%, and 4.6% of the world average. And the energy consumption is large, the utilization rate is low, and there is still a large gap compared with other developed countries [1-2]. The issue of saving raw materials, reducing energy consumption, and improving the efficiency of heat transfer equipment becomes very important. Since the enhanced heat transfer technology has a good development prospect in the heat exchange process, various enhanced heat transfer measures are competing to develop, and the research on various heat transfer enhancement technology has emerged one after another.

Webb [3] summarizes various methods to enhance heat transfer and divides them into two categories: active enhanced heat transfer technology and passive enhanced heat transfer technology. Various inserts such as ties, blades, cross zigzag belts, and spiral springs are typical passive enhanced heat transfer technologies, because it does not need additional electromagnetic field, surface vibration and other external energy, easy to install, so it has been widely used. However, most of the inserts can only be used in a certain Reynolds number range due to their disadvantages such as the difficulty of processing and the inconspicuous effect of strengthening heat transfer outside the applicable range. The interpolation spiral spring is easy to process and install, which can greatly reduce the processing cost; at the same time, the spring pitch can be freely changed, which is suitable for heat exchange tubes with different tube diameters, which has attracted many scholars to research.

At present, domestic and foreign scholars have carried out a series of meaningful research work on the insertion of spiral spring heat exchange tubes. M.Chhandrasekar [4] et al. studied the heat transfer of Al_2O_3/water nanofluids in the internal spiral spring heat exchange tube under laminar flow conditions, analyzed the relationship between the convective heat transfer characteristics and the pressure drop coefficient. Smith eiamsa-ard [5] et al. 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. Liu Lifang [6-7] et al. 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. Xu Jianmin [8] et al. studied the effect of built-in coil spring on the heat transfer performance of heat transfer tubes through particle imaging velocimetry (PIV) technology, analyzed the influence of the pitch, wire diameter and middle diameter of the coil spring on the flow field in the tube, through experiments, the best way to enhance the degree of turbulence is determined. M.A.Akhavan-behabadi [9] et al. studied the enhanced heat transfer and increased pressure drop during evaporation of R-134a in the presence of coiled wire in the horizontal evaporator by experiment, established an empirical correlation to predict the heat transfer coefficient of evaporation process in horizontal tube with spiral wire insertion. Shyy Woei Chang [10] et al. 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.

To sum up, most scholars seldom make the spring contact with the inner wall when studying the spiral spring heat tube, which will cause the heat conduction loss between the spring and the wall, at the same time, the shape of the cross section of the spring is only circular, which is lack of other cross section shapes. 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. Therefore, the new spiral spring heat exchange tube is adopted to study the influence of flow field change and spring structure parameters on the heat transfer process, in order to explain the internal spiral spring heat exchanger heat transfer mechanism and promote the development of new efficient heat transfer element.

2. Physical model and mathematical description

2.1 Physical model

The calculation model is established by 3D software Proe, and the schematic diagram of the model is shown in Fig.1, the structure of the spiral spring heat exchange tube is shown in Fig.2.

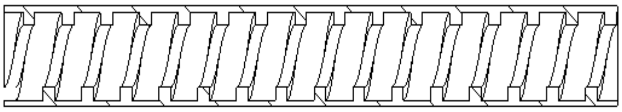

Figure. 1 Model diagram of spiral spring heat exchange tube

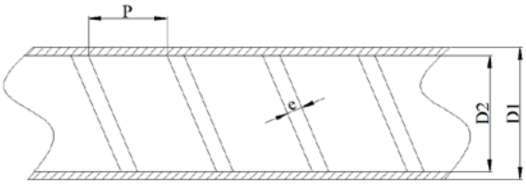

Figure. 2 Structure diagram of spiral spring heat exchange tube

Table 1 Structure parameter value

structure diagram	value				
D1(mm)	76				
D2(mm)	67				
l(mm)	500				
e(mm)	26.5	30.0	33.5	37.0	40.5
p(mm)	4	5	6	7	8

The spiral spring tube length used in the simulation is *l*, D1 is the outer diameter of the heat exchange tube, D2 is the inner diameter of the heat exchange tube, “p” is the pitch, “e” is the equivalent diameter, and the values of each structure parameter are shown in the Tab.1. The mesh is divided by ICEM, as shown in Fig.3, Fig.4 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.

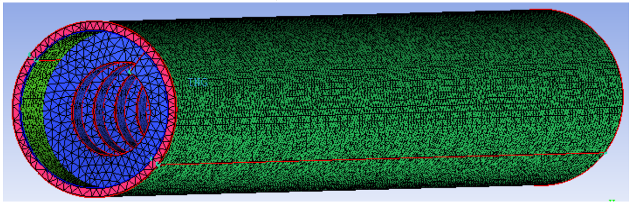

Figure. 3 Diagram of grid division

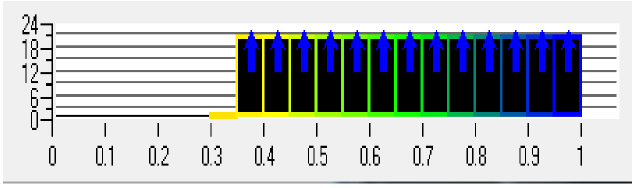

Figure. 4 Grid quality detection

2.2 Mathematical description

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:

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

Energy equation:

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

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.

2.3 Initial and boundary conditions

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.

3. Results

3.1 Influence of section shape

The circular, triangle and square section springs were respectively simulated with equivalent diameter e=6mm and pitch p =33.5mm of the same size, and the simulation results were compared with the smooth tube. Fig.5 shows the comparison of the change in outlet temperature with the Reynolds number. Obviously, compared with the smooth tube, the air temperature at the outlet of the spring heat exchange tube with various cross sections has been greatly increased, this is because the spring breaks the fluid boundary layer in the tube, increasing the turbulence of the fluid, resulting in the increase of the heat transfer between the air and the inner wall of the heat exchange pipe.

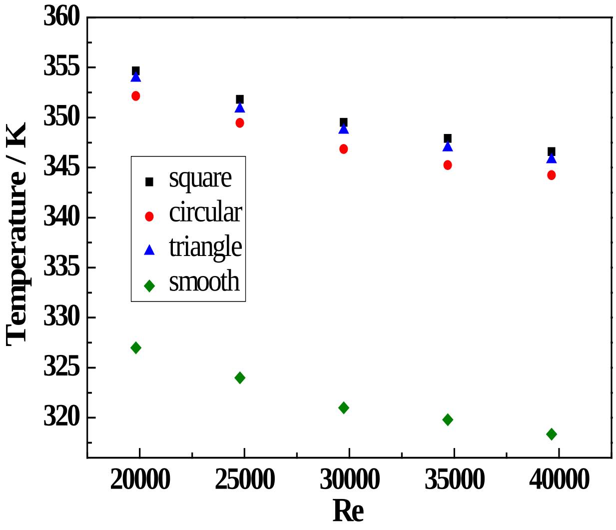

Figure. 5 The variation of the outlet temperature of different cross sections with the Reynolds number

Fig.6 shows the change in pressure drop of different cross section springs and smooth tubes with different Reynolds numbers. It can be seen from the figure that the pressure drop in the tube is significantly higher than that of the smooth tube when the fluid flows through the spring of various cross sections. This is because when the fluid in the tube passes through the spring, the flow will produce more flow distance and residence time, thus producing more frictional resistance, causing an increase in pressure drop.

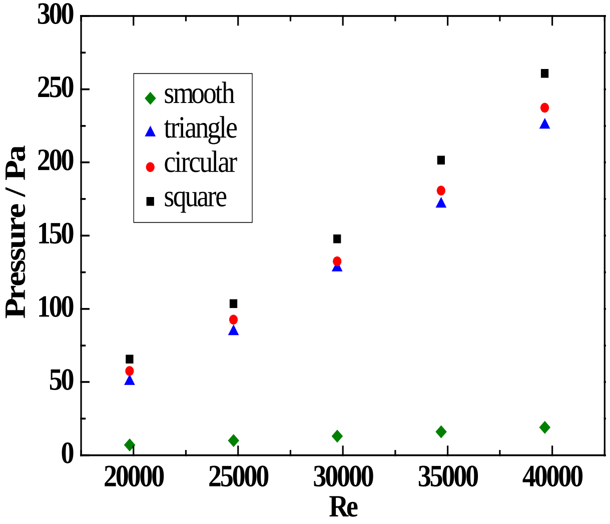

Figure. 6 The variation of the pressure drop of different cross sections with the Reynolds number

Fig.7 shows the comparison of the change in heat transfer coefficient with the Reynolds number. Obviously, compared with the smooth tube, the air temperature at the outlet of the spring heat exchange tube with various cross sections has been greatly increased. With the increase of Reynolds number, the heat transfer coefficient of heat exchange tube presents an increasing trend, in addition, compared with the smooth tube, the heat transfer coefficient increases less when the Reynolds number is low, and more when the Reynolds number is high. The heat transfer coefficients of square, triangle and circular cross section springs increased 1.4 times, 1.3 times and 1.1 times on average compared with smooth tube.

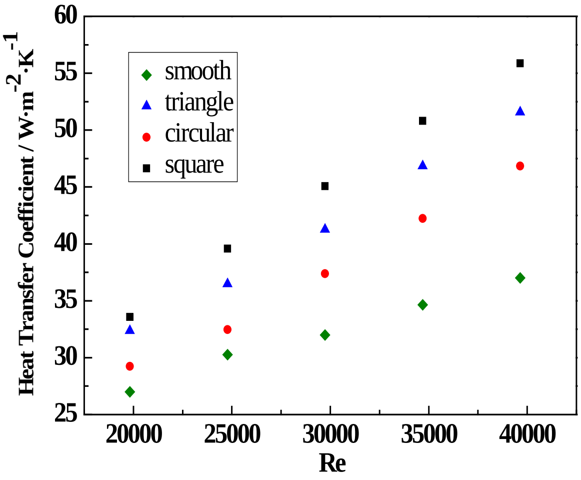

Figure. 7 The variation of heat transfer coefficient of different cross sections with the Reynolds number

3.2 Influence of equivalent diameter

Fig.8 shows the temperature nephogram of the inlet air flow rate of 7.5m/s, and the equivalent diameter of spring at different times in the heat exchange tube. As can be seen from the figure, when the temperature of the tube wall is the same, the temperature gradient near the wall surface of the smooth tube is large, and the heat transfer near the wall surface is strong, while the temperature gradient of the fluid in the core flow area in the middle of the tube is small, indicating that the disturbance of the flow is small and the heat transfer capacity is weak. However, the heat transfer in the spring heat exchange tube is obviously better than that in the smooth tube, because the existence of the spring destroys the fluid flow state near the wall, and the heat exchange 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 to a certain extent.

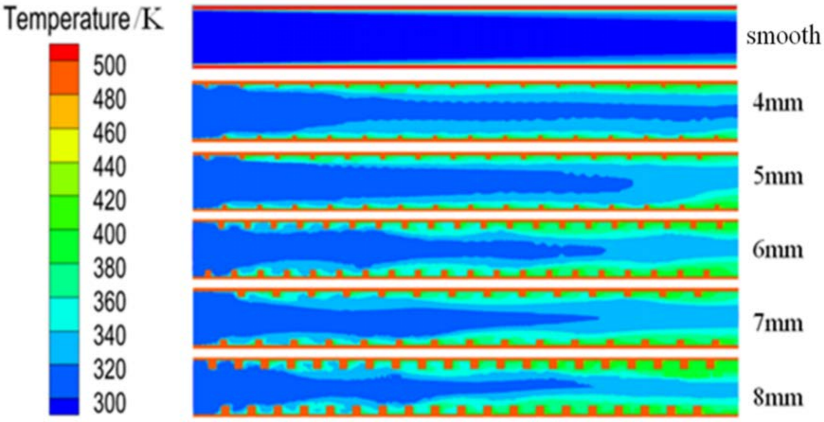

Figure. 8 Temperature nephogram of spring heat exchange tube with different equivalent diameters

Fig.9 shows the change of outlet temperature of spiral spring heat exchange tube with Reynolds number when spring pitch is fixed and equivalent diameter is changed. As can be seen from the figure, the outlet temperature of the spiral spring heat exchange tube with different equivalent diameters is significantly higher than that of the smooth tube, when the Reynolds number is 20000, the outlet temperature increases by 247%~280%, and 406%~471% when the Reynolds number is 40000. This is because the insert spring breaks the flow state of the fluid near the spring, causing it to flow around the spring, while the heat transfer area increases, resulting in a significant increase in the outlet temperature compared with the smooth tube. It can also be seen from the figure that when the equivalent diameter increases from 4mm to 8mm, the outlet temperature of the spiral spring heat exchange tube gradually increases, this is because with the increase of equivalent diameter, the destruction degree and heat exchange area of the fluid at the boundary layer increase, and the heat exchange effect is enhanced, which makes the outlet temperature rise. However, when the equivalent diameter is the same, the outlet temperature of the spiral spring heat exchange tube decreases with the increase of Reynolds number. This is because when the Reynolds number increases, the fluid flow rate in the tube increases, resulting in the increase of the 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.

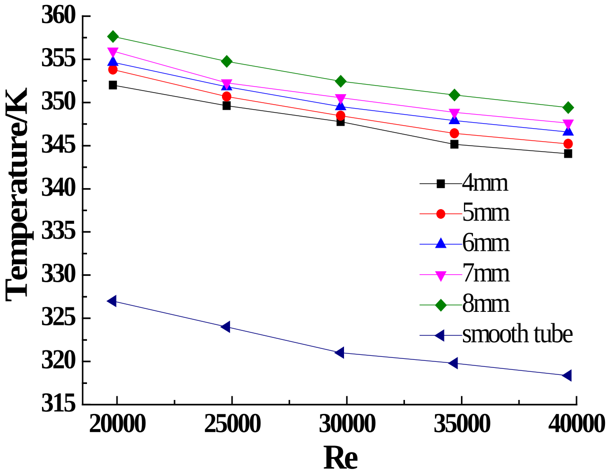

Figure. 9 Variation of the outlet temperature of spring exchange tubes with Reynolds number

Fig.10 shows the change of pressure drop of spiral spring heat exchange tube with Reynolds number when spring pitch is fixed and equivalent diameter is changed. As can be seen from the figure, the pressure drop of the smooth tube is less affected by the Reynolds number, while the pressure drop of the spiral spring heat exchange tube changes significantly with the Reynolds number, and the larger the equivalent diameter is, the more obvious the change is. When the equivalent diameter is 8mm, the maximum pressure drop is 3.72 times of the minimum pressure drop. When the Reynolds number is 20000, the pressure drop of the spiral spring heat exchange tube increases by 5~13 times compared with that of the smooth tube; when the Reynolds number is 40000, the pressure drop increases by 8~19 times. This is because when the equivalent diameter increases, the resistance of the spring to the fluid increases, and the restriction of the fluid flow near the wall increases, resulting in an increase in the pressure drop of the body, this results in an increase in the spiral motion of the fluid, the pressure drop loss.

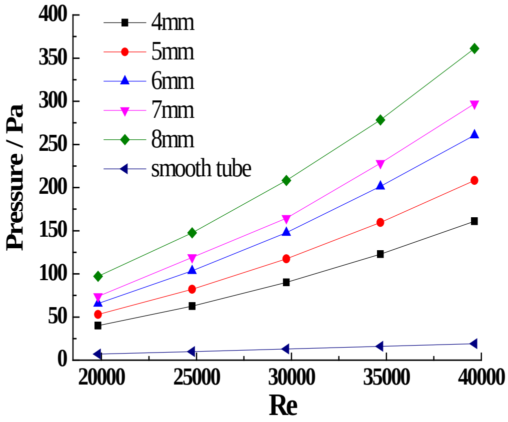

Figure. 10 Variation of pressure drop of spring heat exchange tubes with Reynolds number

Fig.11 shows the change of heat transfer coefficient of spiral spring heat exchange tube with Reynolds number when spring pitch is fixed and equivalent diameter is changed. As can be seen from the figure, the heat transfer coefficients of both the smooth tube and the spiral spring heat exchange tube have a similar variation trend with the Reynolds number, and both increase linearly with the increase of the Reynolds number. When the Reynolds number is 20000, the heat transfer coefficient of the spiral spring heat exchange tube increases by 109%~132% compared with that of the smooth tube; when the Reynolds number is 40000, the heat transfer coefficient increases by 141%~164%, and the larger the equivalent diameter, the greater the heat transfer coefficient. This is because when the equivalent diameter increases, the spring has a greater impact on the flow state of the fluid at the boundary layer, resulting in a decrease in the thickness of the laminar bottom of the boundary layer and a decrease in the thermal resistance of the wall, thus increasing the enhanced heat transfer coefficient.

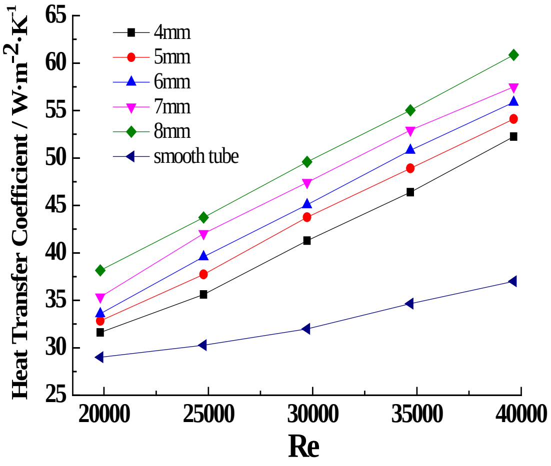

Figure. 11 Variation of heat transfer coefficient of spring heat exchange tubes with Reynolds number

3.3 Influence of pitch

Fig.12 shows the temperature nephogram of the inlet air flow rate of 7.5m/s, and the pitch of spring at different times in the heat exchange tube. It can be seen from the figure that the temperature variation in the spring heat exchange tube with different pitches is similar to that in the case of different equivalent diameters, when the air velocity and the wall temperature are the same, the heat transfer in the spring heat exchange tube is obviously better than that in the smooth tube.

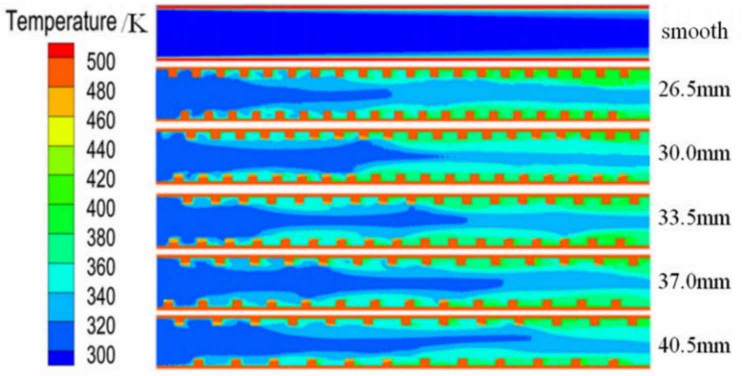

Figure. 12 Temperature nephogram of spring heat exchange tube with different pitches

Fig.13 shows the change of outlet temperature of spiral spring heat exchange tube with Reynolds number when equivalent diameter is fixed and spring pitch is changed. As can be seen from the figure, the outlet temperature of the spiral spring heat exchange tube with different pitch is significantly higher than that of the smooth tube. The outlet temperature is 247%~277% higher when the Reynolds number is 20000, and 419%~479% higher when the Reynolds number is 40000. It can also be seen from the figure that, when the pitch increases, the outlet temperature of the spiral spring heat exchange tube decreases gradually, this is because, with the increase of the pitch, the space between the two adjacent coils of spring is larger, which weakens the guiding and disturbing effect of the fluid; at the same time, the increase of pitch will also lead to the reduction of heat exchange area, both of which will lead to the reduction of heat exchange and the decrease of outlet temperature. When the pitch is the same, the outlet temperature of the spiral spring heat exchange tube decreases with the increase of Reynolds number. This is because when the Reynolds number increases, the fluid flow rate in the tube increases, and the heating time of the tube wall to the fluid is shortened, resulting in the reduction of heat exchange and the decrease of outlet temperature.

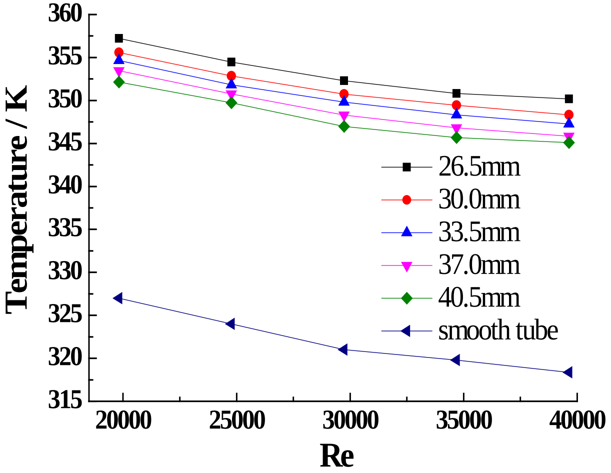

Figure. 13 Variation of outlet temperature of different heat transfer tubes with different Reynolds

Fig.14 shows the change of pressure drop of spiral spring heat exchange tube with Reynolds number when equivalent diameter is fixed and spring pitch is changed.As can be seen from the figure, the pressure drop of the smooth tube is less affected by the Reynolds number, while the pressure drop of the spiral spring heat exchange tube varies significantly with the Reynolds number, and the smaller the pitch, the more obvious the change, when the pitch is 26.5mm, the maximum pressure drop is 4.3 times of the minimum pressure drop. When the Reynolds number is 20000, the pressure drop of the spiral spring heat exchange tube increases by 8~10 times compared with that of the smooth tube; when the Reynolds number is 40000, the pressure drop increases by 12~16 times. This is because when the pitch increases, the number of springs within the same length decreases, and the disturbing effect of springs on the boundary layer is significantly weakened, resulting in lower pressure drop loss and lower pressure drop in the heat exchange tube.

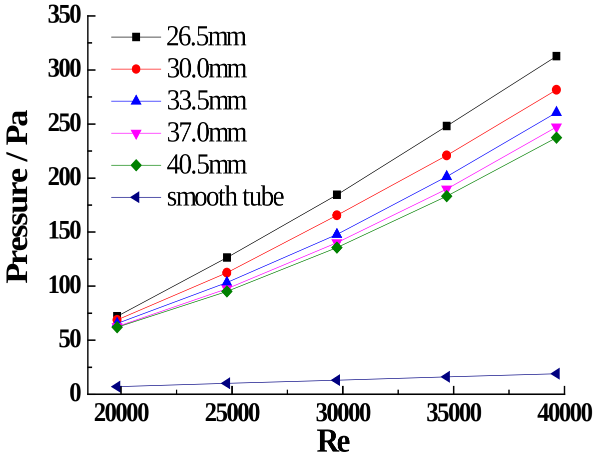

Figure. 14 Variation of pressure drop of different heat transfer tubes with different Reynolds

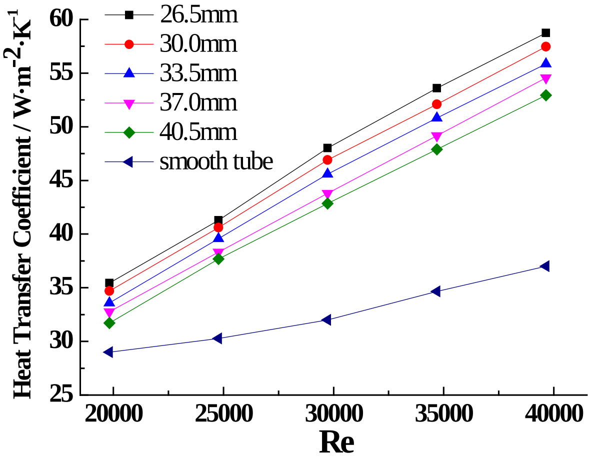

Figure. 15 Variation of heat transfer coefficient of different heat transfer tubes with different Reynolds

Fig.15 shows the change of heat transfer coefficient of spiral spring heat exchange tube with Reynolds number when equivalent diameter is fixed and spring pitch is changed. As can be seen from the figure, the heat transfer coefficients of both the smooth tube and the spiral spring heat exchange tube have a similar variation trend with the Reynolds number, and both increase linearly with the increase of the Reynolds number. When the Reynolds number is 20000, the heat transfer coefficient of the spiral spring heat exchange tube increases by 109%~120% compared with that of the smooth tube; when the Reynolds number is 40000, the heat transfer coefficient increases by 143%~158%, and when the Reynolds number is the same, the smaller the pitch, the greater the heat transfer coefficient. This is because when the pitch increases, the length of the spring interval region will increase, and the thickness of the laminar bottom layer of the boundary layer will become thicker, and the thermal resistance of the wall surface will become larger, therefore, the enhanced heat transfer coefficient will decrease and the enhanced heat transfer effect will decrease.

4. Conclusion

(1) Compared with the smooth tube, the heat transfer coefficient of square, triangle and round section spring heat exchange tube increases by 1.4 times, 1.3 times and 1.1 times on average, and the heat transfer performance of square section spring heat exchange tube is the best, followed by triangle section, and finally is the circular section.

(2) Due to the disturbance of the spiral heat exchange tube with square section on the fluid near the wall, the boundary layer on the wall is thinned, and the heat exchange area between the wall and the spring is increased, the heat exchange process in the tube is significantly enhanced compared with that in the smooth tube, and the heat transfer coefficient is increased by 109%~164%.

(3) When the pitch remained unchanged, the outlet temperature, heat transfer coefficient and pressure drop of the spiral spring heat exchange tube increased with the increase of the equivalent diameter of the spring. Compared with the smooth tube, the outlet temperature increased by 247%~471%, the heat transfer coefficient increased by 109%~164%, and the pressure drop increased by 5~19 times. At the same time, with the increase of equivalent diameter, the increasing trend of pressure drop is much higher than that of heat transfer coefficient and outlet temperature.

(4) When the equivalent diameter is unchanged, the outlet temperature, heat transfer coefficient and internal pressure drop of the spiral spring heat exchange tube increase with the decrease of spring pitch. Compared with the smooth tube, the outlet temperature increased by 247%~479%, the heat transfer coefficient increased by 109%~158%, and the pressure drop increased by 8~16 times. With the decrease of the pitch, the increasing trend of pressure drop is much higher than that of heat transfer coefficient and outlet temperature.

Acknowledgements

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