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ORIGINAL RESEARCH ARTICLE

Study on heat transfer characteristics of flow heat coupling of horizontal spiral tube heat exchanger

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ABSTRACT

In view of the complex structural characteristics and special operating environment of the horizontal spiral tube heat exchanger of the shaft sealed nuclear main pump, the numerical simulation method of flow heat coupling is used to analyze the influence of the flow and temperature changes of the fluid on the shell side on the flow field and temperature field of the heat exchanger, explore the influence rules of the inlet parameters on the flow and heat transfer characteristics of the fluid in the heat exchanger, and analyze the enhanced heat transfer performance of the heat exchanger by using the relevant heat transfer criteria. The results show that the horizontal spiral tube fluid generates centrifugal force under the influence of curvature, forming a secondary flow which is different from the straight tube flow heat transfer, and the velocity distribution is concave arc, which will enhance the heat transfer efficiency of the heat exchanger; with the increase of shell side velocity, the degree of fluid disturbance and turbulence increases, while the pressure loss does not change significantly, and the heat transfer performance of the heat exchanger increases; under the given structure and size, the heat transfer performance curve of the heat exchanger shows that the increase of shell side flow and Reynolds number has a significant impact on the enhanced heat transfer of the spiral tube. In practical engineering applications, the heat transfer can be strengthened by appropriately increasing the shell side flow of the heat exchanger.

Keywords: Shaft Seal Nuclear Main Pump; Horizontal Spiral Tube Heat Exchanger; Coupled Heat Transfer; Numerical Simulation; Performance Analysis

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1. Introduction

Horizontal spiral tube heat exchanger has the advantages of compact structure, large heat exchange area, high temperature resistance and strong pressure bearing capacity. It is widely used in nuclear reactors, environmental engineering, power production and other engineering fields[1,2]. In the primary circuit system of the nuclear island, the spiral tube heat exchanger is installed above the impeller of the nuclear main pump, the only rotating equipment, to prevent the heat of the reactor high-temperature coolant from transmitting to the upper part of the pump and prevent the heat damage of the pump bearing and shaft seal. It can be seen that the heat transfer characteristics of the spiral tube heat exchanger directly affect the safe operation of the main pump, so it is necessary to analyze the flow and heat transfer characteristics of the heat exchanger more systematically and accurately. There are many factors that affect the flow and heat transfer of the heat exchanger. Reasonable geometric parameters, flow, temperature and working environment play an important role in improving the heat transfer efficiency of the heat exchanger and ensuring the safe operation of the unit.

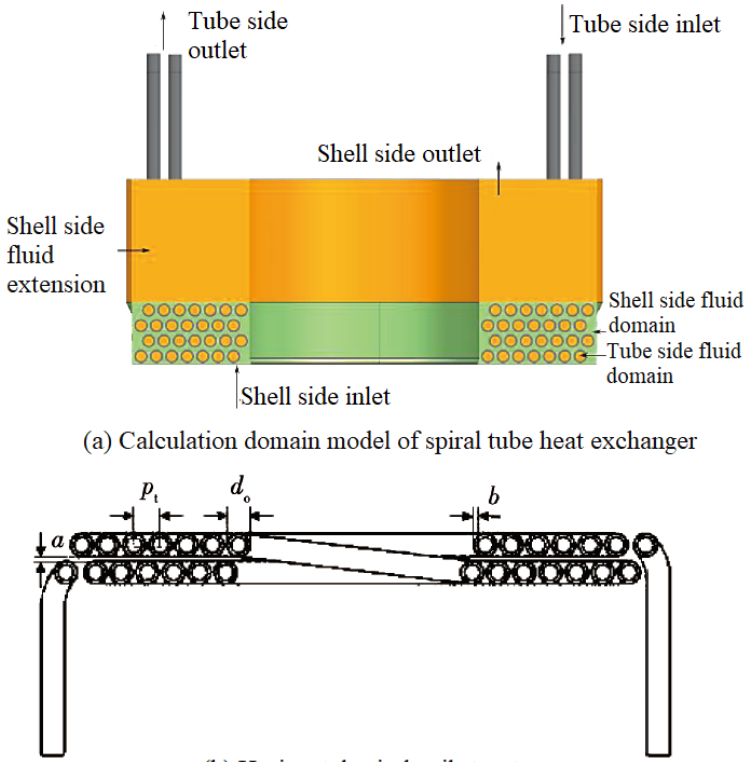
At present, scholars at home and abroad have made in-depth research and elaboration on the influencing factors of flow and heat transfer in spiral tubes. For example, Vocale[3] considered the coupled heat transfer of spiral tubes and evaluated the influence of the selection of thermal boundary conditions on the local heat transfer phenomenon in coils. Ren[4], Lu[5] and Zeng *et al.*[6] analyzed the influence of different boundary conditions and different geometric parameters on the conjugate heat transfer of spiral tube heat exchangers, and concluded that curvature, pipe diameter and grid thickness are the main factors for the optimal design of heat exchangers. Sun[7] and Yu[8] explores the shell side flow and heat transfer characteristics of spiral wound heat exchangers in floating liquefied natural gas, including experimental research on the influence of tilt, yaw and pitch on the pressure drop of spiral wound heat exchangers. Chen *et al.*[9], Guo *et al.*[10] and Yu[11] studies the properties of forced convection heat transfer of helical tubes under different conditions, and obtains the distribution of local heat transfer coefficient and the empirical formula of average heat transfer coefficient under different conditions. Most of the above studies are aimed at analyzing the heat transfer characteristics of the heat exchanger in a specific working environment. For the horizontal spiral tube heat exchanger of the nuclear main pump, the high temperature and high-pressure operating environment in the pump needs higher requirements for the performance of the spiral tube heat exchanger. The research on the inlet parameters and comprehensive performance evaluation of the shell side needs to be deepened.

In view of the complexity of the fluid flow field and heat transfer process in the horizontal spiral tube heat exchanger, considering the conjugate heat transfer under the joint action of the convective heat transfer of the fluid medium and the heat conduction of the tube wall, this paper uses the numerical simulation method to comprehensively analyze the heat transfer performance of the spiral tube heat exchanger under different flow rates and different heat source temperatures on the shell side, and uses the relevant heat transfer criteria to analyze the comprehensive energy transfer performance of the heat exchanger. It provides some guidance for solving the problems of heat transfer of the heat shield heat exchanger of the shaft seal nuclear main pump.

2. Structure and model parameters of spiral tube heat exchanger

The heat exchanger of the main pump is composed of 8 groups of cooling coils located inside the heat shield cover. Each group of cooling coils is coiled by a single cooling pipe according to the spiral, and is stacked in the heat shield cover cylinder in turn. The temperature difference of each component changes greatly, and the physical parameters of materials and media change significantly with temperature. At the same time, the structural characteristic scale span of the heat exchanger is large, and the shell side channel is narrow. These factors make the heat transfer numerical simulation of the main pump heat shield heat exchanger become very complex. In order to save calculation time and resources, the solid model of spiral tube heat exchanger is reasonably simplified, and a group of horizontal spiral tubes are taken for numerical simulation research. The simplified model is shown in **Figure 1**.

The flow and heat transfer of two spiral tubes are selected for numerical analysis. In order to ensure the full development of turbulence and make it closer to the boundary conditions of the real flow field, the fluid domain at the outlet of the spiral tube shell side is appropriately extended. The calculation domain model is shown in **Figure 1(a)**. The cooling water in a single spiral pipe enters from the right side of the coil, gradually rises to the upper level after heat exchange through the lower coil, and then continues heat exchange, and finally flows out from the left spiral pipe. The spiral pipe is composed of two layers of concentric spiral coil, which is made of stainless-steel pipe with a diameter of 19 mm bent into a spiral shape. Each layer of steel pipe is bent for seven turns. The geometric model of the coil is shown in **Figure 1(b)**, and the basic parameters are shown in **Table 1**.



(a) Calculation domain model of spiral tube heat exchanger

(b) Horizontal spiral coil structure

Figure 1. Schematic diagram of horizontal spiral tube heat exchanger.

Table 1. Geometric parameters of horizontal spiral tube

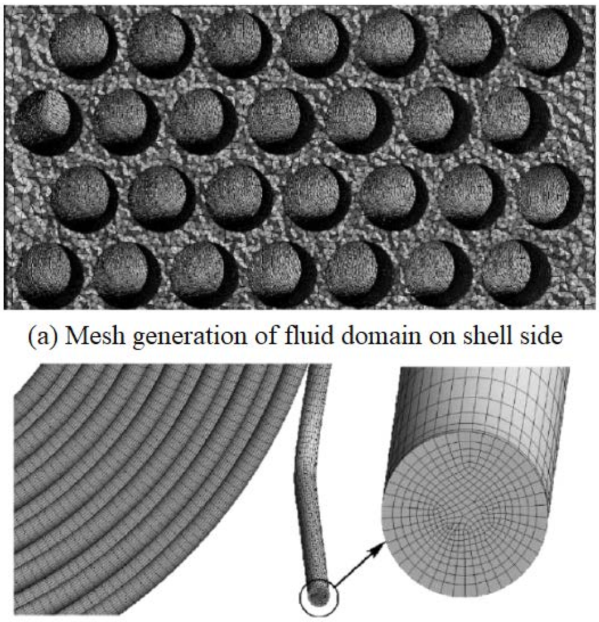
Parameter	Value
Length of heat transfer tube L/m	19
Pipe inner diameter d_i/mm	12.8
Tube outer diameter d_o/mm	19
Screw diameter d_h/mm	473.5
Wall thickness of heat transfer tube b/mm	3.1
Heat transfer tube spacing a/mm	2.5
Heat transfer tube pitch P_t/mm	21.5

3. Numerical calculation method

3.1 Grid division and boundary conditions

The structure of the fluid domain on the shell side of the spiral tube heat exchanger is complex, and the unstructured tetrahedral mesh with strong self-adaptive is used to divide its calculation domain. In order to ensure the calculation accuracy, the calculation domain of the main heat exchange zone on the shell side is encrypted. Considering the calculation equipment and calculation cycle, the total number of grids of the model is about 16 million after the grid independence test. The mesh division of fluid domain of heat exchanger is shown in **Figure 2**.

High temperature water and cooling water are used for heat exchange at shell side and tube side respectively. In view of the large temperature difference of each component and the obvious change of the physical parameters of the medium with the temperature, in order to obtain more accurate calculation results, considering that the physical parameters of the fluid will change with the temperature, thus affecting the heat transfer, the material physical variable function is added to CFX-Pre, and the physical parameters of the spiral tube metal material are shown in **Table 2**. The inlet of the working medium is the mass flow and temperature boundary condition, and the outlet is the static pressure boundary condition. The interface between the spiral coil and the fluid domain is set as the heat flow coupling interface, and the other outer walls are set as the non-slip insulation wall. The parameter settings of boundary conditions are shown in **Table 3**.



(a) Mesh generation of fluid domain on shell side

(b) Mesh generation of fluid domain on tube side

Figure 2. Schematic diagram of the fluid domain grid for spiral tube heat exchanger.

Table 2. Thermophysical properties of spiral tube

Material	Density/kg·m^{-3}	Constant pressure specific heat capacity/J·kg^{-1}·°C^{-1}	Thermal conductivity/w·m^{-1}·°C^{-1}
Austenitic stainless steel	7,930	502	19

Table 3. Boundary condition setting parameters

Boundary condition	Import		Export
	Flow/L·h^{-1}	Temperature/°C	Static pressure/MPa
Tube side	11,000	38	0.1
Shell side	600 ~ 1,800	150 ~ 290	0.1

3.2 Calculation method

In the process of fluid flow research, the computational domain is discretized based on the finite volume method. In order to solve the momentum and energy equations, the discrete format adopts high resolution, and the continuity equation, momentum equation and energy equation formed a control equation group for solving turbulent flow and heat transfer.

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U U) = - \nabla p + \nabla \tau + S_M \tag{2}$$

Energy equation:

$$\frac{\partial (\rho h_{tot})}{\partial t} - \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U h_{tot}) = \nabla \cdot (\lambda \nabla T) + \nabla \cdot (U_\tau) + U \cdot S_M + S_E \tag{3}$$

Among them, the total enthalpy h_{tot} is related to the static enthalpy $h(T, p)$:

$$h_{tot} = h + \frac{1}{2} U^2 \tag{4}$$

Where: ρ—density, kg·m^{-3}; ∇—divergence; t

—time, s; U—velocity vector; τ—viscous stress, which is produced by the viscous action of molecules; p—pressure on fluid microelement, Pa; S_M—generalized source term; T—temperature, K; λ—second viscosity; $\nabla \cdot (U \cdot \tau)$—viscous stress does work; $U \cdot S_M$ work for external momentum heat source.

The flow velocity in the inner shell side and tube side of the spiral tube heat exchanger is small, and the pressure gradient is relatively small, so k-ε turbulent model is used to study the heat transfer and fluid characteristics of spiral tube heat exchanger[12]. The solution equation is as follows:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_i}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \tag{5}$$

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial t} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_i}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \frac{C_{1\varepsilon}\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{6}$$

Where: ε—turbulent dissipation rate; G_k—generation term of turbulent kinetic energy k caused by average velocity gradient, $\sigma_k, \sigma_\varepsilon, C_{1\varepsilon}, C_{2\varepsilon}$ is an empirical constant, where $\sigma_k = 1.0, \sigma_\varepsilon = 1.3, C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92$; μ—physical parameters; μ_i—turbulent viscosity, Pa·s. CFX solver is used for steady-state calculation. When the residual errors of continuity, momentum and energy are less than 10^{-4}, 10^{-5} and 10^{-6} respectively, it is judged that the physical quantities of flow field and temperature field of heat exchanger have converged.

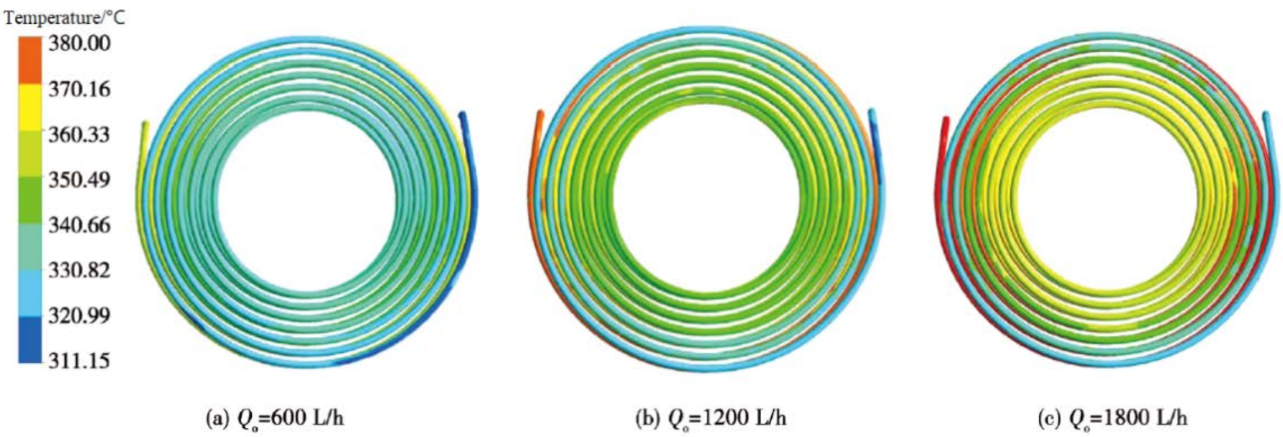


Figure 3. Temperature contours for lower spiral tube.

4. Calculation results and analysis

4.1 Temperature field and velocity distribution of fluid at pipe side

In order to study the influence of shell side fluid inlet parameters on the temperature distribution of fluid heat transfer, the temperature field and velocity field of fluid in spiral tube under different volume flow were numerically simulated and analyzed. By analyzing the temperature distribution nephogram of the spiral tube in **Figure 3** and **Figure 4**, it can be seen that the temperature in the lower spiral tube gradually increases from the outer ring of the coil to the inner ring, and the temperature in the upper spiral tube gradually increases from the inner ring of the coil to the outer ring. By comparing and analyzing the temperature distribution nephogram of spiral tube under different inlet flow, it can be seen that the coil temperature increases significantly with the increase of fluid flow on the shell side. Under the given structure and size, with the increase of flow rate, the surface heat transfer coefficient increases, and more heat is transferred to the spiral tube.

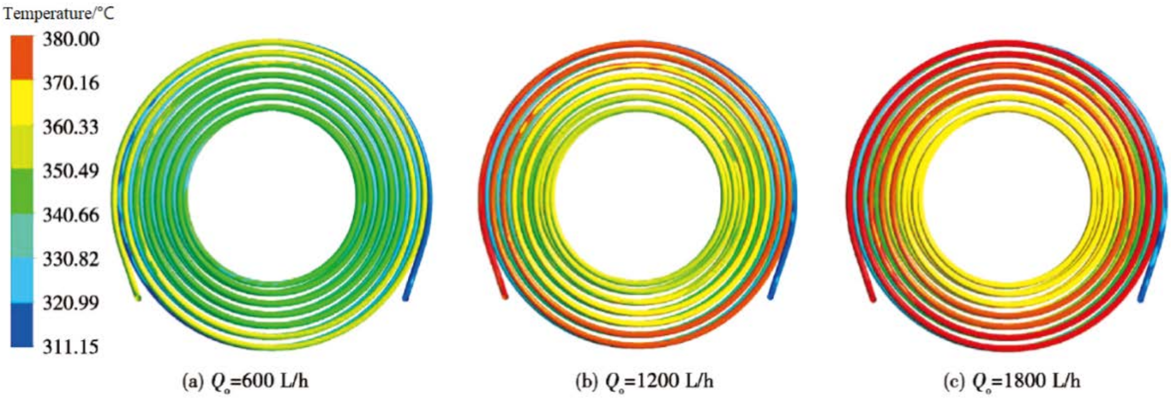


Figure 4. Temperature contours for upper spiral tube.

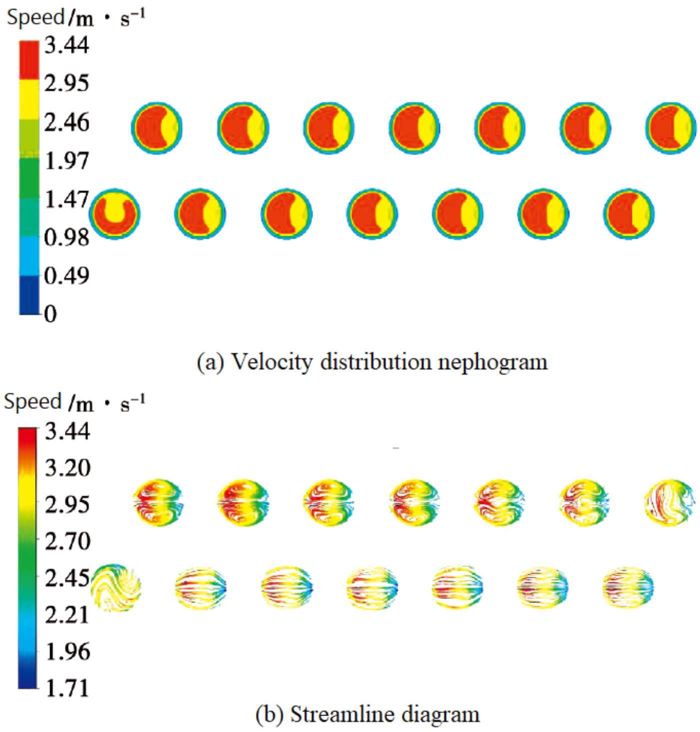


Figure 5. Fluid velocity profile inside horizontal spiral tube.

In order to further understand the influence of the structural characteristics of the spiral tube on heat transfer, the velocity distribution of the spiral tube is analyzed. As the structural size of the model is large, **Figure 5** shows the velocity distribution nephogram and streamline diagram of some characteristic sections of the spiral tube. Due to the dependence of the secondary flow characteristics on the curvature of the coil, the centrifugal force generated by the bending of the spiral pipe makes the maximum velocity of the fluid close to the outside of the pipe, and the fluid flow velocity on the inner wall of the pipe is relatively small, and the velocity distribution presented the shape of concave arc. At the same time, according to the streamline diagram, the secondary flow effect of the lower coil is not obvious. When the fluid rises to the upper coil, the fluid disturbance intensifies, producing obvious secondary circulation, and enhancing the heat exchange effect of the heat exchanger.

4.2 Influence of shell side fluid inlet parameters on heat transfer characteristics of heat exchanger

Figure 6 shows the relationship of the shell side fluid heat transfer coefficient h_o and the total heat transfer coefficient K of the heat exchanger with the flow rate.

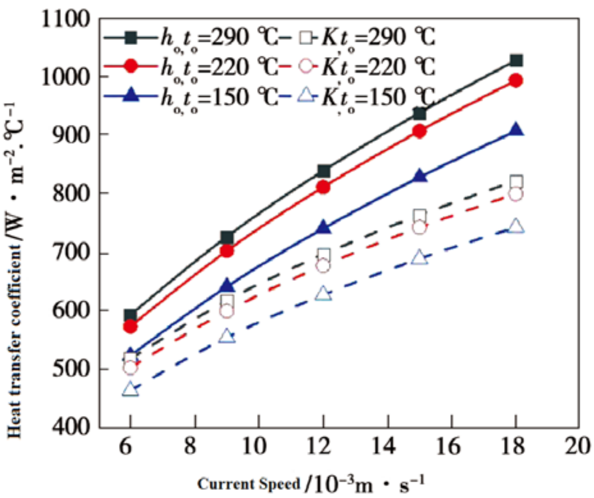


Figure 6. Heat transfer coefficient vs. flow rate of shell-side.

At different inlet temperatures, the variation trends of total heat transfer coefficient K and shell side fluid boundary film heat transfer coefficient h_o with the change of flow velocity are basically the same, both of which increase with the increase of shell side flow velocity u. Under the same shell side flow rate, the heat transfer coefficient increases with the increase of temperature, but the increase of heat transfer coefficient shows a decreasing trend. Compared with the inlet temperature of 150 ℃, the increase of total heat transfer coefficient at 220 ℃ is between 7.6% and 8.3%, and the increase value at 290 ℃ is between 2.8% and 3.0%. Therefore, improving the heat transfer coefficient of the heat exchanger by changing the inlet temperature is limited

Figure 7 shows the change curve of the heat transfer power P of the heat exchanger change with the shell side flow rate u and temperature t_o. It can be seen that with the increase of temperature, the temperature difference between the fluid inside and outside the horizontal spiral tube increases, the heat transfer per unit time increases, and the heat transfer power shows an increasing trend. The flow rate has little effect on the heat transfer power, and its change gradually decreases with the increase of flow rate.

Figure 8 shows the relationship between the pressure drop on the shell side of the heat exchanger and the flow rate. At the same flow rate, because the incompressible fluid has little dependence on pressure, the pressure drop on the shell side varies little with the fluid temperature. Although the pressure drop on the shell side gradually increases with the increase of inlet flow rate, the test flow rate is small, and the pressure drop on the shell side of the spiral tube heat exchanger does not change significantly.

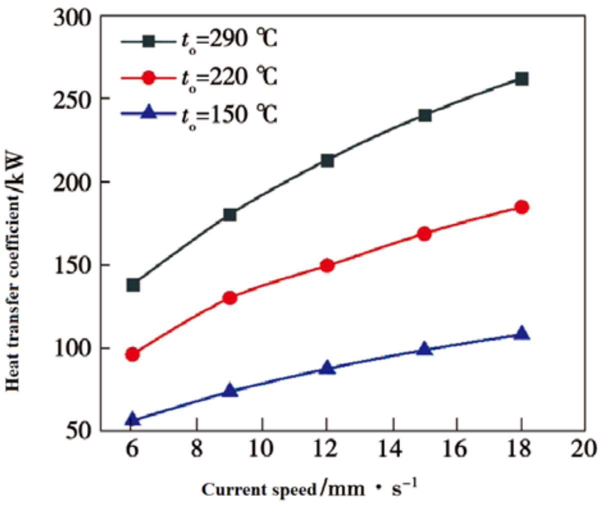


Figure 7. Heat transfer power vs. flow rate of shell-side.

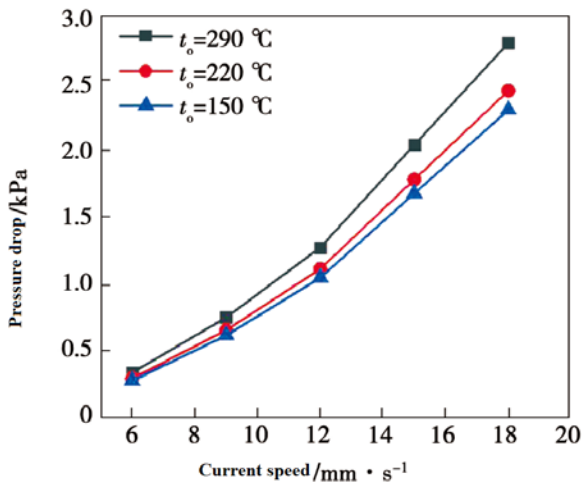


Figure 8. Pressure drop vs. flow rate of shell-side.

3.3 Comprehensive performance analysis of spiral tube heat exchanger

The flow and heat transfer of fluid in the heat exchanger is an important index to evaluate the comprehensive performance of the spiral tube heat exchanger. According to the temperature results obtained from numerical simulation research, based on the performance evaluation criteria of the first law of thermodynamics, the influence of shell side Reynolds number and temperature in the spiral tube heat exchanger on the conjugate heat transfer of the heat exchanger is analyzed.

In the comprehensive performance analysis of heat exchanger, the Nusselt number Nu_o represents the strength of the average heat transfer coefficient of the fluid, and the heat transfer factor j_H reflects the relationship between the average friction coefficient and the heat transfer coefficient of the convective heat transfer surface, and the efficiency of the heat exchanger η reflects the influence of the temperature difference between the inlet and outlet of the fluid on the heat transfer of the spiral tube heat exchanger. The expression of the number of relevant criteria is[13]:

$$Re_o = \frac{d_e G_o}{\mu_o} \tag{7}$$

$$Nu_o = \frac{h_o d_e}{\lambda_o} \tag{8}$$

$$Pr_o = \frac{c_{p,o}\mu_o}{\lambda_o} \tag{9}$$

The expression of heat transfer factor JH is[14]:

$$j_H = \frac{Nu_o}{Re_o Pr_o^{1/3}} \tag{10}$$

Where: d_e—equivalent diameter of shell side, m; λ_o—thermal conductivity of shell side fluid, W/m·K; G_o—mass flow rate of fluid at shell side, kg/(m²·h); μ_o—hydrodynamic viscosity at shell side, PA·s; $c_{p,o}$—constant specific pressure heat capacity of shell side fluid, J/(kg·K).

The efficiency of heat exchanger is defined as[15]:

$$\eta = Q_{avg}/Q_{max} \tag{11}$$

Among them,

$$Q_{avg} = (Q_i + Q_o)/2$$

$$Q_{max} = (q_m c_p)_{min}(t_{o,in} - t_{i,in})$$

Where: Q_{avg}—average heat exchange capacity of heat exchanger, W; Q_i—heat exchange of fluid at pipe side, W; Q_0—heat exchange of fluid at shell side, W; q_m—mass flow, kg/s; $t_{i,in}$—pipe side inlet temperature, °C; $t_{o,in}$—inlet temperature at shell side, °C.

According to the analysis of the Nu_0 change curve in **Figure 9**, Nu_0 gradually increases with the increase of Re_0, and the average heat transfer coefficient of the shell side fluid gradually increases; under the same Re_0, Nu_0 increases with the increase of temperature. The temperature difference between the fluid inside and outside the tube increases, and the average heat transfer coefficient of the fluid on the shell side increases, which is conducive to the heat transfer of the fluid in the heat exchanger.

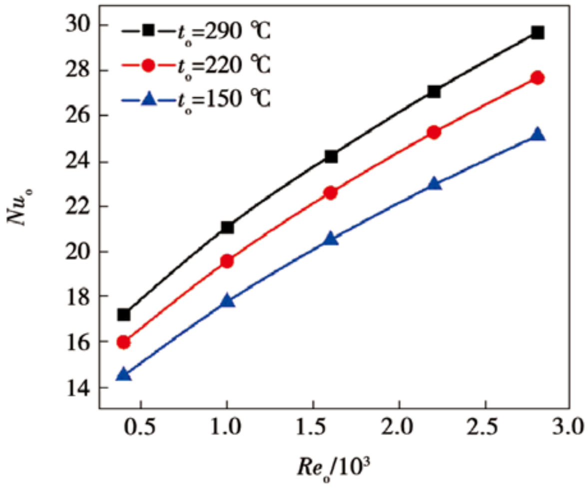


Figure 9. Nusselt number vs. Reynolds number of shell-side.

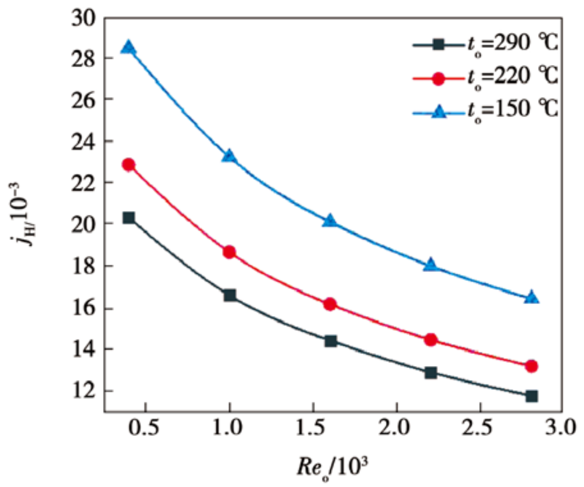


Figure 10. Heat transfer factor vs. Reynolds number of shell-side.

The heat transfer factor j_H change curve in **Figure 10** shows that j_H decreases with the increase of temperature, and the amount of change gradually decreases. This is because the physical properties of the fluid have changed significantly affected by temperature. j_H decreases gradually with the increase of Re_0, and the heat transfer coefficient of shell side fluid increases, which further improves the heat transfer performance of horizontal spiral tube heat exchanger.

Figure 11 shows the relationship between heat exchanger efficiency η and Re_0. The analysis shows that η gradually decreases with the increase of Re_0, which is attributed to the increase of q_m with the increase of Re_0, leading to the increase of Q_{max}, so the efficiency of heat exchanger η decreases. At the same time, when the flow rate is constant, the efficiency η of the spiral tube heat exchanger is slightly higher when the temperature is 220 °C, and it can be judged that the inlet temperature of the shell side has no significant effect on the enhanced heat transfer of the spiral tube.

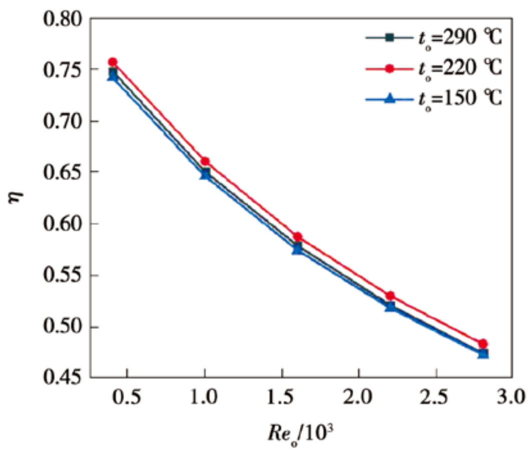


Figure 11. Efficiency vs. Reynolds number of shell-side.

5. Conclusion

(1) The fluid temperature of the spiral tube gradually increases along the flow direction, and the centrifugal force generated by its bending makes the maximum velocity of the fluid close to the outside of the tube, and the velocity is distributed in a concave arc shape. When the fluid rises to the upper coil of the spiral tube, the fluid disturbance intensifies, producing obvious secondary circulation, and enhancing the heat exchange effect of the heat exchanger.

(2) The inlet flow rate of shell side fluid is in the range of 600 ~ 1,800 L/h. With the increase of flow rate, the shell side heat transfer coefficient and total heat transfer coefficient increase by 73% and 59% respectively, which has a positive impact on the enhancement of heat transfer; the heat transfer power and pressure loss have no obvious change with the increase of fluid inlet flow on the shell side.

(3) Temperature has little effect on the heat transfer coefficient and pressure drop. The heat transfer coefficient on the shell side and the total heat transfer coefficient increased by 13% and 11% respectively, but the increase rate gradually decreased. It shows that the change of shell side inlet temperature has limited effect on improving the heat transfer capacity of the heat exchanger.

(4) In the range of Reynolds number from 400 to 2,800, the Nusselt number on the shell side increases with the increase of Reynolds number, and the heat transfer factor and efficiency show a downward trend, which is conducive to improving the heat transfer performance of the heat exchanger. Compared with Reynolds number, shell side inlet temperature has little effect on shell side Nusselt number, heat transfer factor and efficiency of heat exchanger.

Conflict of interest

The authors declared no conflict of interest.

References

1. Wu Z, Xi H, Xu P. Numerical studies on geometric parametric analysis of helical-wound tube heat exchangers. Chemical Engineering 2019; 47(9): 12–17.
2. Fsadni AM, Whitty JPM. A review on the two-phase heat transfer characteristics in helically coiled tube heat exchangers. International Journal of Heat and Mass Transfer 2016; 95: 551–565.
3. Vocale P. Influence of thermal boundary conditions on local con-vective heat transfer in coiled tubes. International Journal of Thermal Sciences 2019; 145: 106039.
4. Ren Y. Numerical study on the shell-side flow and heat transfer of superheated vapor flow in spiral wound heat exchanger under rolling working conditions. International Journal of Heat and Mass Transfer 2018; 121: 691–702.
5. Lu X. Shell-side thermal-hydraulic performances of multilayer spi-ral-wound heat exchangers under different wall thermal boundary conditions. Applied Thermal Engineering 2014; 70(2): 1216–1227.
6. Zeng M, Zhang G, Li Y, *et al*. Geometrical parametric analysis of flow and heat transfer in the shell side of a spiral-wound heat exchanger. Heat Transfer Engineering 2015; 36: 790–805.
7. Sun C. Experimental study on shell-side pressure drop and offshore adaptability of LNG-FPSO spiral wound heat exchanger. Experimental Thermal and

Fluid Science 2019; 109: 109874.

8. Yu S. Experimental and numerical investigation of two-phase flow outside tube bundle of liquefied natural gas spiral wound heat exchangers under offshore conditions. Applied Thermal Engineering 2019; 152: 103–112.
9. Chen Z, Qin C, Dai W. Experimental research on heat transfer coefficient of spiral tube and numerical simulation of temperature field. Gas & Heat 2010; 30(1): 16–18.
10. Guo L, Chen X, Zhang M. Research on the forced convective boiling heat transfer characteristics of steam-water two-phase flow in horizontal helically coiled tubes. Journal of Xi'an Jiaotong University 1994; 28(5): 120–124.
11. Yu Q. Research on calculation method for helical wound coil tube heat exchangers [MSc thesis]. Dalian: Dalian University of Technology; 2011.
12. Naphon P. Study on the heat transfer and flow characteristics in a spiral-coil tube. International Communications in Heat and Mass Transfer 2011; 38: 69–74.
13. Zhang Z, Li Y, Wang Y, *et al*. Numerical simulation of fluid enhanced heat transfer in a helical tube under constant wall temperature condition. Refrigeration and Air-Conditioning 2016; 16(2): 43–48.
14. Sharqawy MH, Saad SMI, Ahmed KK. Effect of flow configura-tion on the performance of spiral-wound heat exchanger. Applied Thermal Engineering 2019; 161: 114–157.
15. Elattar HF. Thermal and hydraulic numerical study for a novel multi tubes in helically coiled tube heat exchangers: Effects of operating/geometric parameters. International Journal of Thermal Sciences 2018; 128: 70–83.