Research on the Thermal Performance of a Helical Coil Heat Exchanger

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Abstract. Helical coil heat exchanger has been widely used in hydraulics engineering, and plays an important role in modern industry. The distribution of fluid field which would be influenced by helical coil structural parameters is an important factor affecting its thermal performance. In this paper, CFD analysis is conducted to study the effects of the inlet flow, the mid-diameter of coils, the pitch, and the number of helical coil turns on the thermal performance of a heat exchanger. Results show that the outlet temperature and pressure drop of the helical coil heat exchanger are affected significantly by the inlet mass flow rate, and varies with the mid-diameter and pitch. And it approximately linearly increases with the number of coil turns.

Keywords: Helical coil · Thermal performance · CFD analysis · heat exchanger · hydraulic

1 Introduction

Helical coil heat exchanger with the advantage of high heat transfer efficiency and compact structure, has been highly applied into hydraulic and plays a very important role in modern industry due to the secondary flows induced by the centrifugal force. This force generated as fluid flows through the curved tubes would significantly enhance the heat transfer rate. The heat transfer and flow characteristics in curved tubes have been widely studied by researchers both experimentally and numerically.

Vinous M. Hameed [1] adopted multiple passive enhancement techniques and fabricated triangular fins on the outside surface of the longitudinal helical heat exchanger to improve the performance of heat exchangers, and experimentally and mathematically investigated the performance of this new heat exchanger. Ahmad Zarei [2] experimentally investigated the cold thermal energy storage performance of a helical coil heat exchanger modified with bubble injection and found that it is an effective methods for increasing the heat transfer rate in heat exchangers by bubble injection. Davood Majidi [3] proposed a double-pipe helical heat exchanger to improve the heat exchange rate by soldering a copper-wire fin on the outside area of the internal tube and experimentally investigated the heat transfer coefficient. C.E. Kalb and J.D. Seader [4, 5] studied the heat-transfer problem at entrance-region in a uniform wall-temperature helical coil

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experimentally. A novel gradient method about heat-transfer investigation was developed based on the measurement of the wall internal and external surface-temperature distributions. Garimella [6] presented average heat transfer coefficients of laminar and transition flow for forced convection heat transfer in coiled annular ducts. H. J. Kang [7] experimentally investigated a helical tube to obtain the heat transfer data and correlations condensing the heat transfer and pressure drop characteristics of an ozone-friendly refrigerant HFC-134a. Prabhanjan [8] compared the heat transfer rates between a helically coiled heat exchanger and a straight tube heat exchanger. P. Naphon [9] developed a mathematical model and investigated the heat transfer characteristics and the performance of a spiral coil heat exchanger under cooling and dehumidifying conditions by using the Newton-Raphson iterative method. Y. Murai [10] experimentally investigated an air-water two-phase flow in helically coiled tubes to elucidate the effects of centrifugal acceleration on the flow regime map, the spatial and the temporal flow structure distribution. Three kinds of test tubes with 20 mm inner diameters including a straight tube are used to compare the turbulent flow structure.

Due to complexity of the heat transfer processes in curved tubes, experimental studies are very difficult to conduct. Numerical investigations has become an important method. Bolinder and Sunden [11] solved the parabolized Navier-Stokes and energy equations by using a finite volume method. The steady, fully developed laminar forced convective heat transfer process in helical square ducts for various Dean and Prandtl numbers were analyzed. Lin and Ebadian [12] utilized standard k-ε model to investigate the three-dimensional turbulent developing convective heat transfer in helical pipes with finite pitches. The effects of pitch, curvature ratio and Reynolds number on the development of effective thermal conductivity and temperature fields, local and average Nusselt numbers were discussed. Sillekens [13] employed the finite difference discretization to solve the parabolized Navier-Stokes and energy equations. Zheng [14] applied a control-volume finite difference method with second-order accuracy for solving the three-dimensional governing equations to analyze the laminar force convection and thermal radiation in a participating medium inside a helical pipe. Acharya [15] numerically studied the phenomenon of steady heat transfer enhancement in coiled-tube heat exchangers due to chaotic particle paths in steady, laminar flow with two different mixings. The velocity vectors and temperature fields were discussed. Sheeba A. [16] Numerically studied the performance of a double-pipe helical coil heat exchanger in the laminar flow regime and found the effect factors. Shuai Xie [17] proposed a novel type of tube with helical dimples and numerically investigated its turbulent heat transfer and flow resistance. The results indicated that the spiral pitch, transverse length, number of starts, depth, and radius would influence on the performance. N Sreenivasalu Reddy [18] investigated the effect of different configurations of the tube-in-tube helically coiled heat exchanger using ANSYS Workbench and predicted the fluid flow and heat transfer in a tube-in tube helical heat exchanger. Md. Jahid Hasan [19] used Computational fluid dynamics (CFD) solver of ANSYS to numerically investigate the heat transfer performance of a helical heat exchanger using various water-based nanofluids, considering multiple head-ribbed geometries with different coil revolutions.

In recent years, ANSYS-FLUENT is widely used in fluid simulation for hydraulic field. In this paper, the heat transfer characteristics of a helical coil heat exchanger with various parameters are discussed and analyzed using ANSYS-FLUENT.

2 Governing Equations

Continuity equation can be written as:

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

where, v is velocity vector, ρ is density.

Momentum equations are as follows:

$$\frac{\partial (\rho \vec{v})}{\partial \mathrm{t}} \cdot \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla P + \nabla \cdot \left(\vec{\vec{\tau}}\right) + \vec{F} \tag{2}$$

$$\vec{\vec{\tau}} = \mu \left[\left(\nabla \vec{v} + \nabla \vec{v}^T \right) - \frac{2}{3} \nabla \cdot \vec{v} I \right] \tag{3}$$

where, P is pressure, F is external volume force, τ is the stress tensor, I is unit tensor.

Energy Equation is:

$$\frac{\partial (\rho T)}{\partial t} + div(\rho \vec{v} T) = div\left(\frac{k}{C_P} gradT \right) + S_T \tag{4}$$

where, C_p is specific heat capacity, k is heat transfer coefficient of fluid, S_T is dissipative term.

3 CFD Model and Simulation

3.1 The Design Parameters and CFD Model

The helical-coil heat exchanger consists of a shell and a helically coiled tube unit which contains two layers of tubes. The CFD model is developed as shown in Fig. 1 and Fig. 2. The water with different temperature in hot and cold side is used as working medium. The inlet and outlet sections of the helical-coil heat exchanger are shown in Fig. 1. The hot water flows into the outer coil, then radially through the inner coil before leaving the heat exchanger at the outlet-hot section. The cold water flows from the inlet of shell, then passes through the center and across the helical coils before leaving the heat exchanger at the outlet-cold section (Fig. 1). The helically coiled tube unit is constructed by bending a 10.2 mm diameter straight tube into a helical-coil of 18 turns. The inner and outer mid-diameters of helical coil are designed as 70 and 100 mm, respectively. The dimensions of the helical-coil heat exchanger are listed in Table 1. The design temperatures and flow rate are shown in Table 2.

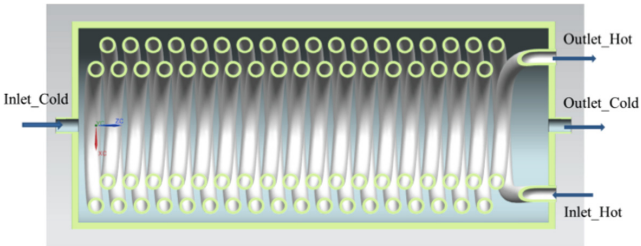


Fig. 1. Schematic diagram of helical-coil heat exchanger

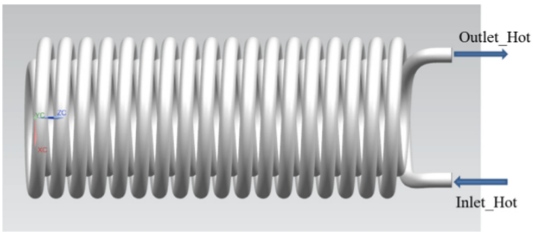


Fig. 2. 3D Model of steel helical-coil

Table 1. Dimensions of the helically coiled tube heat exchanger

Dimension parameters	Value
Outer diameter of tube (mm)	10.2
Inner diameter of tube (mm)	7
Middle-diameter of inner coils (mm)	100
Middle-diameter of outer coils (mm)	70
Number of coil	2
Number of coil turns	18
Pitch (mm)	4
Distance between the helical coil layer (mm)	4.8
Diameter of shell (mm)	149.3
Length of shell (mm)	310
Diameter of hole at cold water-inlet (mm)	10
Diameter of hole at cold water-outlet (mm)	10

Table 2. Design temperatures and flow rate

Parameters	Value
Inlet temperature of cold water (°C)	25
Inlet temperature of hot water (°C)	70
Mass flow rate of cold water (kg/s)	0.2766
Mass flow rate of hot water (kg/s)	0.09013

Table 3. Material parameters

Material parameters	Value
Density of water at 30 °C (kg/m^3)	995.65
Thermal conductivity of water at 30 °C [W/(m·°C)]	0.529
Specific heat capacity of water at 30 °C [J/(kg·°C)]	4180.7
Density of water at 60 °C (kg/m^3)	983.2
Thermal conductivity of water at 60 °C [W/(m·°C)]	0.566
Specific heat capacity of water at 60 °C [J/(kg·°C)]	4180.3
Density of steel at 50 °C (kg/m^3)	7850
Thermal conductivity of steel at 50 °C [W/(m·°C)]	425
Specific heat capacity of steel at 50 °C [J/(kg·°C)]	16

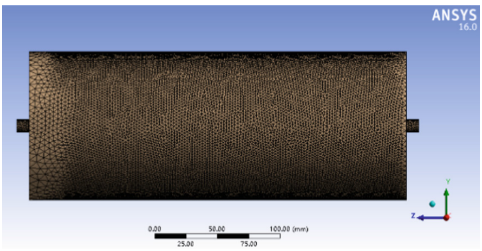


Fig. 3. The mesh model of helical-coil heat exchanger

Both the material of shell and helical coils are stainless steel, and the material parameters are listed in Table 3.

To explore the distribution of fluid field caused by helical coil parameters change and its effects on thermal performance, a CFD model are built and meshed by ANSYS FLUENT 16.0. The grid independence analysis is conducted. The mesh size is initially set as 290, 000 (coarse) and then increased to 350, 000 (medium) and 420, 000 (fine) by 1.2 times of the cell number in axial direction. After comparing the simulation results about the pressure drop at the outlet., the mesh with a total of 3,495,158 elements and

the average skewness is 0.22867 was adopted ultimately in the following simulation considering the calculation accuracy and time. The grid is shown in Fig. 3.

3.2 Assumptions

The CFD analysis on the heat transfer characteristics of the helical coil heat exchanger is conducted with the following assumptions:

- Both hot and cold water flows are steady.
- The wall between the system and surrounding is considered as adiabatic wall.
- The thermal conductivity and specific heat capacity of the helically coiled tube is constant.
- The thermal resistance of liquid film is neglected.

3.3 Boundary Conditions and Calculation Parameters

The Navier-Stokes equations are solved in steady pressure state. The operating pressure is set as 101325 Pa. The boundary condition is set as mass flow inlet and pressure outlet, the "mass flow rate" is altered with various values while the "pressure outlet" with gauge pressure at zero Pascal. Standard k-ε model is used in the whole 3-D CFD model, and the enhanced wall function is used at the near wall region.

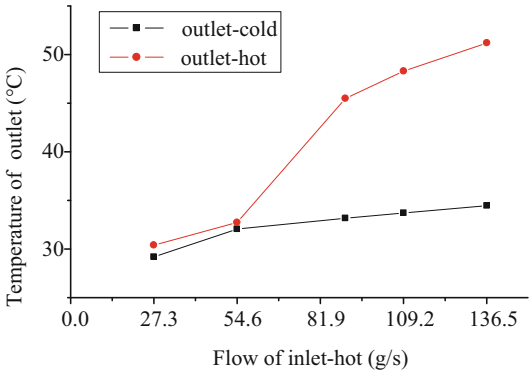
The segregated solver is chosen, and the pressure-velocity coupling is treated by using the SIMPLE algorithm, the second-order upwind scheme is used for momentum. A value of 10^{-3} is used for continuity, velocity and k-ε residual terms, while a value of 10^{-6} is used in energy residual terms.

4 Results and Discussion

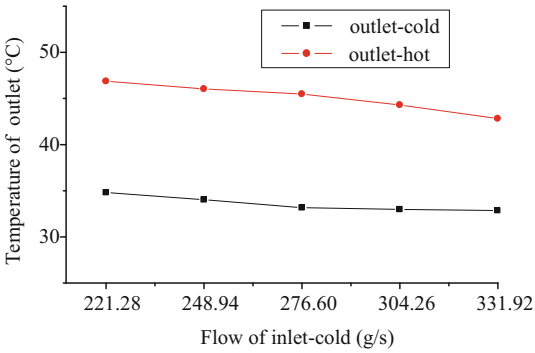
CFD analysis is conducted to study the impacts of inlet flow, mid-diameter, pitch, and number of coils turns on the thermal performance of the helical-coil heat exchanger. And the results are got as follows:

4.1 Impacts of the Inlet Flow

Figure 4 and Fig. 5 shows the influences of inlet flow on the thermal performance. And Fig. 6 and Fig. 7 illustrates the temperature contours at hot water region with different inlet flow. The inlet mass flow rate has significant effect on the increase of water temperatures at outlet. When the inlet-cold flow = 0.2766kg/s, both the temperature and pressure drop of outlet rise as the inlet-hot flow increases. When the inlet-hot flow = 0.09013 kg/s, the temperature at outlet would decrease with the inlet-cold flow increasing because the increasing cold inlet flowrate would carry off more heat, and the pressure drop at outlet-hot would decrease because the temperature decrease result in viscosity decreasing. However, the pressure drop at outlet-cold would increases with the inlet-cold flow increasing.

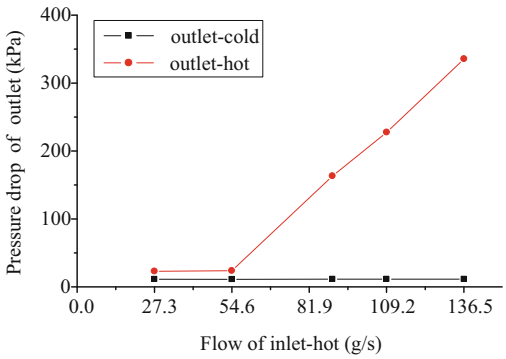


(a)When flow of inlet-cold=276.6 (g/s)



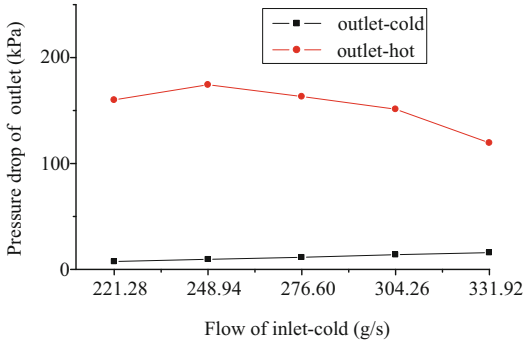
(b)When flow of inlet-hot=90.13 (g/s)

Fig. 4. Temperature of outlet with different inlet flow



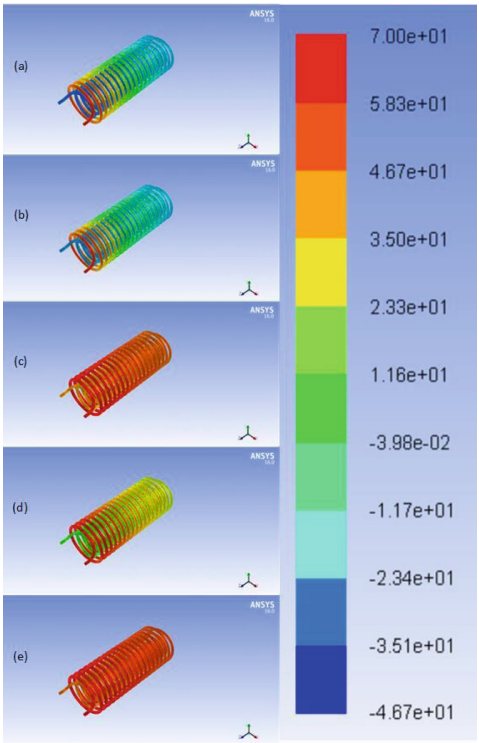
(a)When flow of inlet-cold=276.6 (g/s)

Fig. 5. Pressure drop of outlet with different inlet flow



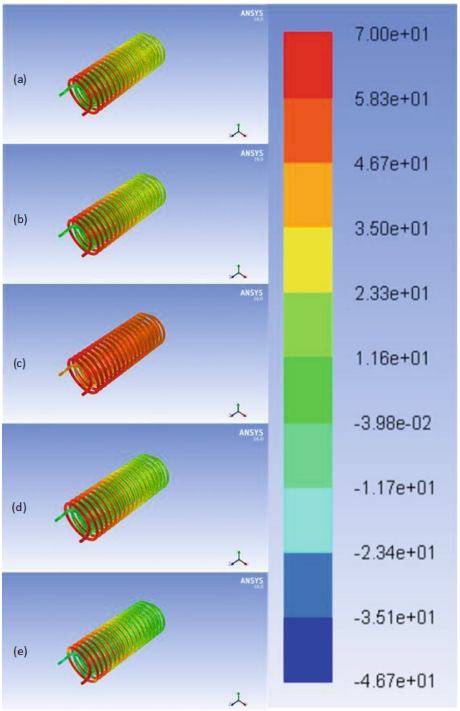
(b)When flow of inlet-hot=90.13 (g/s)

Fig. 5. (*continued*)



(a) Flow rate =0.02731 kg/s, (b) Flow rate =0.05462 kg/s, (c) Flow rate =0.09013 kg/s, (d) Flow rate =0.1092 kg/s, (d) Flow rate =0.1366 kg/s

Fig. 6. Temperature contours at hot water region with different inlet-hot flow when inlet-cold flow = 0.2766 kg/s

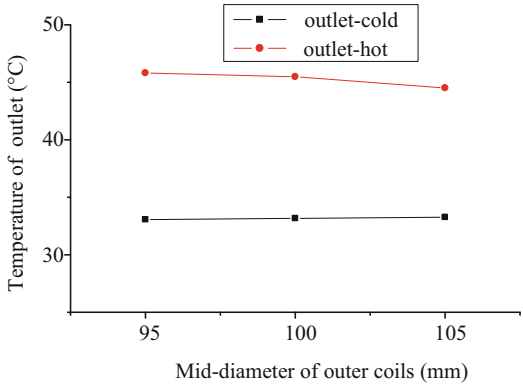


(a) Flow rate =0.2213 kg/s, (b) Flow rate =0.2489 kg/s, (c) Flow rate =0.2766 kg/s, (d) Flow rate =0.3042 kg/s, (e) Flow rate =0.3318 kg/s

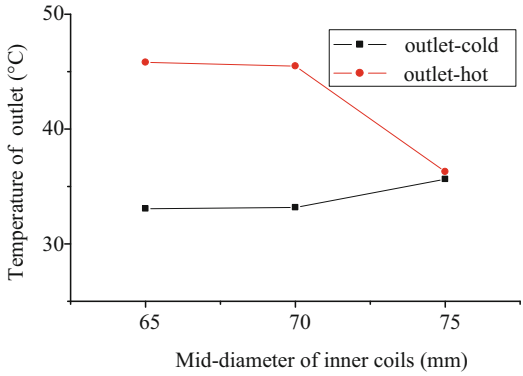
Fig. 7. Temperature contours at hot water region with different inlet-hot flow when inlet-cold flow = 0.09013 kg/s

4.2 Impacts of the Mid-diameter

The CFD simulation results of the impacts of the inner and outer mid-diameter of the helical coil are as shown from Fig. 8 to Fig. 10, the temperature and pressure drop at outlet are shown in Fig. 8 and Fig. 9, and the temperature contours at hot water region are shown in Fig. 10, respectively. It makes the temperature both at outlet-cold and outlet-hot a little change when the mid-diameter of the outer coil increase because it has litter enhance about the heat exchange area. The temperature at outlet-cold would increase when the mid-diameter of the inner coil increase, and the temperature at outlet-inlet would decrease because the increase of mid-diameter of inner coil would raise the heat transfer area and enhance the heat exchange efficiency. However, the pressure drop at the outlet would increase as the mid-diameter of coils increases because the distance and fluid resistance increase.

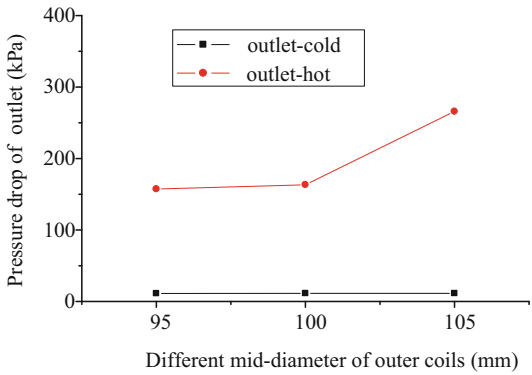


(a) Temperature varies with outer coils mid-diameter



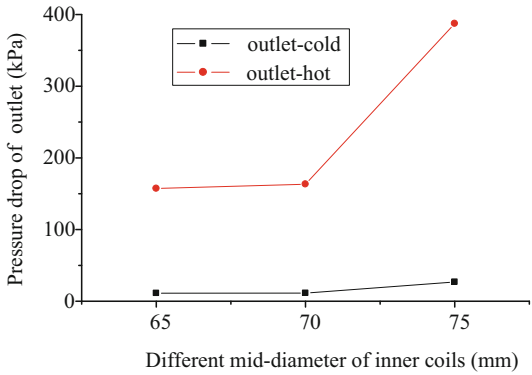
(b) Temperature varies with inner coils mid-diameter

Fig. 8. Temperature of outlet with different mid-diameter



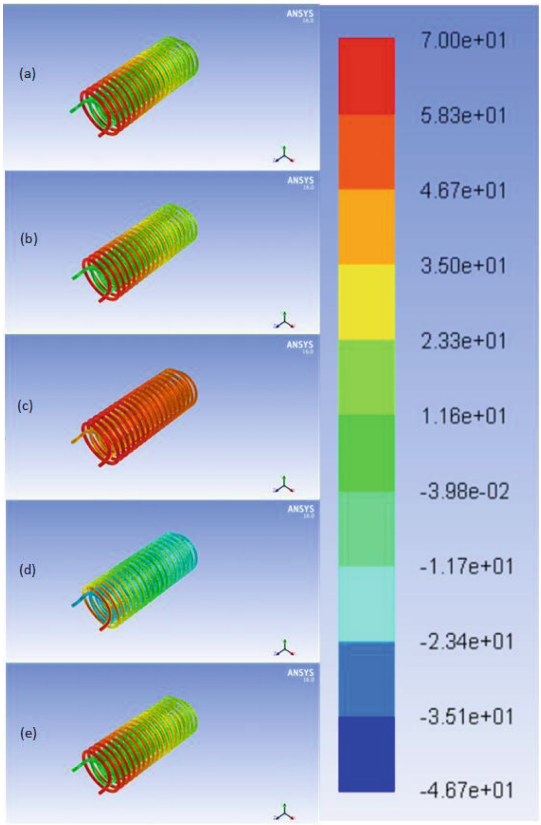
(a) Pressure varies with outer coils mid-diameter

Fig. 9. Pressure drop of outlet with different mid-diameter



(b) Pressure varies with outer coils mid-diameter

Fig. 9. (*continued*)



(a) (Outer mid-diameter, Inner mid-diameter) = (105, 70), (b) = (95, 70),

(c) = (100, 70), (d) = (100, 75), (e) = (100, 65)

Fig. 10. Temperature contours at hot water region with different mid-diameter

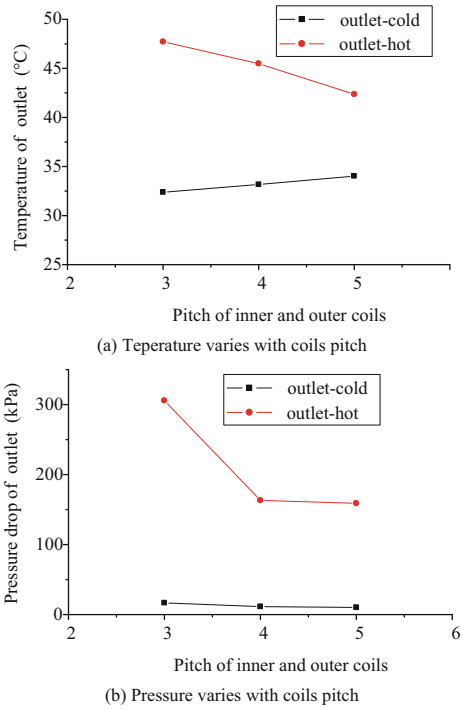
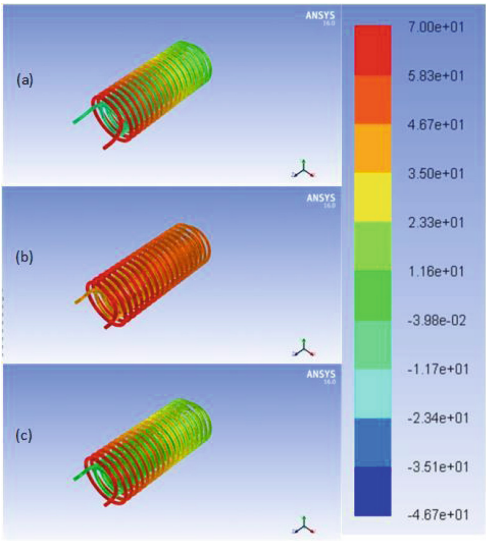


Fig. 11. Temperature and pressure drop at outlet with different pitch



(a) Pitch=3, (b) Pitch=4, (c) Pitch=5

Fig. 12. Temperature contours at hot water region with different pitch

4.3 Impacts of the Pitch

The impacts of pitch is illustrated in Fig. 11, and the temperature contours at hot water region are shown in Fig. 12, respectively. The pressure drop would increase as the pitch increases because it would increase the fluid resistance and pressure loss. The temperature at outlet-cold would increase when the pitch increases, however, the temperature at outlet-hot decreases correspondingly. That means the increase of pith would improve the heat exchange efficient.

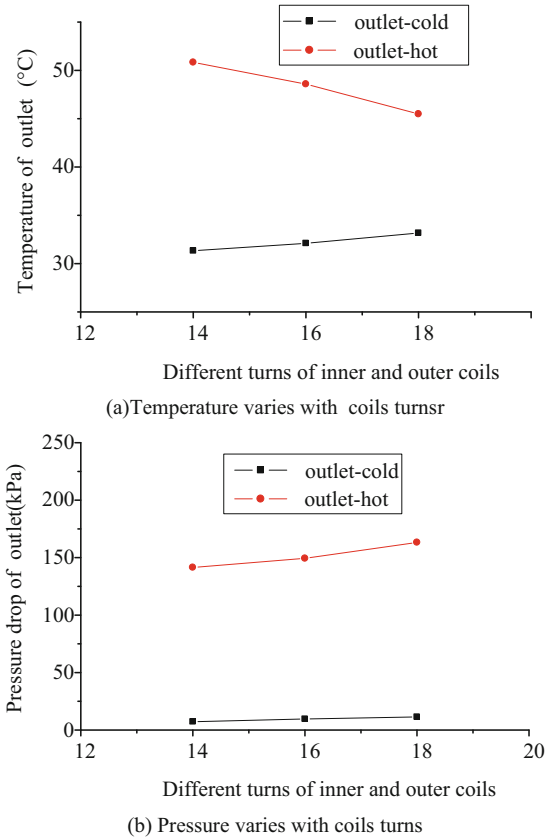
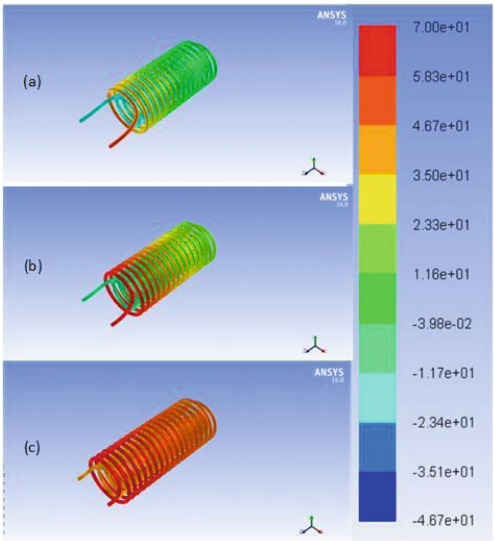


Fig. 13. Temperature and pressure drop at outlet with different turns



(a) Turns=14, (b) Turns=16, (c) Turns=18

Fig. 14. Temperature contours at hot water region with different turns

4.4 Impacts of the Number of Turns

Figure 13 shows the variation of outlet temperatures and pressure drop with different number of inner and outer coil turns, Fig. 14 represents the temperature contours at hot water region. The temperature and the pressure drop of outlet-cold approximately linearly increase with the number of coil turns, because the increase of coil turns number makes the length of tube and the heat exchange area increase. it would improve the heat exchange efficient and raise the pressure drop. The temperature at outlet-cold and both the pressure drop of outlet-cold and outlet-hot linearly increase as the number of turns increase, while the temperature of outlet-hot decreases.

5 Conclusions

The CFD simulation on the heat transfer characteristics of a helical coil heat exchanger are presented, and the results indicates that the heat transfer performance would be significantly influenced by the inlet mass flow rate, the mid-diameter, the pitch, and the number of coil turns. Both the temperature and pressure drop of outlet would increase as the inlet-hot flow increases. The temperature at outlet would decrease with the inlet-cold flow increasing, and the pressure drop at outlet-hot would decrease, the pressure drop at outlet-cold has the contrary performance.The outlet temperature has little change when the mid-diameter of the outer coil varies. The temperature at outlet-cold would increase while the temperature at outlet-inlet would decrease when the mid-diameter of the inner coil increase. The pressure drop would increase with the coils mid-diameter. The pressure drop and heat exchange efficient would increase as the pitch increases. The increase of

coil turn number is also benefit to improve the heat exchange efficient. Consequently, increasing the inlet-cold mass flowrate and decreasing the inlet-hot mass flowrate, raising the inner mid-diameter, increasing the pith and coil turns are flexible method to decrease the outlet temperature, while it will take the disadvantage of increasing pressure drop. Balancing the heat exchange efficient and pressure drop is an important issue to improve the whole performance of heat exchanger.

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