Numerical simulation and analysis of enhanced heat transfer in corrugated tube heat exchanger

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Abstract. At present, in many fields such as petrochemical industry, in order to make better use of heat energy and reduce energy consumption in the process of equipment operation, heat transfer enhancement of heat exchange equipment has attracted more and more attention. Corrugated tube has many advantages compared with other smooth tubes, which are enhancing heat transfer, strong anti-fouling ability and easy to clean. In this paper, a heat exchanger with corrugated tube is studied. The geometry is meshed with the software GAMBIT. It is used with Fluent software and the initial and boundary conditions are set. Heat transfer performance between smooth tube and corrugated tube at the same inner wall temperature and velocity. Then, the influence from inlet velocity on heat transfer performance is investigated. The variation of temperature field, pressure field and velocity field in corrugated tube heat exchanger with different inlet velocity is discussed. The results show that the enhanced heat transfer effect of corrugated tube is much better than that of smooth tubes. At three different inlet velocities (0.5m/s, 1m/s, 3m/s), the enhanced heat transfer effects of the corrugated tube heat exchanger are different. With the increase of inlet velocity, the heat transfer effects of corrugated tube heat exchanger are enhanced, but the extent of enhancement decreases. In the range of this paper, the optimal inlet velocity is 0.5m/s in order to obtain the more heat transfer quantity and lower operation cost.

1. Introduction
Due to the wide application of heat exchangers in various industries, improving the heat transfer and increasing the efficiency are very important. In the past thirty years, scientists and relevant researchers around the world have spent a lot of effort on increasing heat transfer. Heat exchangers are widely used as key equipment in industrial and engineering applications. The shell and tube heat exchanger is characterized by simple structure, high reliability, low cost and mature design and manufacturing technology. In order to get a more optimized structure and better heat exchange effect of the heat exchanger, many researchers have carried out research. Among the heat exchangers, the corrugated tube heat exchanger is widely studied and a lot of important results are obtained[1-2].

A. Barba [3] et al. studied the heat transfer and resistance performance of single-phase flow of corrugated tubes. It is found that the Nusselt number of corrugated tubes is higher than that of smooth tubes and their friction coefficient of corrugated tube is 1.83–2.45 times higher than that of smooth ones in the range 100–800 of the Reynolds number. P. G Vicente [4] conducts many experiments to study the heat transfer performance and resistance properties of corrugated tubes with Reynolds numbers ranging from 2000–90000 and Prandtl number within 2.5–100 he concludes that corrugated tubes increase the theoretical integrity of corrugated tubes heat exchanger. Uaizhi Han [5] et al. study
the flow and heat transfer characteristics of corrugated tube with two opposite flow directions by numerical simulation. By comparing the performance and mechanism between the two flow opposite directions in corrugated tube, it is found that the improvement of the overall heat transfer performance is mainly determined by the radius of the large corrugated groove located at the upstream side.

Chen Keping's [6] results show that the corrugated tube are much better than smooth tubes in scale inhibition and heat transfer enhancement, The Reynolds number is about 1.5 times that of smooth tubes. Sun Fengyu [7] experimentally studied the flow characteristics of three kinds of corrugated tube with different diameters (6mm, 8mm and 10mm) using special working fluids (liquid nitrogen and nitrogen). The pressure loss of nitrogen flow in corrugated tube s increases with the increase of Reynolds number. Dang Gaojian [8] found when the fluids is water and kerosene that the heat transfer coefficient increased with the increase of Reynolds number, and the boiling heat transfer effect of corrugated tube was better than that of smooth tube. Zhang Guozhao [9] mainly studied the heat transfer performance and scale inhibition performance of smooth tube and corrugated tube heat exchanger by experimental method. The total heat transfer coefficient of corrugated tube is 1.1 to 1.2 times higher than that of smooth tubes, and the fouling thermal resistance of corrugated tube is about 35% lower than that of smooth tubes. Yang Husheng [10] found that the heat transfer with high peak is better than that with low peak.

Enhanced heat transfer technology is a new energy-saving technology that can improve the heat transfer performance. The main content is to adopt enhanced heat transfer tubes, improve the structure of heat exchanger, improve the efficiency of heat exchanger, so as to reduce the operating cost of equipment and achieve the optimization of production. While the temperature and velocity distribution in the heat transfer exchangers have a critical influence on the design and optimization of the equipment. With the development of numerical simulation technology in recent years, the accuracy of simulation data is higher and higher. The error between the simulated data and the experimental data is getting smaller and smaller, so the numerical simulation software has become the most widely used tool. The Fluid computing software FLUENT have obtained more attention because of many advantages such as wide range of application, multiple models of heat transfer, visualization and high-precision. In this paper, the software FLUENT is used to simulated the heat transfer performance of fluids in corrugated tube and smooth tube and the fluid field of corrugated tube heat exchangers at different inlet velocities were simulated and the influence on the enhanced heat transfer performance by different inlet velocities are investigated.

2. Exchanger geometry

2.1. Physical model

Figure 1 shows the corrugated tube structure. Data in Table 1 are related to the structural dimension of Corrugated tube. Figure 2 shows the structural schematic diagram of heat exchanger and dimensions are given in Table 2.

2.2. Mathematical model

According to the flow characteristics in the corrugated tube, the working fluid i.e.water in the heat exchanger is assumed as incompressible fluid.

Table 1. Structural parameters of corrugated tube.

| Classification                        | Parameter value |
|---------------------------------------|-----------------|
| Corrugated tube Total length          | 800mm           |
| Intermediate segment of Corrugated tube Length | 720mm           |
| Peak diameter of Corrugated tube      | 25mm            |
| Diameter of Corrugated tube           | 19mm            |
| Diameter of Import and Export Section | 25mm            |
| Length of import and export section   | 40mm            |
Table 2. Dimension table of main structure of model.

| Classification                          | Parameter value |
|-----------------------------------------|-----------------|
| Shell diameter                          | 200mm           |
| Heat exchanger tube length              | 1600mm          |
| Inlet nozzle diameter                   | 60 mm           |
| Length of inlet nozzle                  | 45 mm           |
| Arrangement of heat exchanger tubes     | Orthogonal triangle arrangement |
| Wave crest diameter                     | 25 mm           |
| Nodal diameter                          | 19 mm           |
| Number of Heat Exchange Tubes           | 19              |

Figure 1. Corrugated tube structure.  
Figure 2. Structure of corrugated tube heat exchanger.

The governing equations include mass conservation equation, momentum conservation equation and energy conservation equation. The mathematical expressions in cartesian coordinates are as follows.

1. Mass conservation equation
   \[
   \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0
   \]

2. Momentum conservation equation
   \[
   \frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = \frac{\partial}{\partial x_i} \left( \mu \frac{\partial u_i}{\partial x_j} - \rho \bar{u}_i \bar{u}_j \right) + S_i
   \]

3. Energy conservation equation
   \[
   \frac{\partial (\rho T)}{\partial t} + \frac{\partial (\rho u_i T)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \Gamma \frac{\partial T}{\partial x_j} - \rho \bar{u}_i \bar{u}_j T \right) + S
   \]

2.3. Mesh generation

Grid independent verification. Firstly, the heat exchanger zone is discretized and the intervals of nodes are set 4 and 5. When the intervals of nodes are 4, the quality of the meshes is better and the number of meshes obtained is about 3 million after the discretization of the model zone. When the software is used for simulation, the software runs very slowly. When the interval of nodes is 5, the quality of mesh files can be accepted, and the number of meshes obtained is about 2.4 million. When the software is running, numerical simulation is carried out under the same boundary and almost coincidence temperature and pressure distributions are obtained. Therefore, the interval of nodes is 5 is selected to discretize the model area in this paper. Results in Table 3 imply that boundary conditions of flow in tube.

Table 3. Boundary conditions of flow in tube.

| Classification          | Parameter value                      |
|-------------------------|--------------------------------------|
| inlet                   | inlet velocity: V=0.25m/s,0.5m/s,1m/s; T=298 |
| outlet                  | Outflow;                             |
| The fluid tube wall     | Fixed wall: T=373K                    |
3. Fluent parameter setting

3.1. Model parameter
$k - \varepsilon$ turbulence model is selected, the energy equation in fluid region is opened, steady state, hidden test and separation solver are used to solve the problem. SIMPLEC algorithm is used.

3.2. Initial condition and boundary condition setting
Comparative analysis of heat transfer performance between smooth tube and corrugated tube. The fluid inlet velocity is 0.25 m/s, 0.5 m/s, 1 m/s separately with the temperature of 298 K. The boundary condition of fluid outlet is outflow. The fluid tube wall is set as the fixed wall with the temperature of 373 K. The working fluid is water.

Table 4. Boundary conditions of heat exchanger.

| Classification         | Parameter value             |
|------------------------|-----------------------------|
| inlet                  | inlet velocity: V=0.5 m/s, 1 m/s, 3 m/s; T=298 |
| outlet                 | Outflow;                    |
| The fluid tube wall    | Fixed wall: T=400 K         |

Comparative analysis of enhanced heat performance of corrugated tube heat exchanger at different inlet velocity are made. The fluid inlet velocity is 0.5 m/s, 1 m/s, 3 m/s separately with the temperature of 298 K. The boundary condition of fluid outlet is outflow. The fluid tube wall is set as the fixed wall with the temperature of 400 K. Results in Table 4 imply that boundary conditions of flow heat exchanger.

For the heat exchanger, you have two fluids =) two inlet conditions. These are not given

4. Results and analysis

4.1. Contrastive analysis of corrugated tube and smooth tube
Figure 3 shows the temperature, pressure and velocity vectors distribution of the smooth tube when the fluid inlet velocity is 0.5 m/s. Figure 4 shows the temperature, pressure and velocity distribution of the corrugated tube in the same condition. Figure 5 and Figure 6 show the temperature, pressure distribution along the central axis in the smooth tube and corrugated tube. In the figure 3 and figure 4 the right side of the heat exchange tube is the fluid inlet, while the left side is the outlet. Comparing the temperature distribution of the outlet of the corrugated and smooth tube, the fluid outlet temperature of the corrugated tube is 320 K, and the fluid outlet temperature of the smooth tube is 313 K. The velocity in the corrugated tube changes periodically because of the periodic design of the wave crest and valley of corrugated tube, which destroys the boundary layer and enhances the heat transfer. The flow in the smooth tube creates a boundary layer on the tube wall, which increase the heat transfer resistance. The pressure difference between the inlet and outlet of the corrugated tube is 2960 Pa while the smooth tube is 170.98 Pa. The pressure difference between the inlet and outlet faces of corrugated tube is much greater than that of the smooth tube. The flow friction coefficient in the corrugated tube is higher than that in the smooth tube. Corrugated tube has enhanced heat transfer compared smooth tubes but the pressure drop increase.

4.2. Contrastive analysis of corrugated tube at different velocities
Figure 4, Figure 7 and Figure 8 show the distribution of the temperature, pressure and velocity at three different inlet velocities (0.25 m/s, 0.5 m/s, 1 m/s) in the corrugated tube. Figure 9 and Figure 10 shows the temperature, pressure distribution of the central axis. In the figure 4, figure 7 and figure 8 the right side of the corrugated tube in the picture is the fluid inlet, and the left side is the outlet. At three different inlet velocities (0.25 m/s, 0.5 m/s, 1 m/s) the enhanced heat transfer effects of the corrugated tube are different. With the increase of inlet velocity, the heat transfer effects of corrugated tube are enhanced, but the enhancement extent decreases. With the increase of inlet velocity, the pressure
difference between the fluid inlet and outlet of corrugated tube increases. Figure 4 (c), Figure 7 (c) and Figure 8 (c) show the distribution of the velocity vectors in corrugated tube. With the increase of the inlet velocity, the velocity vectors state near the wall of the corrugated tube becomes more disordered, the turbulence becomes stronger and the pressure drop of fluid flow increases.

**Figure 3.** Temperature, pressure, velocity vectors distribution of smooth tube when \( v = 0.5 \) m/s. (a) Temperature; (b) Pressure; (c) Velocity vectors.

**Figure 4.** Temperature, pressure, velocity vectors distribution of corrugated tube when \( v = 0.5 \) m/s. (a) Temperature; (b) Pressure; (c) Velocity vectors.

**Figure 5.** Pressure distribution of the central axis

**Figure 6.** Temperature distribution of the central axis

4.3. **Contrastive analysis of corrugated tube heat exchangers at different velocities**

Figure 11, Figure 12 and Figure 13 show the temperature, pressure and velocity distribution of the whole flow field inside the heat exchanger shell when the inlet velocities are 0.5m/s, 1m/s and 3m/s respectively. From the Figure 11 (a), Figure 12 (a) and Figure 13 (a), it is found that the temperature distribution of the flow field in the heat exchanger shell is uniform, and the fluid temperature increases gradually along the flow direction. The temperature difference between the inlet and outlet is reduced with the inlet velocity increase. With the increase of the inlet velocity, the velocity vectors state near the wall of the corrugated tube becomes more disordered and the turbulence degree of fluid flow increases. From the pressure distribution of the internal flow field in Figure 11 (b), Figure 12 (b) and
Figure 13 (b), it can be seen that the pressure decreases along the direction of fluid flow in the shell, which is caused by flow resistance near the wall. At three different velocities, the pressure drop between the inlet and outlet is not obvious. It is concluded that in a certain range of flow velocities, it is feasible to increase the turbulence degree and enhance the heat transfer by increasing the flow rate while the pressure drop has little change in the corrugated tube heat exchanger.

![Figure 7. Temperature, pressure, velocity vectors distribution of corrugated tube when \( v = 0.25 \) m/s. (a) Temperature; (b) Pressure; (c) Velocity vectors.](image)

![Figure 8. Temperature, pressure, velocity vectors distribution of corrugated tube when \( v = 1\) m/s. (a) Temperature; (b) Pressure; (c) Velocity vectors.](image)

![Figure 9. Pressure distribution of the central axis.](image)

![Figure 10. Temperature distribution of the central axis.](image)

5. Conclusions
In the numerical simulation of corrugated tube, with the increase of inlet fluid velocity, the turbulence degree of fluid in corrugated tube increases, and the heat transfer effect of corrugated tube increases. Under the same conditions, the turbulence degree of the corrugated tube with the same diameter is greater than that of the smooth tube, and its heat transfer effect is stronger than that of the smooth tube.

The flow friction coefficient in the corrugated tube is higher than that in the smooth tube. At three different inlet velocities (0.25m/s, 0.5m/s, 1m/s) the enhanced heat transfer effects of the corrugated tube are different. With the increase of the inlet velocity, the velocity vectors state near the wall of the corrugated tube becomes more disordered, the turbulence becomes stronger and the pressure drop of fluid flow increases.
The heat transfer of corrugated tube heat exchanger under constant wall temperature and different flow velocities is studied by numerical simulation. With the increase of the fluid velocity, the temperature in the shell of the heat exchanger increases gradually along the fluid direction while the pressure drop has little change. So, it is feasible to increase the turbulence degree and enhance the heat transfer by increasing the flow rate in the corrugated tube heat exchanger.

**Figure 11.** Temperature, pressure, velocity vectors distribution when \( v = 0.5 \text{ m/s} \). (a) Temperature; (b) Pressure; (c) Velocity vectors.

**Figure 12.** Temperature, pressure, velocity vectors distribution when \( v = 1 \text{ m/s} \). (a) Temperature; (b) Pressure; (c) Velocity vectors.

**Figure 13.** Temperature, pressure, velocity vectors distribution when \( v = 3 \text{ m/s} \). (a) Temperature; (b) Pressure; (c) Velocity vectors.

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