Analysis of Heat Exchange Performance of Heat Exchange Tubes of Evaporative Heat Exchanger Based on Fluent

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Abstract: In order to study the influence of the heat exchange tubes length of the evaporative heat exchanger on the heat exchange performance of the organic Rankine cycle technology (ORC) in automobile exhaust heat recovery, four kinds of three-layer tube heat exchange tube models with the length of 500mm, 800mm, 1100mm and 1400mm are designed by DM modeling software, and they are simplified into a quarter calculation domain model. The simulation calculations of the coupling heat exchange of four different lengths of heat exchange tubes are performed by using the Couple algorithm of Fluent fluid simulation software and the κ-ε model. Through the simulation calculation of the heat exchange of the four three-layer heat exchange tubes, it can be seen that the temperature in the three-layer heat exchange tubes changes along the Z axis direction. The heat exchange performance of different lengths of heat exchange tubes can be obtained by analyzing the temperature cloud diagrams of the XY plane at both ends of the heat exchange tubes and the temperature change curve along the Z axis direction. The heat exchange simulation analysis results of the four three-layer heat exchange tubes show that under the set parameter model, only the inlet and outlet boundary temperature is considered, and the three-layer heat exchange tube with a length of 1400mm has better heat exchange performance.

1. Introduction

Energy is one of the five essential elements for human survival and development. With the rapid development of the global economy, energy shortage has become a serious practical problem facing all countries. In order to realize the sustainable development of society, in view of the shortage of energy, waste heat recovery technology has become the focus of global attention and research[1-2]. In the engine intake and exhaust system, after the engine cylinder has completed its work, the residual exhaust gas temperature from the cylinder is about 700-900°C[3], therefore, the heat contained in automobile exhaust has great application value.

Recycling technology for waste heat of organic Rankine cycle for automobile exhaust, a large number of experiments and explorations have been carried out by scientific research institutions and researchers in various countries. Some developed countries have conducted research on engine exhaust and waste heat recovery since the 1980s. Manzela et al[4] studied the ammonia refrigeration system driven by the exhaust heat of the engine exhaust, analyzed the economic performance, and determined that the exhaust heat of the exhaust of the engine can be used as a potential power for the absorption refrigeration system. Hsu et al[5] studied the use of 24 thermoelectric generators (TEGs) in the entire diesel engine exhaust heat recovery system to convert exhaust heat energy into electrical
energy. The electrical energy generated by diesel engine exhaust waste heat power generation can be used for most automotive electronic systems. The main problem facing power supply is the low efficiency of thermoelectric conversion. Rajesh Ravi et al.[6] designed an extended fin heat exchanger for the exhaust heat recovery of diesel engines, and calculated and analyzed this exchanger, which can greatly improve the efficiency of the heat exchanger. Based on the organic Rankine cycle (ORC) of automobile exhaust waste heat recovery, foreign research has matured, but China's research and application of ORC system started late. In recent years, Tsinghua University, Zhejiang University, Central South University and other scientific research units have conducted certain theoretical or small-scale experimental studies on organic working fluids and thermal cycles[7-9].

In summary, although the organic Rankine cycle (ORC) technology based on automobile exhaust waste heat recovery has been studied for many years, it has not been popularized and widely used so far, and there is still much room for improvement in the research of this technology. Many researches and experiments have been conducted on waste heat recovery and utilization systems at home and abroad, this paper designs the heat exchange tubes of the shell-and-tube evaporative heat exchanger in this system, and uses Fluent fluid simulation software to calculate and analyze the heat exchange tubes. The heat exchange tube is the core component of the evaporative heat exchanger, and the evaporative heat exchanger is the core component of the vehicle exhaust heat recovery system. Therefore, the design and calculation of the heat exchange tube will be particularly important. This paper simulates and analyzes the length of heat exchange tubes of the same structure.

2. Heat exchange tube design

This paper uses Ansys DesignModeler (DM) 3D modeling software in Ansys Workbench[10], Design different size parameters for the straight three-layer heat exchange tubes of the same structure, In this paper, we mainly study the effect of heat exchange tube length on its heat exchange performance, that is, the four heat exchange tubes have the same cross-sectional size and different lengths. The geometric parameters of the four heat exchange tube calculation models are shown in Table 1, where the diameter parameters of the heat exchange tubes are formulated by reference[11]. And the models of the four heat exchange tubes are shown in Figure 1.

| Serial number | Heat Exchange Tube | Inner diameter of inner tube /mm | Inner diameter of middle tube /mm | Inner diameter of outer tube /mm | Tube wall thickness /mm | Heat exchange tube length /mm | Material       |
|---------------|--------------------|---------------------------------|-----------------------------------|-------------------------------|-------------------------|-----------------------------|----------------|
| 1             | Tube 1             | 32                              | 46                                | 62                            | 2                       | 500                         | stainless steel |
| 2             | Tube 2             | 32                              | 46                                | 62                            | 2                       | 1000                        | steel          |
| 3             | Tube 3             | 32                              | 46                                | 62                            | 2                       | 1500                        |                |
| 4             | Tube 4             | 32                              | 46                                | 62                            | 2                       | 2000                        |                |

(a) Cross section of heat exchange tube
3. Meshing division

This paper uses Ansys Mesh software to mesh the model, which is a grid generation module in Ansys Workbench and can only be started in Workbench. The Ansys Mesh software main function is to provide computing grid for Ansys series products[12-14]. The four heat exchange tube models are processed before meshing the heat exchange tubes. The heat exchange tube in this paper is a plane symmetry model, which can be simplified to a quarter calculation domain model (because it contains two symmetry planes). As shown in Figure 2, a quarter calculation domain model for a 500mm length heat exchange tube, the other three heat exchange tube models are processed in the same way.

In this paper, the mesh calculation parameters of the four heat exchange tubes quarter calculation domain model are set the same and the processing process is consistent. Taking the quarter calculation domain model of a heat exchange tube with a length of 500 mm as an example, meshing is performed, in which Element Size is 5 mm, and Method adopts the Sweep method[15], the generated meshing is shown in Figure 3. After the meshing of the quarter calculation domain model of the four heat exchange tubes is completed, the number of meshes is 1923443, 3068653, 4213863, and 5535073.
4. Simulation calculation

4.1. Calculation condition setting

The four models after the meshing are completed are imported into Fluent for simulation calculation. The physical models in the boundary parameters are set to three-dimensional, steady state, steady density, off-flow, κ-ε turbulence models, and the Energy equation is activated[16-17]. The model calculation domain includes three fluid domains and three solid domains. The fluid domain medium is liquid water, and the solid domain material is set to stainless steel "Steel". The physical property parameters are shown in Table 2.

| Types           | density / (kg·m⁻³) | Specific heat capacity c_p / (J/(kg·K)) | Thermal conductivity / (W/(m·K)) | Viscosity / (kg/(m·s)) |
|-----------------|--------------------|----------------------------------------|----------------------------------|------------------------|
| liquid          | 998.2              | 4182                                   | 0.6                              | 0.001003               |
| stainless steel | 8030               | 502.48                                 | 16.27                            | —                      |

The boundary conditions of the four heat exchange tubes are the same. Take the heat exchange tube with a length of 500 mm as an example. The model calculation boundary conditions are shown in figure 4, entrance1, output 2, and output 3 are coordinate origins, and the length of the pipeline is along the Z axis. The boundary conditions of the three entrances of the heat exchange tubes are shown in Table 3. From Table 3, it can be seen that the temperature of the middle layer pipe is high, and the temperature will be transmitted to the inner and outer pipes.

Figure 3. Grid of quarter calculation domain of heat exchange tube

Figure 4. Model calculation boundary conditions
Table 3. Boundary conditions at the three entrances

| Location | Temperature /K | Flow rate / (m/s) |
|----------|----------------|------------------|
| Inlet1   | 365            | 0.5              |
| Inlet2   | 295            | 1                |
| Inlet3   | 280            | 0.1              |

4.2. Mathematical model of heat flow coupling

In Fluent software, the mathematical model calculation method of heat flow coupled is used when calculating the model. The heat flow coupling mathematical model equation is mainly composed of heat conduction differential equation and convection heat exchange equation[18-19].

4.2.1. Thermal conduction differential equation.

The meaning of the differential equation of thermal conductivity is that the total increment of the micro-body thermodynamic energy per unit time is equal to the sum of its ability to conduct heat through the interface and the source term per unit time. The differential equation of heat conduction is established by Fourier's law and the conservation equation of energy. After calculation, it can be expressed by (1):

\[
\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{q_v}{c\rho}
\]

In the formula: \( \alpha \) is the thermal conductivity; \( \rho \) is the density of the micro-body; \( c \) is the specific heat capacity; \( T \) is the temperature; \( t \) is the time; \( q_v \) is the heat generated per unit time per volume.

4.2.2. Convection heat exchange equation.

The convection heat exchange equation is composed of mass, momentum and energy conservation equations. The mass conservation equation characterizes the mass increase in the fluid micro-units per unit time, which is equal to the net mass of fluid flowing into the micro-units within the same time interval.

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

In the formula: \( u, v, w \) are the velocity components along the x, y, z axis directions.

Since the fluid medium in the paper is an incompressible fluid, its density does not change with time, that is, the first term in equation (2) is 0, and equation (3) can be obtained:

\[
\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

The conservation equations of momentum along the x, y, and z directions can be expressed by equations (4), (5), and (6):

\[
\frac{\partial (\rho u)}{\partial t} + \text{div}(\rho u U) = \text{div}(\mu \text{grad} u) + S_u - \frac{\partial p}{\partial x} \tag{4}
\]

\[
\frac{\partial (\rho v)}{\partial t} + \text{div}(\rho v U) = \text{div}(\mu \text{grad} v) + S_v - \frac{\partial p}{\partial y} \tag{5}
\]

\[
\frac{\partial (\rho w)}{\partial t} + \text{div}(\rho w U) = \text{div}(\mu \text{grad} w) + S_w - \frac{\partial p}{\partial z} \tag{6}
\]

In the formula: \( \mu \) is the dynamic viscosity of the fluid, \( U \) is the velocity vector, \( p \) is the stress tensor, \( S_u, S_v, S_w \) are the source terms of the momentum conservation equation.

The energy conservation equation characterizes that the rate of increase of energy inside the microelement body is equal to the net heat flux into the microelement body plus the work done by the volume force and surface force on the microelement body.
In the formula: ST is the viscous dissipation term.

The above heat conduction differential equations and convection heat exchange equations are the basis of the mathematical calculation model in Fluent. Only through thorough analysis of the mathematical calculation model can we understand Fluent's calculation basis and calculation principle, which is convenient for subsequent analysis of the calculation results.

4.3 Calculation result analysis

According to the above boundary conditions and model parameters, through Fluent software simulation calculation, 500mm, 800mm, 1100mm, 1400mm heat exchange tubes calculate the curve convergence after 458, 539, 641, 805 steps, and finally get the temperature changes of the four heat exchange tubes Cloud chart and temperature change curve along the Z axis.

(1) When Z is 0mm, the temperature cloud of XY plane. Through Fluent calculation, when Z is 0mm, that is, at the outlet boundary of the center tube, the outermost tube and the inlet boundary of the middle tube, the XY plane temperature cloud diagram of the four lengths of heat exchange tubes is shown in Figure 5. It can be seen from Figure 5 that as the length of the heat exchange tube increases, the color at the outlet boundary of the center tube and the outermost tube gradually changes from dark blue to light blue, indicating an increase in temperature; the red color at the inlet boundary of the inner tube remains basically unchanged, indicating that the temperature at the inlet of the intermediate tube is basically constant.

(2) When Z is 500mm, 800mm, 1100mm, and 1400mm, the XY plane temperature cloud map. According to Fluent calculation, corresponding to the four heat exchange tubes, when Z is 500mm, 800mm, 1100mm and 1400mm, that is, the XY plane temperature cloud diagram of the heat exchange tubes at the inlet boundary of the center tube, the outermost tube, and the outlet boundary of the middle tube is shown in Figure 6. It can be seen from Figure 6 that the color at the outlet boundary of the middle tube gradually changes from dark yellow to light yellow, indicating that the temperature gradually decreases. The color at the inlet boundary of the outer layer tube remains basically
unchanged, indicating that the inlet temperature of the two-layer tube is basically constant.

![Heat exchange tube with length of 500 mm](image1)

(a) Heat exchange tube with length of 500 mm

![Heat exchange tube with length of 800 mm](image2)

(b) Heat exchange tube with length of 800 mm

![Heat exchange tube with length of 1100 mm](image3)

(c) Heat exchange tube with length of 1100 mm

![Heat exchange tube with length of 1400 mm](image4)

(d) Heat exchange tube with length of 1400 mm

Figure 6. The temperature cloud of XY plane when Z is 500mm, 800mm, 1100mm and 1400mm

(3) The temperature change trend along the Z axis, where the radii are 16mm, 23mm and 31mm, respectively. According to Fluent calculation, the temperature change curve along the Z axis, that is, the axial direction of the heat exchange tube, at a radius of 16mm, 23mm and 31mm, as shown in Figure 7. As can be seen from Fig. 7 (a) -Fig. 7 (d), the temperature at the outlet of the outermost tube (that is, the part indicated by the green curve) is about 294K, 300K, 305K and 310K, respectively. Before the heat exchange of the heat exchange tube is completed, its length increases and the temperature at the outlet of the outermost tube increases, that is, the heat exchange effect is better. It can be seen from Figure 7 (a)-Figure 7 (d) that the temperature at the output boundary of the intermediate pipe (that is, the part indicated by the blue curve) is about 346K, 343K, 340K and 337K, respectively. Before the heat exchange of the tube is completed, its length increases and the temperature at the output of the middle tube decreases, that is, the heat exchange effect is better; as can be seen from Figure 7 (a)-Figure 7 (d), the central tube output temperature at the boundary (that is, the part indicated by the red curve) does not change much. The temperature change trend of the outermost tube is large, because the flow velocity of the fluid medium in the central tube is large, and the temperature difference with the intermediate tube is small, and the heat completed with the intermediate tube The exchange is relatively inadequate, resulting in relatively insignificant temperature changes in the central tube.

![Heat exchange tube with length of 500 mm](image5)

(a) Heat exchange tube with length of 500 mm

![Heat exchange tube with length of 800 mm](image6)

(b) Heat exchange tube with length of 800 mm
According to the above analysis, according to the set boundary conditions and model parameters, the designed four types of heat exchange tubes have a large temperature difference between the three-layer tubes of the four heat exchange tubes when using Fluent calculation to converge. It means that the temperature of the three layers of tubes in the heat exchange tube does not reach the state of being consistent. In an ideal state, if the heat exchange tube is long enough, it is at the inlet boundary of the center tube and the outermost tube (the outlet boundary of the middle tube). In the adjacent length, the temperature of the three-layer tube will not change significantly, that is, the three-layer tube completes the heat exchange. Since the heat exchange tube in an ideal state has lost the meaning of the heat exchange tube and no longer has the characteristics of a heat exchange tube, the length of the heat exchange tube cannot be too long.

5. Conclusion

(1) Simulation analysis shows that the color difference of the three-layer heat exchange tubes is large, indicating that there is a large temperature difference between the three-layer heat exchange tubes. By analyzing the temperature cloud diagram on the XY plane, we can know that the four different lengths of the exchange for the heat pipe, the length of the heat exchange tube is increased, and the heat exchange effect is better. If only the temperature of the inlet and outlet boundaries is considered, the heat exchange effect of the 1400mm length heat exchange tube is better.

(2) According to the analysis of the temperature change curve, for the four different lengths of heat exchange tubes in this paper, the outlet boundary temperature of the middle tube decreases with the increase of the length of the heat exchange tubes, which are about 346K, 343K, 340K and 337K, respectively; the temperature at the outlet boundary of the layer tube increases with the length of the heat exchange tube, about 294K, 300K, 305K and 310K, respectively. It can be seen that when only the temperature of the inlet and outlet boundaries is considered, the heat exchange effect of the 1400mm length heat exchange tube is good, the same result as the analysis of conclusion (1), indicating that the research in this article is rigorous and in line with reality.

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