Design and performance analysis of a discontinuous spiral baffle heat exchanger

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Key words： Marine Engineering; Compact Heat Exchanger; Discontinuous Helical Baffle; Wall Cooling; Numerical simulation

Abstract

In this paper, a new type of discontinuous spiral baffle heat exchanger is designed, and its heat transfer performance is analyzed by numerical simulation. Considering that the wall of heat exchanger is subjected to high temperature at the same time, a preliminary study on the wall cooling is also carried out. The results show that there is no “Flow dead zone” of relatively stagnant flow, and the air temperature drops to about 38% of the original airflow temperature . The heat transfer Coefficient of the Heat Exchanger is k = 344.4 W/(M2 · K),and the heat transfer performance is better.

1. Introduction

Heat exchanger is a kind of heat transfer device, which is widely used in the fields of ship, petroleum, automobile, aerospace and so on. In Engineering, a heat exchanger is a device that transfers the heat of a fluid that needs to change temperature to another fluid in a specific way.

High efficiency and compact design are the trend of heat exchanger research and development, so improving the efficiency of heat exchanger has become the main goal of heat exchanger research and development. Compact heat exchangers can be divided into gas-to-gas heat pipe heat exchangers and gas-to-liquid heat exchangers, depending on the state of the Monitor and shell-side heat transfer media. The gas-liquid heat exchangers are divided into three main types: tube-fin heat exchangers, plate-fin heat exchangers and helical baffle heat exchangers. Different types of heat exchangers according to their own characteristics, applied to the corresponding occasions. Spiral baffle heat exchangers are divided into continuous spiral baffle heat exchangers and non-continuous spiral baffle heat exchangers. This paper mainly aims at the latter to carry out a preliminary study.

At present, domestic scholars mainly focus on spiral baffle heat exchanger in the structure and connection mode of spiral baffle, a large number of numerical and experimental studies have been carried out on the angle of baffle, the type of Tube Bundle, the pitch, the flow field characteristics and the media on different shell sides.

Liu Feng analyzed the heat transfer effect of heat exchangers with different spiral angles at different shell-side flow velocities of 20 ° , 15 ° and 10 ° , and obtained the variation of pressure drop, temperature and flow field distribution between tube-side and shell-side. Wenjian put forward a new type of spiral baffle heat exchanger with spiral trapezoidal structure, that is, two-part spiral baffle heat exchanger, and carried out numerical simulation and parameter optimization. The literature study shows that the heat transfer coefficient and pressure drop on the shell side decrease with the increase of the axial overlap degree of the four-part helical baffle heat exchanger when the angle of the axial overlap degree is fixed at 40 ° , and the pressure drop on the shell side decreases with the increase of the overlap degree, the heat transfer Coefficient and pressure drop of head-tail joint with small angle of 30 ° are higher than the degree of overlap is 40% and 50% respectively with large angle of 40 °. Chen Yaping found that the external notch opened a short-circuit from upstream channel to downstream channel, which was disadvantageous to the flow and heat transfer of the spiral mainstream.

At present, the research on spiral baffle heat exchanger is mainly from the angle of structure design, aiming at how to further improve the heat transfer performance of spiral baffle heat exchanger, and less consider whether the spiral baffle is easy to process. In this paper, a kind of heat exchanger with baffle which is easy to be machined is designed and its performance is investigated. Firstly, according to the engineering design, the heat transfer Coefficient and area of the heat exchanger are obtained. Second , the structure of the heat exchanger and the number of heat exchange tubes are determined .Finally, considering that the wall of heat exchanger is subjected to high temperature at the same time, a preliminary study on the wall cooling is carried out at last.

2. The design of discontinuous spiral baffle heat exchanger

At present, the traditional shell-and-tube heat exchanger design has a complete set of engineering design methods which can be adopted, but for the compact heat exchangers, up to now, there is not a complete and systematic engineering design method to be used for reference.

The main differences between the compact discontinuous spiral baffle heat exchanger and the traditional shell-and-tube heat exchanger are as follows:

(1) the flow patterns between the shell-and-tube side fluids are different,

(2) the influence of flow and heat transfer of Tube Path on the fin and helical plate is also different from that of the traditional bow baffle.

In addition, the wall cooling system is also considered to improve the heat transfer efficiency of the discontinuous spiral baffle heat exchanger, because the enhancement of the heat transfer performance brought by the wall cooling can not be ignored.

In view of the lack of available engineering design methods, a method combining engineering calculation with numerical simulation is proposed to design and analyze the discontinuous spiral baffle heat exchanger.

Firstly, the heat transfer coefficient and heat transfer area of the heat exchanger are calculated by engineering design method.

The basic heat calculation equation for heat exchangers is as follows:

$$\Delta t_m KA = \eta_1 (t_1' - t_1'') M_1 c_{p1} \quad (1)$$

The symbolic meaning in the formula is shown in Table 1.

Table 1 parameters table of basic equations for thermal calculation

Symbols	Parameter name
Δt_m	average temperature difference
A	heat transfer area
η_1	heat loss coefficient, take 0.98
t_1'	inlet temperature
t_2''	outlet temperature
M_1	mass flow rate
c_{p1}	The specific heat of air

The average heat transfer Coefficient k of the whole heat exchanger can be expressed as follow:

$$K = \frac{\alpha_2 \alpha_1}{\alpha_2 + \alpha_1} \quad (2)$$

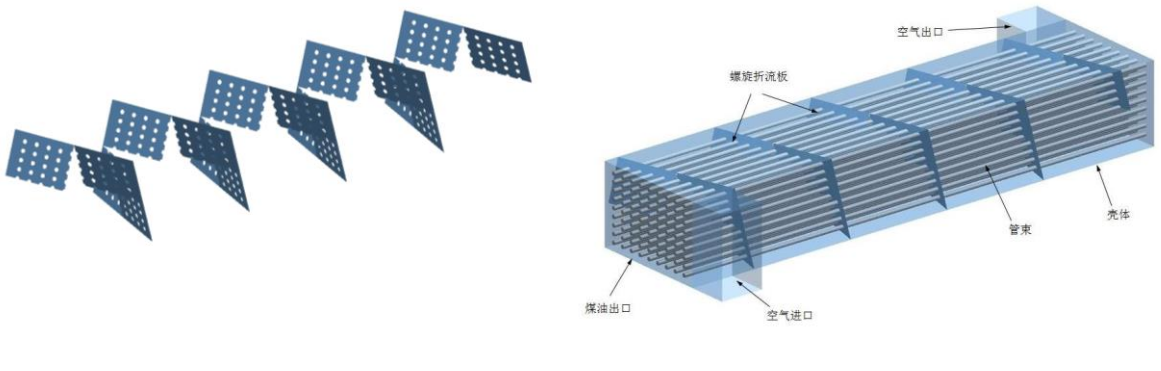
The shell-side heat transfer Coefficient α_1 and tube-side heat transfer Coefficient α_2 were calculated, and the overall heat transfer Coefficient k of the heat exchanger was obtained, and then K was substituted into formula (1), the heat transfer area and the number of heat transfer tubes of the spiral baffle heat exchanger in the traditional shell-and-tube heat exchanger were obtained.

Because the spiral baffle heat exchanger in traditional shell-and-tube heat exchanger is different from the discontinuous spiral baffle heat exchanger in such aspects as the length of the heat exchange tube, the diameter of the heat exchange tube, the flow area of the shell side, etc., the Reynolds number and heat transfer coefficient of fluid flow in Shell and tube side of discontinuous spiral baffle heat exchangers are different from those in traditional shell and tube heat exchangers. Therefore, after obtaining the heat transfer area and the number of heat transfer tubes of the spiral baffle heat exchanger in the traditional shell-and-tube heat exchanger, a series of approximate calculations are needed, the Heat Transfer Coefficient K and the heat transfer area a of the discontinuous helical baffle heat exchanger are obtained.

Then, the engineering calculation results are used to guide the structure design of the heat exchanger. Finally, the commercial software is used to model the designed heat exchanger, divide the grid and carry out the numerical simulation. If it cannot meet the design requirements, then make changes, and then re-numerical simulation, until the optimal solution.

3. Numerical simulation of discontinuous spiral baffle heat exchanger

The internal structure of the discontinuous spiral baffle heat exchanger is shown in Fig. 1. The shape of the heat exchanger is limited by the requirement of the subject. The shape of the spiral baffle heat exchanger designed in this paper is a rectangle with rectangular cross section. The heat exchanger is composed of a shell, a tube bundle, several spiral baffles, a shell-side fluid inlet, an outlet nozzle, a tube-side fluid inlet and an outlet nozzle, etc. . The parameters of the heat exchanger are as follows: the number of heat exchanger tubes is 93, the diameter of the inlet and outlet tubes is 40 mm, the angle of the baffle is 15 ° , the baffle pitch is 134 mm, and the baffle turns right. The baffle is rectangular in shape, simple in structure and easy to be machined. By lapping the four corners of the rectangular baffle respectively, a discontinuous spiral baffle is formed, as shown in Fig. 1(a) . In the numerical simulation, according to the requirements of the project, high-temperature air is selected for shell-side fluid and low-temperature kerosene is selected for pipe-side fluid.



（a）Spiral Baffle （b）Heat Exchange Tube Bundle

Fig. 1 internal structure Diagram of discontinuous spiral baffle heat exchanger

3.1 Analysis of the flow in the discontinuous spiral baffle heat exchanger

3.1.1 Fluid flow analysis in Shell side of heat exchanger

Fig. 2 is the trace diagram of the fluid-air flow in the shell side of the heat exchanger. It can be clearly seen from the diagram that the shell-side fluid flows in a spiral shape under the action of the spiral baffle, and forms the flow pattern of scouring the tube bundle vertically in most areas, thus, the effect of convection heat transfer between air and heat exchanger tube is effectively enhanced. It can also be seen from the figure that there is no"Flow dead zone" of relatively stagnant flow in the air flow affected by the shape of the spiral baffle. From this point of view, it also effectively increases the effect of the heat exchanger, therefore, the convective heat transfer Coefficient of the heat exchanger is increased.

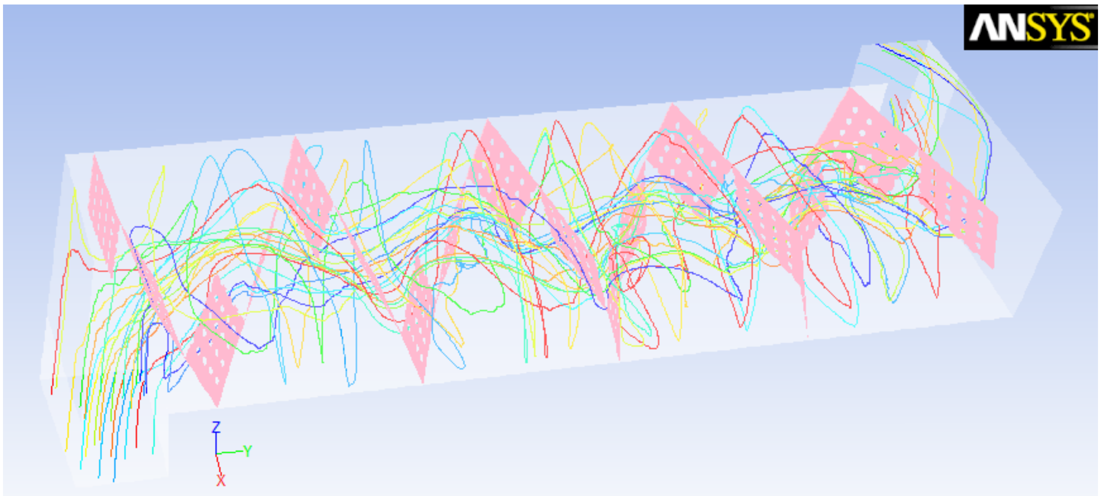


Fig. 2 air trace map

3.1.2 Flow pressure distribution in shell side of heat exchanger

Figures 3,4 and 5 show the total pressure distribution along X, Y and Z directions of the fluid air in the shell side of the heat exchanger. As can be seen in figures 3 and 5, the pressure of the shell-side fluid in the X and Z directions tends to decrease in the direction of the flow, and the pressure of the shell-side fluid remains basically constant in the area in front of each baffle, while after flowing through the baffle, there has been a marked drop in pressure. This shows that the helical baffle can effectively reduce the dead zone of the flow, but it still has a relatively strong disturbance to the flow of the fluid, therefore, the pressure loss caused by the existence of baffles in heat exchangers is inevitable.

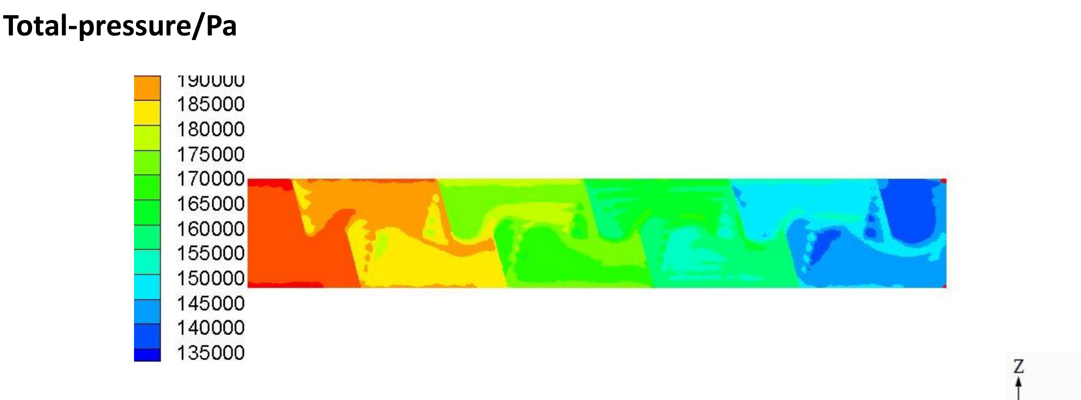


Fig. 3 Total pressure distribution along X direction

Fig. 4 is the distribution of total pressure at Y direction, It shows a spiral decreasing distribution, which indicates that the fluid flow in the circumferential direction is also a spiral flow. It is also noted that there is a distinct step in the pressure on either side of the baffle, which is cut off from the observation plane, and that the pressure is gradually reduced in the direction of the clockwise flow of the fluid, indicating that in the course of the circumferential rotational flow, the existence of Baffles is also the main cause of pressure loss.

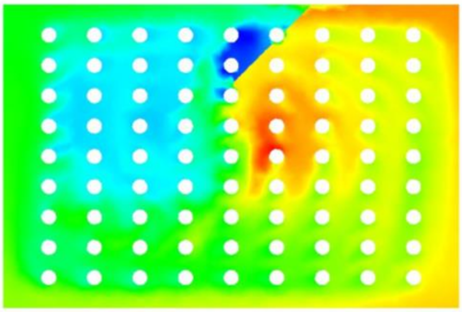


Fig. 4 Distribution of total pressure along Y direction

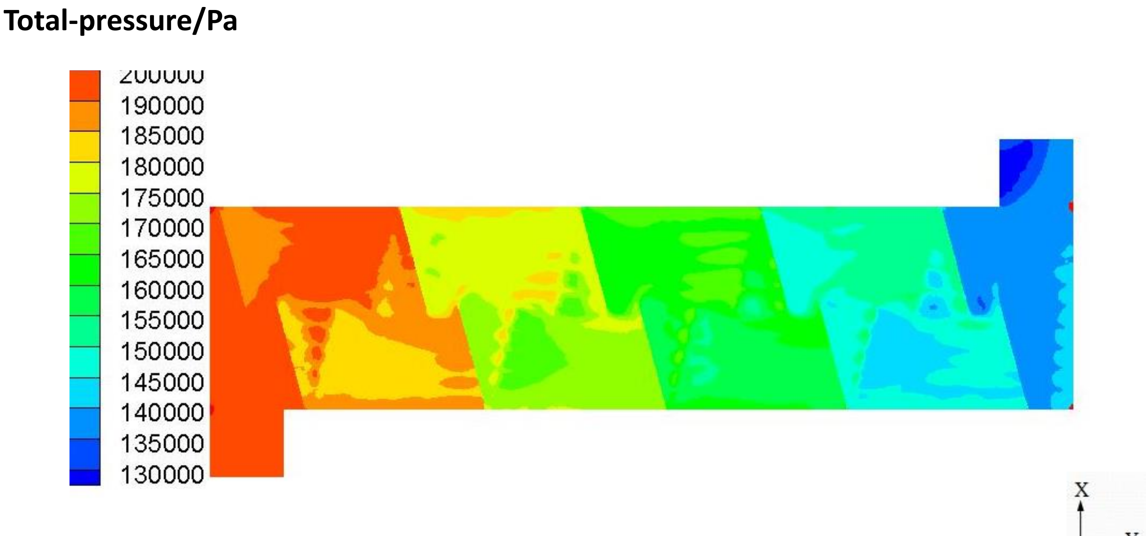


Fig. 5 total pressure distribution along Z direction

The results show that the total pressure loss is 32% in the shell side and 2.9% in the tube side. The pressure loss of shell side fluid is large, and the main reasons are as follows:

(1) the shell of the heat exchanger is a rectangle, the fluid flows helically in the flow section of the rectangle, and there will be a 90 ° bending angle at the boundary, and there will be a great loss of momentum.

(2) from the above analysis, it can be seen that the existence of spiral baffle also causes some flow resistance to the shell side fluid air.

2.1.3 Fluid velocity distribution in shell side of heat exchanger

Fig. 6 shows the velocity distribution of the fluid in the shell side of the heat exchanger in the y-direction. The velocity distribution in the y-direction is v_z, and the velocity distribution in the y-direction is vz, and the velocity distribution in the shell side of the heat exchanger in the y-direction is $\vec{v}_{xy}$.

From the velocity distribution in Fig. 6, it can be seen that the circumferential velocity component v_x and v_y and the axial velocity component vz exist at the same time, which indicates that the fluid flow in the heat exchanger has both rotational flow and longitudinal flow.

The distribution of the axial velocity component v_z can be seen from the velocity cloud diagram: (1) the velocity of the central part is higher than that of the surrounding part, which shows that the longitudinal flow of the heat exchanger is mainly completed in the middle part of the heat exchanger, the longitudinal velocity of the fluid near the wall of the heat exchanger is very small. (2) when the shell-side fluid flows to the baffle, the shell-side fluid is subjected to a large flow resistance, where the longitudinal flow velocity is very small, most of the fluid flows away from the gap at the side of the baffle, and a high-speed flow zone appears near the center.

The distribution of the circumferential velocity $\vec{v}_{xy}$ can be seen in the velocity vector diagram:

(1) because of the guide effect of Baffle, there is obvious secondary flow in the heat exchanger, which makes the air scour the heat exchanger tube bundles vertically, and forms the staggered flow pattern, which is more advantageous to the full heat transfer of the cold and hot medium.

(2) at the center, the gap formed by the installation of the baffle causes the high-speed flow, the distribution of $\vec{v}_{xy}$ is consistent with that of the v_z, while in the wall region of the heat exchanger, the v_z is small but the value is still high, which indicates that the Longitudinal flow is hindered in this region, the spiral flow with higher velocity is formed, and there is no flow stagnation in the wall and corner of the heat exchanger, so the flow dead zone is effectively reduced.

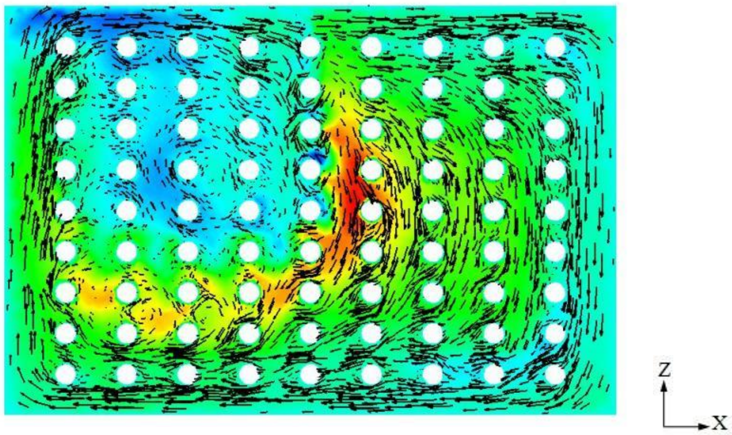


Fig. 6 Velocity cloud and vector along Y direction

3.2 Heat transfer performance analysis of discontinuous spiral baffle heat exchanger

The heat transfer coefficient of the whole heat exchanger is k = 344.4 W/(M2 · K) . The heat transfer performance is good and meets the design requirements.

The distribution of temperature field in x and y directions of the heat exchanger is shown in figure 7 and 8 respectively. Here, the absolute temperature is dimensionless treated by the following formula, that is, the dimensionless temperature $\bar{T}$ is:

$$\bar{T} = 1 - \frac{T_{\max} - T}{T_{\max} - T_{\min}} \qquad (3)$$

T_{max}——Maximum internal temperature of heat exchanger

T_{min}——Minimum internal temperature of heat exchanger

It can be seen that: (1) the temperature of the air flow through the baffle decreases obviously, because the baffle leads the air to form a spiral secondary flow, which scours the heat exchange tube vertically and improves the heat exchange effect. (2) the fluid temperature near the central shaft of the Heat Exchanger is higher than that around it, because the area of the combined gap of the baffle plate is the largest near the central shaft, the Air Flow Velocity is the fastest, and the direction of the flow is basically parallel to the tube bundle, these reasons lead to the poor heat transfer effect and high temperature in such areas.

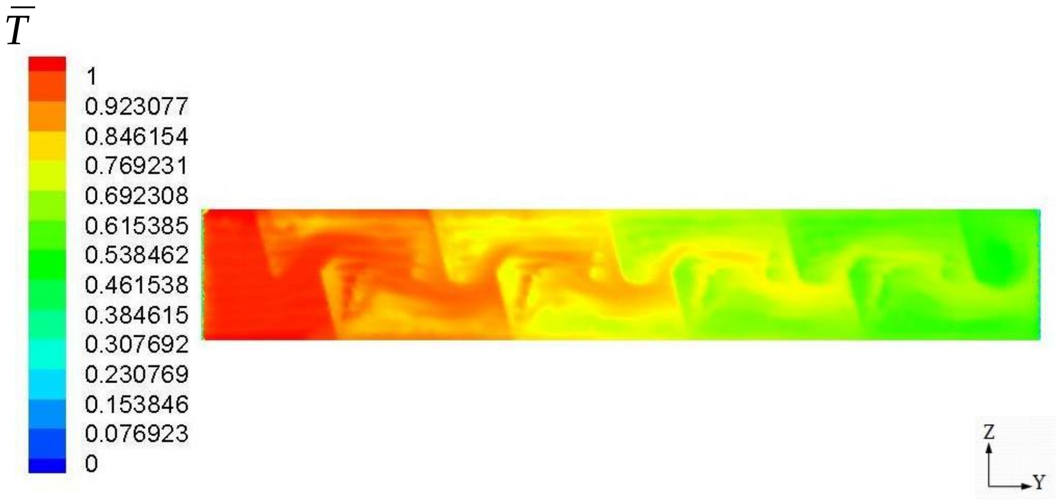


Fig. 7 dimensionless temperature field distribution diagram along X direction

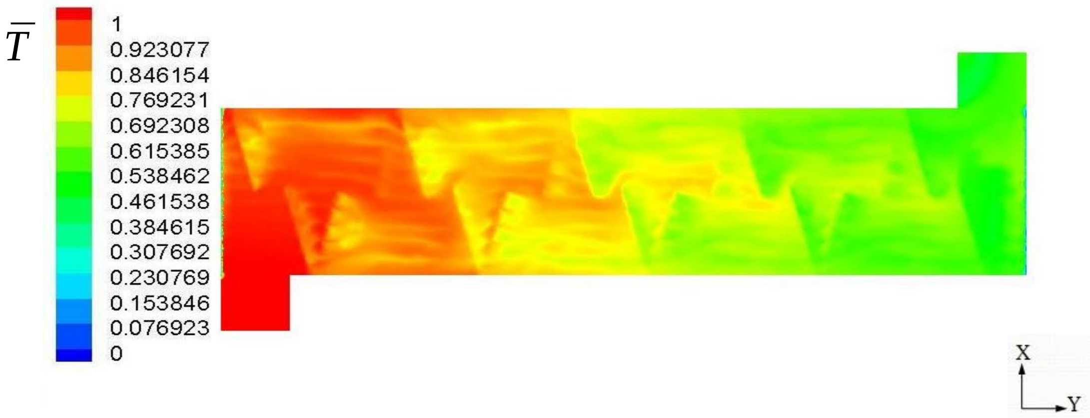


Fig. 8 dimensionless temperature field distribution diagram along Z direction

3.3 Wall cooling of discontinuous helical baffle heat exchanger

Because the inlet temperature of the heat exchanger is very high. if the wall of the heat exchanger is not cooled, there is a danger that the metal wall material will be burnt. Therefore, it is necessary to design a heat transfer system for the side wall of the heat exchanger, or arrange the cooling runner, so that the wall temperature is kept below the safe working temperature of the material. For the spiral baffle heat exchanger, the wall cooling is shown in Fig. 9, and the surface temperature distribution after cooling is shown in Fig. 10. Most areas are between 400K and 500K, and only a few areas reach 800K.

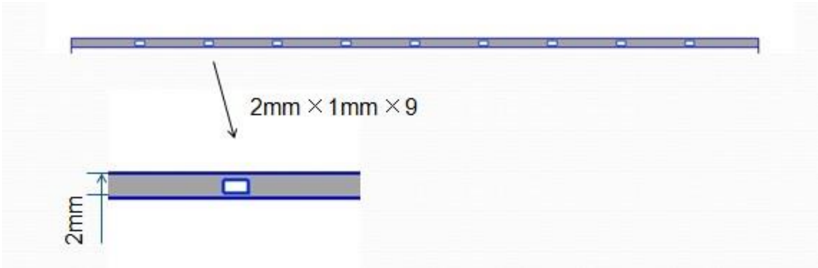


Fig. 9 Wall cooling runner

Although the wall temperature remains within the working range of the material after the wall is cooled, it can be seen that the heat exchange tubes in the spiral baffle heat exchanger are not connected to the wall, so additional oil circulation must be provided to cool the wall, the Wall Cooling oil circuit and the internal heat exchange oil circuit can not be connected as a whole. This not only makes the distribution of the coolant more complicated, but also makes the arrangement of the cooling channel in the wall more difficult. If the channel section is small, the kerosene is liable to coking and blocking the channel If the channel section increases, the thickness of the heat exchanger wall will also increase, which will increase the size and weight of the heat exchanger.

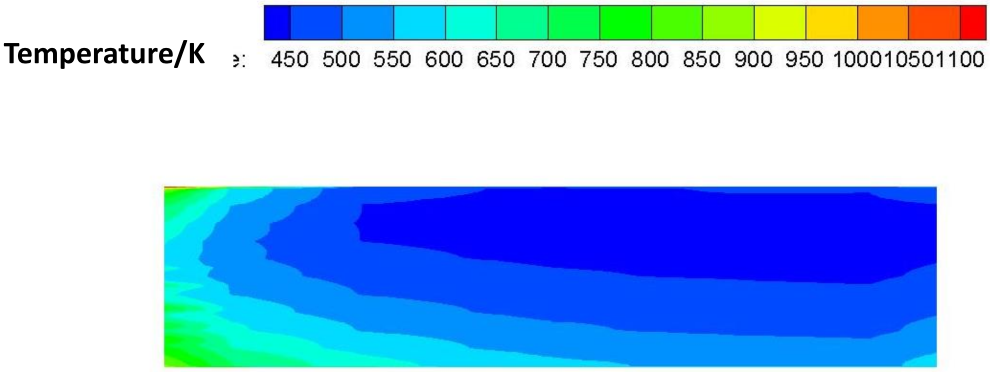


Fig. 10 temperature distribution of the wall after cooling

4. Conclusion

In this paper, a discontinuous helical baffle heat exchanger with wall cooling is studied by combining numerical simulation with engineering calculation. Firstly, the heat transfer parameters are calculated and the calculation model is designed: Then, the performance of the heat exchanger is simulated by numerical simulation, finally， the wall cooling is studied preliminarily. The conclusion is as follows:

(1) the shell side fluid of the discontinuous spiral baffle heat exchanger flows in a spiral shape, which can effectively eliminate the"Flow dead zone" caused by the traditional baffle and enhance the heat transfer effect of the heat exchanger, the temperature drop of the air cooled by the heat exchanger is about 38% of the original air flow temperature, and the overall heat transfer coefficient of the heat exchanger is k = 344.4 W/(M2 · k) , to meet the design requirements;

(2) the total pressure loss of the fluid air in the shell side is larger than that in the other side, up to 30% . Part of the pressure loss is caused by the shape of the shell of the heat exchanger cuboid, and the flow resistance is increased by the rectangular flow section, the other part of the loss is caused by the presence of spiral baffles.

(3) the surface temperature of the spiral baffle heat exchanger, which is designed for Wall Cooling, is

mostly between 400K and 500K after cooling.

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The first author, Pan Jin, has a long history of fluid mechanics work and has been involved in a number of projects funded by the National Natural Science Foundation of China (NSFC) , including 863,973 projects. Published more than 10 academic papers, EI included six, a patent for authorized invention, utility model patents and four transformation.