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Study on Numerical Simulation of Spirality Inserted Piece for Heat Exchanger

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Abstract

Heat exchanger is widely used in energy, power, chemical, metallurgy, machinery, transportation, aerospace and other fields. Heat exchanger with spirality inserted piece is a new type of energy-efficient developed on the basis of traditional shell and tube exchanger. In this paper, the numerical simulation method is used to prove that the spirality inserted piece heat exchanger tube has the characteristics of enhanced heat transfer. At the same time, the finite element model of the spirality inserted piece heat exchanger is used to simulation and analyze. And compared with the heat exchanger without this structure, the influence of size parameters of spirality inserted piece pitch on fluid motion and heat transfer in tube is obtained. Indicating the advantages and characteristics of heat transfer compared with traditional shell and tube exchanger. By comparing the different pitch of the heat exchanger pipe, get the relationship between spirality inserted piece pitch and heat transfer performance of pipe.

Key words

numerical simulation, heat exchange tube, finite element, spiral inserted piece

1. Introduction

In the last century, the world energy crisis has effectively promoted the development of enhanced heat transfer technology. In order to save energy and reduce consumption, improve economic benefits of industrial production. Requiring the development of high performance heat transfer equipment suitable for different industrial processes [7]. Heat exchanger with spirality inserted piece is to meet the needs of modern production, a new type of energy-efficient developed on the basis of traditional shell and tube exchanger [8].

Heat exchanger tube heat transfer technology which used in industry is mainly to strengthen reasonably the basic heat transfer element, namely using finned tube to enhance heat transfer [10]. The fins have a significant effect on enlarging the heat transfer area and improving the flow state of the fluid. Whether it is for single-phase convective heat transfer or with phase change has great application value [3]. Finned tube as an effective heat transfer enhancement elements in the use of heat exchangers more and more widely. Especially the heat transfer coefficient on both sides of the larger difference, the enhanced heat transfer effect is more prominent. The fin spacing has a significant effect on the heat transfer coefficient, the smaller the fin spacing, the greater the surface area of the expanded heat transfer, the higher the heat transfer coefficient. But the fin spacing to a certain short extent, the flow resistance is great, and the tube vortex will be suppressed by the wall effect of the fin. At this time the turbulence in the inter-fin flow field will be greatly reduced, there will be a certain degree of influence on the heat transfer. The fin spacing has different influence on the flow and heat transfer behavior [12]. Therefore, for certain constraints, there is the best value of enhanced heat transfer in the fin spacing.

Based on the above analysis of the mechanism of heat transfer enhancement of swirl and fin, the spirality inserted piece is used to strengthen heat transfer for heat exchanger. Spirality inserted piece is inserted into the heat transfer tube to change the fluid flow direction [1]. The resulting vortices produce a large change in the flow field in the heat transfer tubes. It breaks the original flow field structure and strengthens the tube heat transfer, so that heat transfer performance is greatly enhanced.

2. The structure and advantages of heat exchanger with spiral plug-in

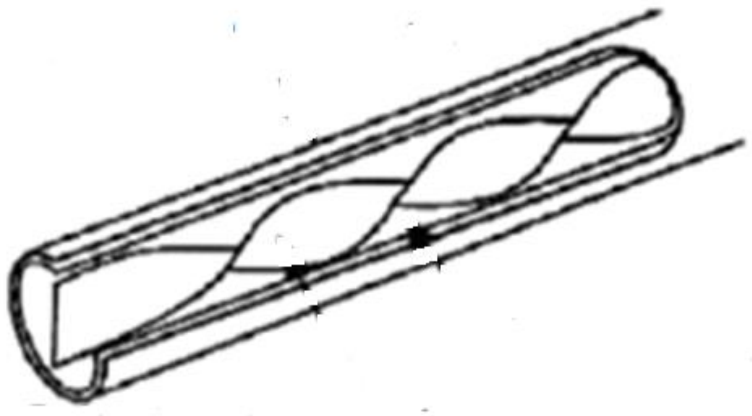

Fig.1 Spirality inserted piece heat transfer tubes

As shown in Figure 1 is the analyzed heat exchanger spoiler model, it is a further improvement on the basis of predecessors summarized. The improved spirality inserted piece manufacturing process is much easier, not only reduces the cost, improves the production efficiency, but also improves the heat transfer efficiency [6]. Since the large helical curved surface including the entire tube bundle, which is difficult to manufacture, is simplified into a spiral insert which can be easily manufactured and embedded in each tube. The laminar motion of the fluid on the tube side becomes a number of localized helical turbulent flows [9]. Furthermore, the spirality inserted piece may be formed by twisting an ordinary thin steel sheet, low cost, low energy consumption, and can get a better heat transfer enhancement effect.

3. Fundamentals of Numerical Simulation

3.1 Mathematical Model Establishment

Fluid flow is governed by the laws of conservation of matter. In the numerical analysis of unit basin, it is necessary to satisfy the three basic governing equations of mass conservation equation, momentum conservation equation and energy conservation equation [13]. While the flow is in a turbulent state, the fluid should also be consistent with the turbulent transport equation.

Mass Conservation Equation:

Any flow problem must satisfy the law of conservation of mass. The mass conservation equation is also called the continuity equation, which can be expressed as: the mass increase in the fluid microcomponent per unit time, which is equal to the net mass flowing into the microcells at the same time interval [2]. The equation is as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

In this formula, ρ is the density, *u, v, w* is the component of velocity vector *u* in the *x, y, z* directions.

Momentum Conservation Equation:

Momentum conservation equation is also called motion equation. The law can be expressed as: micro-body fluid in the momentum of the rate of change is equal to the external role of the micro-body in the sum of the various forces [5]. For Newtonian fluid, the momentum conservation equation is as follows:

$$\frac{\partial(\rho u)}{\partial t}+div(\rho u u)=div(\mu \cdot grad u)-\frac{\partial P}{\partial x}+S_u \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t}+div(\rho v u)=div(\mu \cdot grad v)-\frac{\partial P}{\partial y}+S_v \tag{3}$$

$$\frac{\partial(\rho w)}{\partial t}+div(\rho wu)=div(\mu\, gradw)-\frac{\partial P}{\partial z}+S_w \tag{4}$$

In this formula, symbols S_u, S_v and S_w are the generalized source term of momentum conservation equation, $s_u=F_x+s_x$, $s_v=F_y+s_y$, $s_w=F_z+s_z$.

Energy Conservation Equation:

The law of conservation of energy is a basic law that must be met by a flow system containing heat exchange [4]. The law can be expressed as: The increase rate of the energy in the micro-element is equal to the net heating flow into the microelement plus the work done by the volume force and area force on the microcell. The law is actually the first law of thermodynamics, the energy conservation equation with the temperature T as a variable has the following form:

$$\frac{\partial(\rho T)}{\partial t}+div(\rho \vec{u} T)=div(\frac{k}{c_p}gradT)+S_T \tag{5}$$

In this formula, ρ is the density, c_p is the specific heat capacity, T is the temperature, k is the heat transfer coefficient of the fluid, s_t is the internal heat source of the fluid and the part where the mechanical energy of the fluid is converted to heat due to the viscous action.

Turbulence model:

Numerical calculation of turbulent flow and heat transfer is one of the most active fields in computational fluid dynamics and computational heat transfer. The improved RNG $k-\varepsilon$ model in the turbulence model can fully reflect the flow field in the rotating helical twist pipe [11].

The k, ε - transport equation of RNG $k-\varepsilon$ model is:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[(\alpha_k\mu_{eff})\frac{\partial k}{\partial x_j}\right]+\mu_t S^2-\rho\varepsilon \tag{6}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[(\alpha_k\mu_{eff})\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}\mu_t S^2-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon \tag{7}$$

$$R_\varepsilon=\frac{C_v\eta^3(1-\frac{\eta}{\eta_0})}{1+\beta\eta^3}\frac{\varepsilon^3}{k} \tag{8}$$

In this formula, μ_{eff} is the effective turbulent viscosity coefficient, the term $\mu_t S^2$ is the turbulent energy generation term. Among them, $S=\sqrt{2\bar{S}_{ij}\bar{S}_{ij}}$, and $\bar{s}_{ij}=\frac{1}{2}(\frac{\partial u}{\partial x_j}+\frac{\partial u}{\partial x_i})$ is the average strain rate tensor coefficient, $\eta=\frac{Sk}{\varepsilon}$, the dimensionless strain or the ratio of the mean flow time scale to the turbulence time scale. η_0=4.38, β=0.012, C_v=0.0845.

RNG $k-\varepsilon$ model has good stability and convergence in numerical calculation. Compared with the standard $k-\varepsilon$ model, its calculation is increased by only 10% to 15%, while the accuracy of calculation and scope of application has been greatly improved.

3.2 Establishment of Solid Model

Spirality inserted piece is formed by twisting steel sheet, in this paper, the pitch of spirality inserted piece of heat exchanger is 420mm, its structure is a very complex distortion of the pieces. Due to the cross-section in the process of drawing the image, the finite element software ANSYS is difficult to be used for automatic modeling process. And it is not easy to operate in the process of meshing. But the three-dimensional software Pro/E has a strong solid modeling capabilities, a good solution to the above modeling difficulties. With Pro/E to create inserted piece solid model as shown in Figure 2. The analyzed object of this paper is the change of air flow field and temperature field in the heat exchanger tube, therefore, the solid part of air must be established in the establishment of the finite element model. Fluid and thermal analysis in ANSYS can be directly loaded to the surface or surface of the node. To make the analysis simpler, the air portion is directly modeled as a solid, omitting the heat exchanger tube wall and inserted piece solid model, which can simplify the solid model. Which facilitates the establishment of finite element model, meshing and reducing the workload of analysis, improves the speed of finite element analysis, and can guarantee the accuracy of analysis. Finally, the establishment of solid model shown in Figure 2.

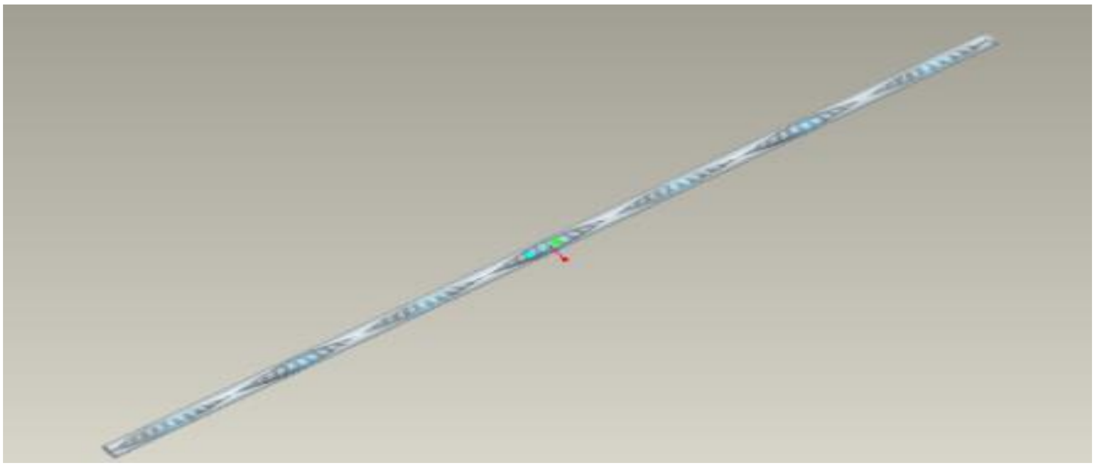

Fig.2 The model of spirality inserted piece heat exchanger

3.3 Solid Model and The Connection of Finite Element Software

Finite element analysis software ANSYS and three-dimensional modeling software Pro/E has a good convergence capacity. Dimensional model built with Pro/E can not be directly processed by third-party software into the ANSYS for analysis. Finite element software ANSYS provides a powerful meshing function, for different shapes of the entity can use a variety of division method, however, the merits of each method depends on the analyst's expertise and practical experience to determine. The flow field and temperature field of a heat exchanger tube with spirality inserted piece were analyzed. Three-dimensional element ANSYS fluid 142 can be greatly used to meet the analysis requirements. The meshing method adopted is divided freely, free meshing not only can get regular grid, but also has the advantages of fast and high efficiency that other meshing methods can not match. In the process of complex model analysis, the advantage of saving time is more obvious. And the regular grid has a great influence on the simulation results, the results of the model meshing are shown in Fig 3. In the process of meshing, there is usually a somewhat inferior quality of the grid, need to be amended artificially. This can make the calculation results more accurate, speed up the calculation speed, poor grid quality affects the simulation results minimally. The divided overall structure of the model after the mesh correction is shown in Fig 3.The refinement degree of the mesh directly affects the speed of solution and the accuracy of the results. Due to the limitations of computer hardware and the need for solving, in the process of meshing, the grid size and the number of nodes are strictly controlled. After dividing the grid, the number of meshes is 52534 and the number of nodes is 13626.

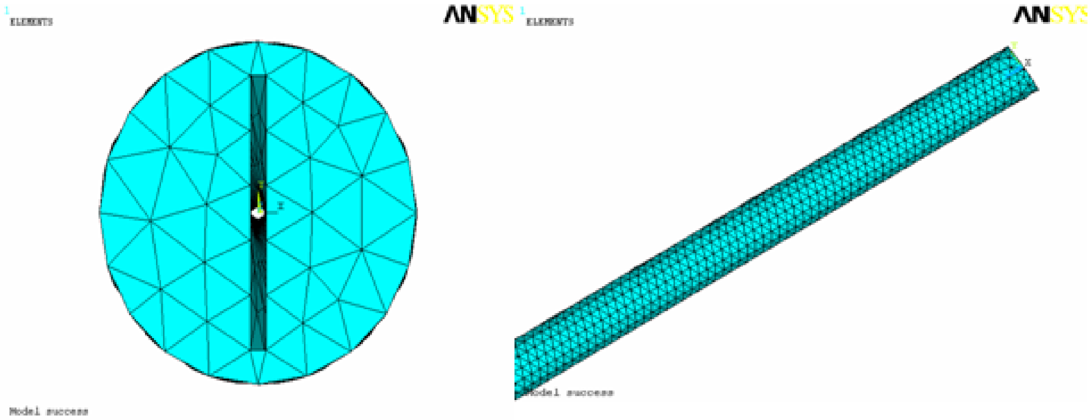

Fig.3 The revised meshing of the whole and end face

4. Numerical Simulation of Spirality Inserted Piece Heat Exchanger

4.1 Model Load Application

The operating conditions of the heat exchanger are that the flue gas passes outside of heat transfer tube wall, at the same time the heated air having a low temperature flows through the inside of the heat transfer tube. As the outside of the entrance of the flue gas temperature is extremely high, the temperature will be significantly reduced before it reaches the outlet through the outer tube wall, and the tube wall receives a lot of heat. Due to the temperature gradient of the larger changes, the wall temperature of the heat transfer tube between the inlet and outlet of the flue gas follows a complex rule, this poses a great challenge to the application of the load. To this end, we have to introduce the function of the editor and loader to ensure that the raising of wall temperature is consistent with the wall temperature changes in the law.

The results of the load function of the external surface temperature of the heat transfer tubes:

First, use the function editor to create any equation or function, and then use the function loader to load the function, use function definition table parameters. Then the table parameters can be applied to the model, that is, the table parameter boundary conditions. In order to obtain the relationship of the heat transfer tube surface and the path of flue gas. The following assumptions are made:

At the inlet and outlet of the flue gas, the temperature of the outer surface is only related to the temperature of the flue gas, not affected by the inlet air temperature, which is there is no temperature change at the inlet and outlet.

The temperature at the node surface of the heat transfer tube is as same as the temperature at the same distance from the end face, has nothing to do with the flue gas conditions but position, and the temperature remains constant.

The temperature value of the outer surface of the heat transfer tube and the direction of flue gas flowing along the surface of the heat transfer tube as a function of the relationship:

$$T = 50 \times Z^2 - 300 \times Z + 700 \tag{9}$$

In this formula, T is the temperature at the surface of heat transfer tube, Z is the distance of the surface of the heat transfer tube from the inlet interface. After applying the load, the temperature profile is shown in Fig 4.

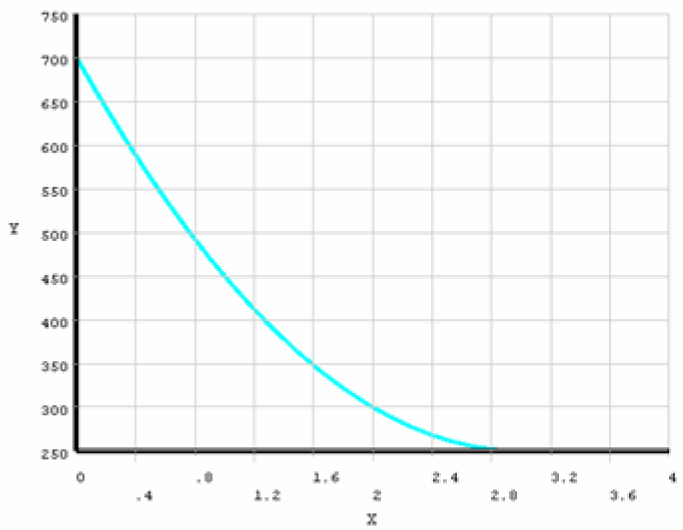

Fig.4 The trend graph of the function loading temperature

The abscissa x represents the distance of the outer surface node of the heat exchanger relative to the end surface, and the ordinate y represents the temperature value corresponding to the outer surface node of the heat exchanger. The trend of temperature from the picture is very clear to see, as the distance of flue gas flowing into the heat exchanger tube increases, the external surface temperature of the heat exchanger tends to decrease. The inlet temperature is about 700 degrees Celsius and the outlet temperature is about 250 degrees Celsius. The temperature distribution of the outer surface of the heat transfer tube after loading is shown in Fig 5.

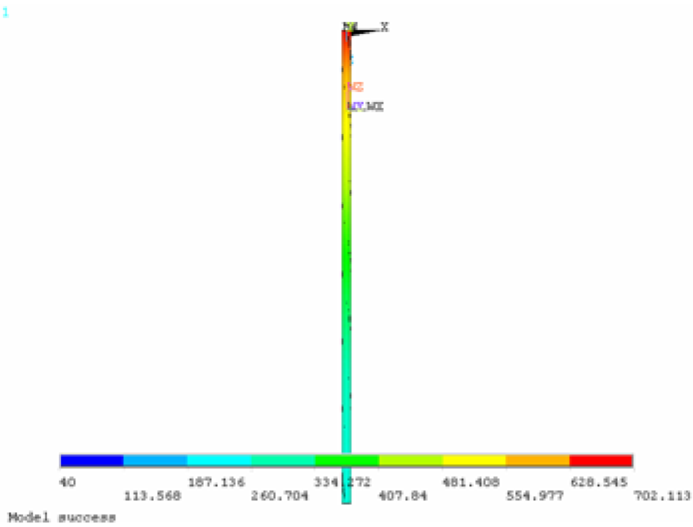

Fig.5 The temperature distribution of the outer surface of the heat exchanger

The results of the load function of the inner surface temperature of the heat transfer tubes:

Before solving the temperature distribution of the spirality inserted piece of the heat exchanger, the following assumptions are made:

The air at the interface with the plug is taken to calculate the average temperature.

Inserted piece temperature only depends on where the node is located. And does not take into account the temperature of plug-in with the air flow transient changes, the surface temperature remains constant during heat transfer.

The temperature of the inserted piece surface is only dependent on the distance from the end face. The temperature of the flue gas is assumed to be stable, the surface temperature of the heat transfer tube is not affected by the operating conditions. The temperature value remains constant and there is no temperature abrupt change at the air inlet and outlet.

The function relationship between the surface temperature values of the spirality inserted piece and the air flow direction is as follows:

$$T = \frac{-25}{3} \times Z^2 + \frac{175}{3} \times Z + 100 \tag{10}$$

In this formula, T is the temperature of inner inserted piece of heat exchanger, and Z is the distance between the surface of the spirality inserted piece of the heat transfer tube and the inlet interface. The temperature profile of the surface of the heat exchanger spirality inserted piece after application of the load is shown in Fig 6.

The abscissa x represents the distance of the spirality inserted piece surface node relative to the end surface, and the ordinate y represents the temperature value corresponding to the node on the spirality inserted piece surface. From the figure can be very clear that the temperature trends, as the distance of flue gas flowing into the surface of the heat transfer tube increases, the temperature tends to increase gradually. The inlet temperature is approximately 100 degrees Celsius, and the plug-in temperature at the outlet is around 210 degrees Celsius.

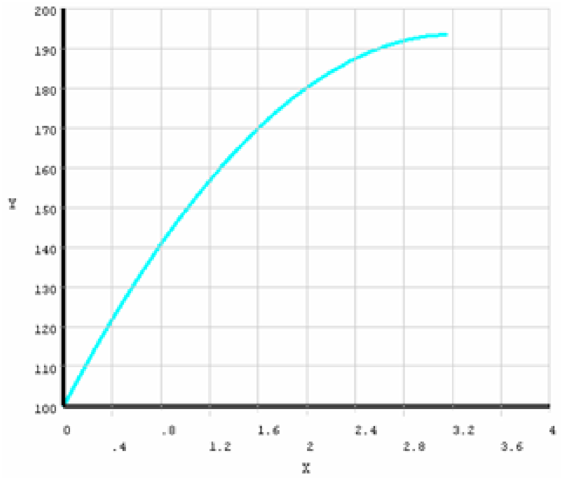

Fig.6 Temperature profile spirality inserted piece surface

Application of other load conditions: The air temperature at the inlet of the heat exchanger tube can reach 40 degrees Celsius with the heating by heat exchanger casing, the inlet temperature was set at 40 degrees Celsius when a finite element load was applied. There is a certain pressure difference between the inlet pressure and the outlet pressure, according to the actual operating conditions, the pressure difference is about 200Pa. According to the actual situation, set the heat exchanger tube outlet air pressure to 0Pa, inlet air pressure to 200Pa. The preheated air has a certain initial velocity as it flows into the heat exchanger tube with the spirality inserted piece. According to the physical model of the calculation results, an inlet wind velocity perpendicular to the cross section is set at the inlet of the heat transfer tube at 14 m/s.

4.2 Analysis of Temperature Field of Heat Exchanger with inserted piece

Fig 7 sectional view of the air temperature at a distance of 0.5 m from the inlet end face, the inlet air temperature is 40 degrees Celsius, the temperature of the gas near the tube wall can reach

600 degrees Celsius or more at the entrance to 0.5 m. The temperature of the air near the wall rises abruptly, the density is sharply reduced, will form a strong local air convection with the central part of the heat exchanger. At the same time the air flows in the direction of the tube wall to produce spoiler, hot and cold air mixing, and the local temperature is increased, temperature at wall decreases.

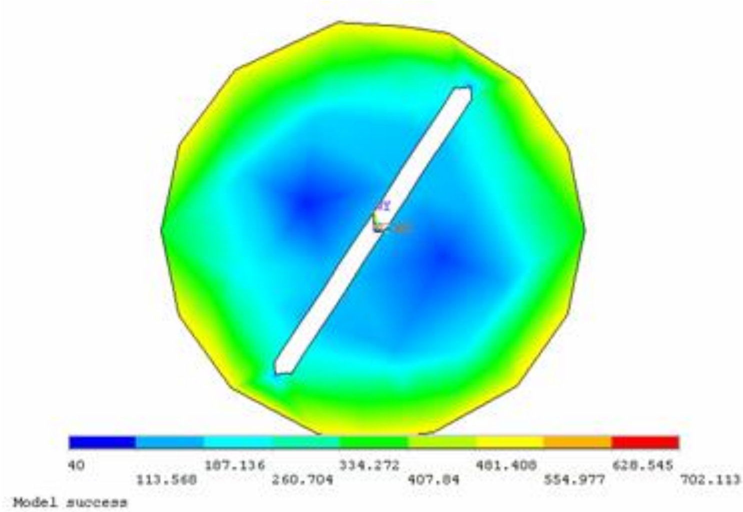

Fig.7 0.5 m from the entrance at the temperature of the air

At the inlet, most of the air near the middle of the tube is in a low temperature (the blue region in Figure 8), the gas near the wall is at a local high temperature. With the air to the internal flow of the process, the air temperature at the wall surface is rapidly increased and the density is lowered, air away from the wall to form a density difference and temperature difference, promote the formation of spoiler. The turbulence in the tube causes the local eddy current to flow continuously, and the high-temperature gas at the wall surface is brought to a low temperature. Low temperature gas flow to the wall at high temperatures, high and low temperature gas in the blending state, the temperature distribution tends to be uniform.

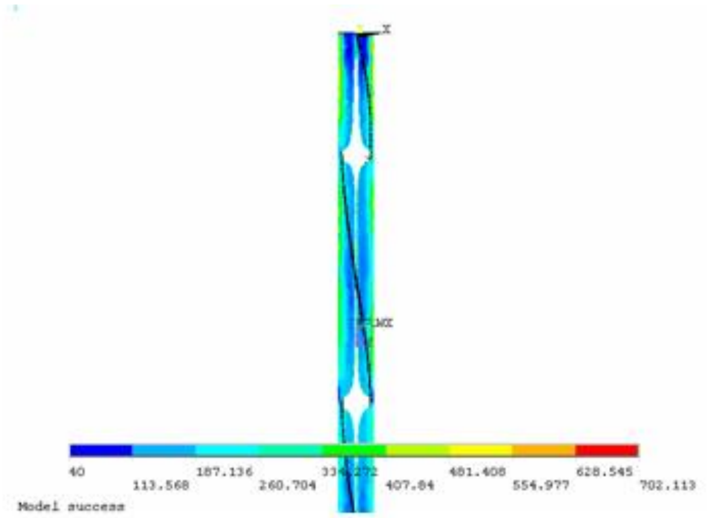

Fig.8 The air temperature distribution profile

Figure 9 is the temperature distribution of air at the outlet of the heat transfer tube, can still be seen that the overall temperature of the air is divided into local high temperature and low temperature gas mixture situation. The temperature of the gas is between 70 degrees Celsius and 270 degrees Celsius. Compared to the temperature distribution at the inlet, the phenomenon of local high temperature becomes no longer obvious, the temperature difference has been reduced with the heat transfer. The average temperature of the air at the outlet also reaches the highest value during the heat exchange process.

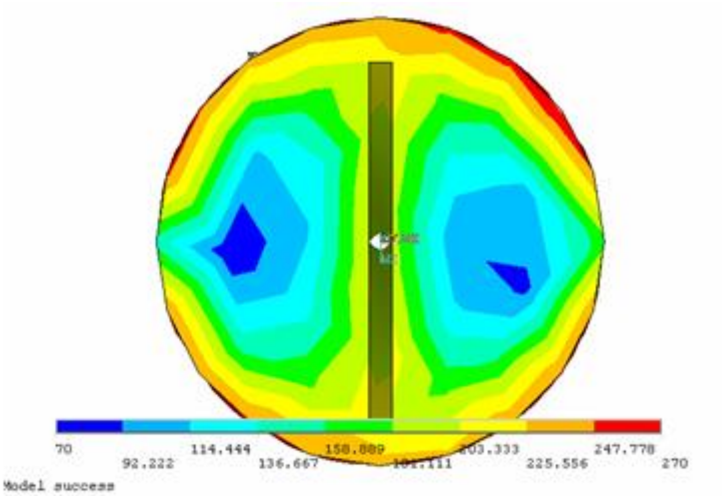

Fig.9 Temperature distribution of gas exports

4.3 Analysis of The Flow Field of Spirality Inserted Piece Heat Exchanger

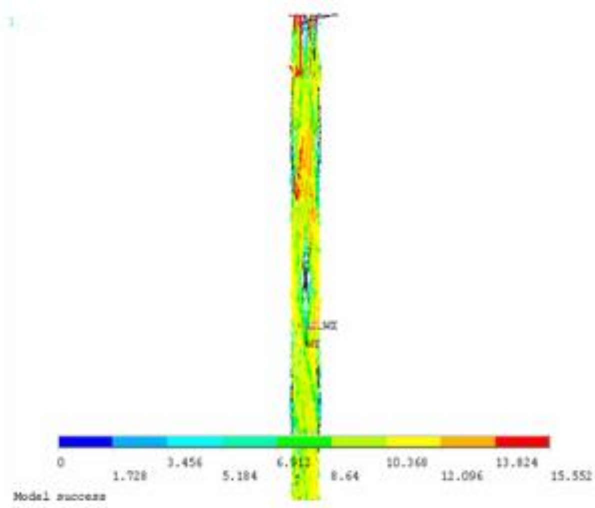

Fig.10 Speed track plans

Figure 10 shows the flow velocity traces. The velocity load applied at the inlet is perpendicular to the inlet cross-section and the velocity value is 14 m/s. The air flows into the heat transfer tube, and the gas near the wall is rapidly heated, the trajectory speed of individual nodes will be increased. In the course of the flow, there is a spoiler of spirality inserted piece and the obstruction of the wall to the fluid. In the x,y direction will produce speed components, The average value of the axial velocity in the z-direction decreases. The velocity of the local air flow is increased, and the maximum wind speed is 15.552 m/s. The gas passes through the heat transfer tubes in the direction of rotation of the spirality inserted piece. In this process compared with the straight tube, flow direction of the flow has been significantly changed. In the heat transfer tube not only the average speed has been reduced, the flow path distance has also been lengthened. Significantly increases the residence time of the fluid in the heat transfer tube, so that heat transfer performance is improved.

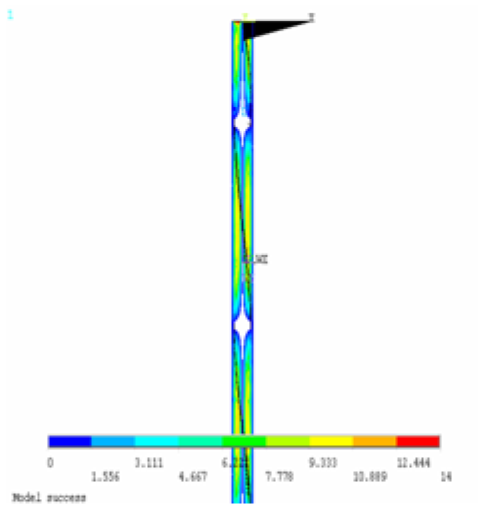

Fig.11 Speed distribution of gas

Fig 11 is a helical inserted piece heat exchanger tube flow field vector, it can be clearly seen in the figure that the gas flow rate at the wall of the tube wall and the spirality inserted piece wall is significantly reduced, and the gas flow velocity at the center of the heat transfer tube is also weakened. The average flow rate down to 10 m/s or so, the overall gas flow rate was significantly reduced.

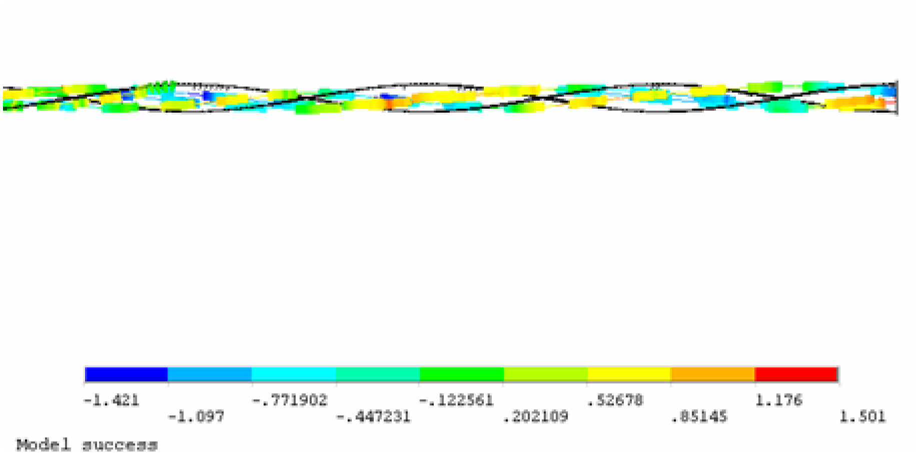

Fig.12 Y direction speed particles plans

Fig 12 is the y-direction velocity particle of the gas flow field in the heat transfer tube, the velocity is positive along the y-axis positive direction. It can be seen that the velocity in the y-direction is from -1.421 m/s to 1.501 m/s, there is only the z-axis speed when the air enters the heat transfer tube. Due to the action of the helical insert and the presence of local eddy currents, So that the speed of air in the y-axis direction of the value has been changed, gas in the process of flowing around the central axis of the heat transfer tube to produce rotary motion. The tendency of air flow is rotated in the direction of rotation of the spirality inserted piece surface. In the process of gas flow, not only the speed of rotation but also the local eddy currents associated with the gas, can take away the high-temperature gas near the wall, increase the temperature difference of the surface of the heat transfer tube and improve the heat transfer efficiency of heat exchanger surface. At the same time due to the presence of the fluid along the y-axis flow velocity, there is a strong erosion on the wall, to prevent wall scaling.

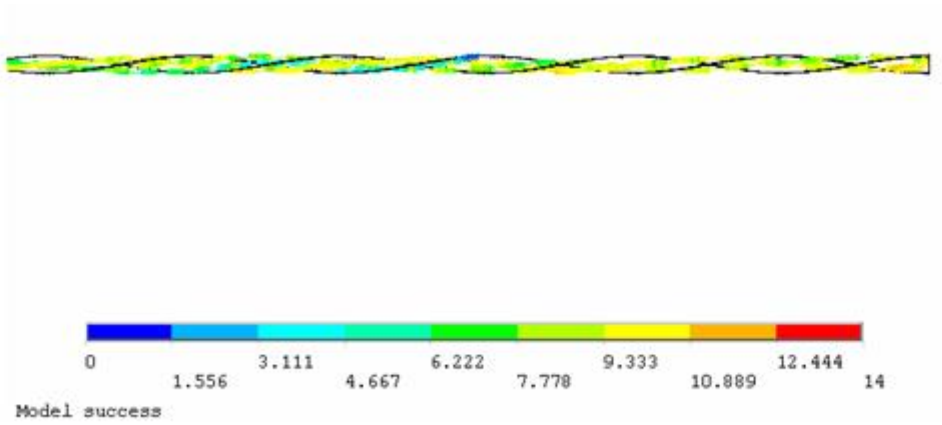

Fig.13 Z direction speed particles plans

Fig 13 is the particle in the z-axis direction, in the overall process of heat transfer, the gas velocity in the z-axis direction tends to decrease, And the main direction of rotation of the gas flow is the same as the direction of rotation of the spiral insert.

5. Conclusion

In this paper, by proper assumptions of the model, the physical model and the mathematical model of spirality inserted piece are given. Using solid modeling software and finite element software, a reasonable analysis model of the heat exchanger is established, the flow field and temperature field of a spirality inserted piece heat transfer tube with a helical pitch of 420 mm were simulated by the method of loading the function, inferred:

In the case of a heat transfer tube passage which is not provided with a screw-type insert, after adding the plug-in, the turbulence of the fluid near the heat transfer tube increases. The flow characteristics of the gas at the exit of the temperature distribution is more uniform, the effect of the boundary layer near the wall of the heat transfer tube is relatively weakened.

In the process of gas flow, spirality inserted piece spoiler makes the heat transfer tube near the heat fluid micro-mission continuously away from the heat transfer wall. The mixing of cold and hot fluids is obvious, So that the temperature in the vicinity of the heat transfer tube can always be maintained at a relatively low temperature, to ensure a higher heat transfer temperature, heat transfer is enhanced.

Due to the presence of spirality inserted piece, the swirling flow produced by Spiral piece, that on a heat transfer tube adjacent to a heat transfer tube, scouring it obliquely. It can aggravate turbulence near the wall of the fluid, destroying the formation of wall scaling conditions.

In the spiral channel, high-temperature fluid micro-groups are constantly taken away from the heat transfer wall, along the flow direction in the intermediate channel. Therefore, the enhanced heat transfer produced by the helix is a complex and integrated effect.

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