Effects of the Fouling on the Convective Heat Transfer Field

Synergy in Round Tube

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Abstract

Numerical simulated for the tube of different scale thickness, and analysis the fouling effect for the velocity and temperature fields and their synergism number and synergism angle. The numerical simulation results show that, in the laminar flow and turbulent flow condition, the average field synergism number increases with the increases of fouling thickness, but decreases with the increases of Reynolds number, while average synergy angle is opposite. The synergy number is greater in turbulent flow than in laminar flow, while synergy angle is less in turbulent flow. The local synergy numbers decrease gradually in the axial direction when the flow is turbulent flow. For the synergy number, the decreased velocity is fastest in entrance region and the change of velocity becomes flat after fully developed flow. In entrance region the local synergy angle increases gradually in the axial direction. The flow starts to become fully-develop turbulent flow in 0.04m, and local synergy angle reaches a certain value gradually. The results can be used to enhance heat transfer and improve the heat transfer coefficient more effectively.

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Keyword: field synergy principle; field synergism number; fouling; convection heat transfer

1. Introduction

Heat exchangers are widely used in chemical, oil refining, power, and many other industries, however, when the device is running, the fouling sediment will inevitably attached to the surface of the heat transfer, and scaling phenomena occurring, it seriously hampering the normal operation of heat exchanger. So the fouling research is of great significance. Professor Xu Zhiming, etc. analyzed the economic losses of condenser fouling based on actual survey data [1]. In the relevant literatures, scholars
have considered the effect of coordination of velocity field and thermal field on the convective heat transfer field synergy in round tube [2]. On this basis, this theory applied the field synergy principle to numerical analysis of the convective heat transfer field synergy in round tube, examining the effect of fouling on the field synergy in round tube. Understanding the effect of fouling on fields in the heat exchanger tubes from whole convection heat transfer field, not only conducive to enhanced heat transfer and more effectively improve the heat transfer coefficient, but also has less resistance than existing heat transfer enhancement technology which conducive to energy conservation and engineering applications.

2.Field Synergy Enhanced Heat Transfer Principle

Chinese scholars Guo Zengyuan and his collaborators proposed the field synergy principle for increase the rate of convective heat transfer by analyzed boundary layer heat transfer mechanism in the year 1998. Literature [4] indicated that convection heat transfer not only depends on fluid velocity, physical properties and solid wall temperature, but also depends on the velocity and heat flow field synergy level. At the same speed and temperature boundary conditions, the higher synergy level they have, the better heat transfer intensity there are. The synergy angle described the synergy level of the velocity field and heat transfer field can be expressed as:

$$\alpha = a \cos \frac{\mid \vec{U} \mid \cdot \mid \nabla \vec{T} \mid}{\vec{U} \cdot \nabla \vec{T}}$$ (1)

Where $\alpha$ is the angle of velocity and temperature gradient vectors (heat flow vector).

The average synergy angle of the overall area as in

$$\bar{\alpha} = \sum \frac{A_i \theta_i}{\sum A_i}$$ (2)

Where $A_i$ is the area of each control volume, m²

The field synergism number is:

$$F_c = \int \frac{\mid \vec{U} \cdot \nabla \vec{T} \mid d y}{\frac{Nu}{Re \cdot Pr}}$$ (3)

The field synergy angle and field synergism number indicated the synergy level of the velocity field and heat transfer field. When the field synergism number $F_c$ equal to 1, the velocity field and heat transfer field of the convection heat transfer field can synergistic completely. It's physical meaning is that the velocity field and heat transfer field coordinated perfectly, and the degree of synergy is the highest, the convective heat transfer coefficient reaches the maximum.

3.Establishment of Models

3.1.Physical Models

The Physical Models of round tube, such as Figure1, used three-dimensional models to numerical simulation. The round tube’s length is 5000mm, and diameter is 20mm. And the effect of wall-thickness had been neglected.
3.2. Mathematical Models

Used water as refrigerant, the flow is assumed as incompressible constant property steady flow. The density $\rho$ is 998.2kg/m³, specific heat $c_p$ is 4183kJ/(kg·K), thermal conductivity $\lambda$ is 0.599W/(m·K), and viscosity $\mu$ is 0.001003kg/(m·s). The operating conditions were set as standard atmospheric pressure, and make a hypothesis as follows.

- The effects of gravity were neglected.
- All interfaces and contact surfaces can not deform, the contact surfaces between liquid and solid are no-slip boundaries.
- The heat conduction of the liquid that flowed along the main flow direction was neglected.
- The liquid don’t get mass incremental after flowed through the tube, and there was not other source terms in the tube.

The flow and heat transfer of liquid in the tube satisfied the continuity equation, momentum equation and energy equation.

**Continuity Equation:**

$$\frac{\partial u}{\partial x} + \frac{1}{r} \frac{\partial (rv)}{\partial r} = 0$$

(4)

**Momentum Equation:**

$$\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial r} \right) = -\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial x^2} \right)$$

(5)

$$\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial r} \right) = -\frac{\partial p}{\partial r} + \mu \left( \frac{\partial^2 v}{\partial r^2} + \frac{1}{r} \frac{\partial v}{\partial r} + \frac{\partial^2 v}{\partial x^2} \right)$$

(6)

**Energy Equation:**

$$\frac{\partial t}{\partial t} + u \frac{\partial t}{\partial x} + v \frac{\partial t}{\partial r} = \frac{\lambda}{\rho c_p} \left( \frac{\partial^2 t}{\partial r^2} + \frac{1}{r} \frac{\partial t}{\partial r} + \frac{\partial^2 t}{\partial x^2} \right)$$

(7)

Where $r$ is the radius of round tube, m

$u, v$ velocity, m/s.

4. Mesh Generation and Numerical Calculation

4.1. Mesh Generation and Independence Verification

This model used structured mesh generating method and infilled the mesh on the walls. Figure2 showed the changes of Nusselt number (Nu) follow the changes of grids when the Reynolds number equal to 2000. The results showed that: when the number of grids is 230000, increase the number, Nusselt number approached to a definite value. That means when the number of grids get to 230000, we can obtain grids independent solution.
4.2. Model Solution and Correctness Verified of Results

Coupling Problem of pressure and velocity are treated with SIMPLEC algorithm. To ensure calculation results close to real results, the iteration accuracy is adopted as follows: for energy equation is $1E-06$, for momentum equation, continuity equation and the other equations is $1E-03$. Set the boundary conditions as follows: set inset boundary as velocity-Inset, outflow as Outflow boundary, inside as liquid and solid coupling face.

The model had been set as 230000 grids, and the Nu’s change with Reynolds number had been calculated. Then we compared the calculation results and the Gnilinski calculation results. Such as Figure3, the relative error is in the range of 10%. So it proved that the grids were good, the model chosen right, the boundary conditions were set correctly, and get correct results.

5. Calculation Result and Analysis

5.1. Calculation Results and Analysis under Turbulent State

- Distribution of velocity field and temperature field

Figure4 is the velocity and temperature coupling graph of the round tube when it no fouling and when the fouling is 2mm. The color section in the graph is temperature contour, and the black line is velocity contour. In this graph, the temperature contour is comparatively dense on the wall, but is sparse in the center. So the heat transfer on the wall should be intense than in the center. And the velocity direction will change along the axial direction. Compared (a) and (b) in Figure4, it can be obtained that
the fouling increased heat transfer resistance and decreased the total heat transfer coefficient of the tube, and the temperature of liquid in the tube had reduced. The difference of adjacent temperature contours is 2.5K when there is no fouling, but it is 1.5K when the tube fouling.

![Figure 4. Velocity and temperature coupling graph](image)

Before fouling

![Figure 4. Velocity and temperature coupling graph](image)

After fouling

Figure 4. Velocity and temperature coupling graph

- Changing trend of average field synergism number and average synergism angle

![Figure 5. Changing situation of average field synergism number and synergism angle with Reynolds number and fouling thickness](image)

As Figure 5, in the turbulent flow, the average field synergism number increases with the increase of fouling thickness. When the fouling thickness is 2mm, the average field synergism number increased 0.0001. That is because when the tube fouling, the surface Nusselt number decreased, but the diameter of tube decreased too. According the formula \( Fc = \frac{Nu}{(RePr)} \), field synergism number increased. With the increases of Reynolds number, average field synergism number decreases. When Reynolds number is 30000, average field synergism number decreased 0.00045. Because field synergism number is the inverse function of Reynolds number, the trend of Reynolds number’ increasing greater than the Nusselt’, the field synergism number decreases with the increases of Reynolds number.

As Figure 5, in the turbulent flow, the average field synergism angle decreases with the increases of fouling thickness. When the fouling thickness is 2mm, the average field synergism angle decreased 0.9. With the increasing of average field synergism number, the temperature gradient was decreasing, but velocity has little increasing. So based on \( Fc = \int (V^2) \cdot |\nabla T| \cos \theta \, d\vec{r} \), average field synergism angle was decreasing. For the same fouling thickness, average field synergism angle increases with the increases of Reynolds number’s. When the Reynolds number was 3000, synergism angle had increased 0.8. Because with Reynolds number’s increasing, the velocity was increasing, the temperature was decreasing, the
temperature contour was becoming sparse and the temperature gradient was decreasing. At the same time, with the increases of the Reynolds number, the field synergism number decreases. The Increasing Speed of the Reynolds number is $5 \times 10^3$, but the Speed of temperature gradient’ decreasing was much less than the speed of the Reynolds number’ increasing. So, accord to the formula

$$F_c = \int \left| \nabla T \right| \cos \theta d\vec{y},$$

the synergism angle was increasing to ensure the field synergism number decreasing.

- Changing trend of Local field synergism number and synergism angle

As Figure 6 (a), the local synergism number was decreasing in axial no matter the tube is fouling or not. In entrance region, the decreasing of local synergism number was the fastest. The decrease rate of synergism number reduced in fully developed flow, and it is relatively flat. This is mainly because the turbulence intensity in entrance region was larger, so the synergism number was larger and the heat transfer was better. But in fully developed flow, the flow was relatively stable, so the changing trend of synergism number was relatively flat.

Figure 6 (b) showed the changing of local synergism angle in axial in the conditions of different fouling thickness. In entrance region, local synergism angle increased significantly in axial. In the department at 0.04m, the flow got into fully developed turbulence, the local synergism angle stop changing and tended to be a constant value. This was also proved the heat transfer is strongly.

5.2. Calculation results and analysis of laminar flows

Calculated the changing of synergism number and synergism angle in the Heat Exchanger tubes (Re equal to 400, 700, 1000, 1200 and 1500 respectively).

- Changing trend of average field synergism number and average synergism angle

In laminar flow, the average field synergism number increases with the increases of fouling thickness, but decreases with the increases of Reynolds number. But the heat exchange capability in turbulent flow is stronger than it in Laminar Flow, so the field synergism number of Laminar Flow is less than it of turbulent flow.
As Figure 7, the average field synergism angle decreases with the increases of fouling thickness, but increases with the increases of Reynolds number. The average field synergism angle in where fouling thickness is 2mm was 1.2° less than it in the no fouling field. The average field synergism angle when Reynolds number is 3000 is 0.8° more than the Reynolds number is 12000.

- Changing tend of Local field synergism number and synergism angle

As Figure 8, the local synergism number was decreasing in axial no matter the tube is fouling or not. But it is different from the turbulent state that the synergism number reached a certain value in the fully developed flow.

6. Conclusions

- Under turbulent flow conditions, the average field synergism number increases with the increases of fouling thickness, but decreases with the increases of Reynolds number. The average field synergism angles decreases with the increases of fouling thickness, but increases with the increases of Reynolds number. The local synergism number tends to decreases in axial no matter whether the tube fouling. This is mainly because the turbulence intensity in entrance region was larger, so the synergism number was larger and the heat transfer was better. But in fully developed flow, the flow was relatively stable, so the changing trend of synergism number was relatively flat. In entrance region, local synergism angle increased significantly in axial. In the department at 0.04m, the flow got into fully developed turbulence, the local synergism angle stop changing and tended to be a constant value. This was also proved the heat transfer is strongly.
- In laminar flow, the average field synergism number increases with the increases of fouling thickness, but decreases with the increases of Reynolds number. The local synergism number
was decreasing in axial no matter the tube is fouling or not. But it is different from the turbulent state that the synergism number reached a certain value in the fully developed flow.

- Because the heat exchange capability in turbulent flow is stronger than it in Laminar Flow, the field synergism number of Laminar Flow is less than it of turbulent flow.

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