Numerical Simulation of Heat Transfer Tube Characteristics of Refrigeration and Air Conditioning Based on Mixed Fractional Model

Weihua Ding¹*, Wei Chen²

¹Department of Automotive and Traffic Engineering, Guangzhou College, South China University of Technology, Guangzhou, 510800, China
²Merchant Marine College, Shanghai Maritime University, Shanghai, 200135, China

*Corresponding author e-mail: dingxing1001@scut.edu.cn

Abstract. The main parameters affecting the heat transfer performance of heat transfer tube heat exchanges include fin shape, fin spacing, fin thickness, tube row arrangement, tube diameter, dry and wet bulb temperature and flow rate. The air side heat transfer performance of heat transfer tube heat exchange and the influence of velocity field and temperature field distribution on heat transfer effect have been the focus of domestic and foreign scholars. In this paper, based on the mixed fraction model, CFD software is used to simulate the absorption process of gravity falling film outside the heat transfer tubes of refrigeration and air conditioning, and to study the flow and heat transfer characteristics of the process. The results show that, for the heat transfer tubes with the selected structure, the heat transfer capacity increases with the increase of water flow velocity, and the heat transfer enhancement effect of turbulence is enhanced. The heat transfer tubes have better comprehensive heat transfer performance than smooth tubes with the same diameter.

Keywords: Mixed Score, Refrigeration, Air Conditioning, Heat Transfer Tube, Numerical Simulation

1. Introduction

In the research process of heat transfer enhancement methods, the heat transfer resistance on the gas side of heat exchange is the main obstacle to improve the heat transfer efficiency of heat exchange. The mature air conditioning condensing heat recovery technology is usually a multi-heat exchange system, which is relatively complex in structure and expensive, and is mostly used in large air conditioning systems, but not suitable for domestic air conditioning [1-2]. The thickness of liquid film increases with the increase of flow rate and decreases with the increase of liquid distribution height. The flow of liquid film outside the tube fluctuates, and the fluctuation of liquid film in the first half is relatively large [3]. Therefore, based on the mixed fraction model, the three-dimensional numerical simulation of fluid flow in heat transfer tubes at different flow rates is carried out, and the velocity field, temperature field and pressure field are obtained, and the variation curves of heat transfer Nusselt number at different Reynolds numbers are given.
2. Physical model
In this paper, the three-dimensional numerical simulation of fluid flow in refrigeration and air conditioning heat transfer tubes is carried out. Under the action of gravity, viscous force and surface tension, the liquid film flows downward and evaporates continuously when heated, and coolant water flows in the tube. The fluid flow rate outside the pipe is given in the form of dimensionless variable \( Re = 4 \Gamma / \mu \). When \( Re \) increases to a certain extent, the liquid film will change from laminar flow to turbulent flow, but different researchers give different change ranges of transition period \( Re \) [4].

Because the chilled water temperature changes along the flow direction \( i \) in the tubes and the refrigerant flow changes along the vertical tube row direction \( j \), the performance of the falling film evaporator, especially the heat transfer characteristics, is different in different positions, which is a function of \( i \) and \( j \). A three-dimensional heat exchange unit of the flat heat transfer tube heat exchange can be intercepted for simulation research, and the heat exchange situation of the whole heat exchange can be analyzed from local to whole. In the model, half of the wet air flow space between two fins and half of the fin thickness on the fluid side are selected.

3. Numerical model

3.1. Heat transfer process model
For the flow with heat transfer, it is necessary to open the energy conservation equation by itself. The inner wall of the tube (refrigerant side) is convective heat transfer; The fluid-solid coupling method is used to determine the heat transfer between the fins and the outer wall of the tube and the air, and the tube wall and fin surface are impermeable and have no slippage [5]. Iterative calculation is carried out for the heat transfer of the unit in each grid. Compared with lumped parameter method, which is widely used in engineering, distributed parameter method has higher calculation accuracy and smaller error. Shear force, pressure gradient and surface tension at the interface of two-phase flow are ignored.

Heat transfer equation:

\[
Q = K A \Delta t_m
\]  

(1)

In formula (1), \( K \) is the heat transfer coefficient; \( A \) is the heat exchange area; \( \Delta t_m \) is the heat transfer temperature difference.

Heat transfer temperature difference.

There is counter heat transfer between water and refrigerant, and the logarithmic average temperature difference is:

\[
\Delta t_{m-w} = \frac{\Delta t_{\text{max}} - \Delta t_{\text{min}}}{\ln \frac{\Delta t_{\text{max}}}{\Delta t_{\text{min}}}}
\]

(2)

In formula (2), \( \Delta t_{\text{max}} \) is the larger of the heat transfer temperature difference; \( \Delta t_{\text{min}} \) is the smaller of the heat transfer temperature difference.

The heat transfer temperature difference between air and refrigerant can be calculated by the following formula.

\[
\Delta t_{m-a} = \frac{t_1' - t_2}{\ln \frac{t_1' - t_2}{t_k - t_2}}
\]

(3)

In formula (3), \( t_1' \) is the air outlet temperature; \( t_2 \) is the air inlet temperature; \( t_k \) is condensation temperature
On the boundary of fluid motion, the fluid flow equation needs to meet certain boundary conditions, and different types of boundary conditions will have an important impact on the numerical results. Estimate and report its power adjustment range, and receive and execute control signals from microgrid, so as to participate in coordinated control. Assuming that the fluid is continuous and incompressible, the shear force and pressure gradient between the gas-liquid interface are neglected, and it is in a thermodynamic flat state. Physical parameters such as specific heat capacity, density, viscosity and thermal conductivity of fluid are functions of temperature.

3.2. Governing equation

Three-dimensional in compressible, steady and turbulent flow. In order to improve the accuracy of calculation, the air physical properties are correlated with temperature. The inner and outer walls of the heat exchange tube are coupled wall boundary conditions, and the inlet and outlet of the heat exchange tube are velocity inlet and pressure outlet boundary respectively [6]. Check the quality of the grid to ensure that the minimum length and volume of the grid do not have negative values and zeros.

It is assumed that the physical characteristics of fluid change slowly along the circumferential direction, and the average \( \frac{(T_w + T_v)}{2} \) of wall temperature and evaporation temperature is taken as the qualitative temperature. The ambient pressure outside the heat transfer tube remains unchanged, which is equal to the saturation pressure at the evaporation temperature of the liquid outside the tube.

According to the above assumptions, the following equation can be obtained:

**Continuity equation**

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{4}
\]

**Momentum equation**

\[
u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} = g \sin(x / R) + v \frac{\partial^2 u}{\partial y^2} \tag{5}
\]

**Energy equation**

\[
\frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{k}{\rho C_v} \frac{\partial^2 T}{\partial y^2} \tag{6}
\]

Using the relationship between flow rate and velocity, the expression of liquid film thickness can be obtained as follows:

\[
\sigma = \frac{\Gamma}{\rho} \int_0^1 ud\gamma \tag{7}
\]

Among them \( y' = \frac{y}{\sigma} \).

3.3. Generation of unstructured grid in computing area

Unstructured mesh is a kind of mesh generation technology suitable for any shape, which came into being in 1980s. The basic idea of unstructured mesh has the following assumptions: tetrahedron is the simplest shape in three-dimensional space, and any space area can be filled with tetrahedron units, that is, any space can be divided by tetrahedron-based meshes. Periodic boundary conditions greatly reduce the number of computational grids. Simple algorithm is used to solve the discrete equations of
the above governing equations, and the momentum equation and energy equation are coupled to solve [7].

4. Results and discussion

4.1. Influence of tube spacing on heat transfer performance of evaporator

The general fluid dynamics software Fluent is used to numerically analyze the heat transfer characteristics of round tubes and heat transfer tubes after the flow enters the full development stage [8]. In the model, the influence of radiation heat transfer, buoyancy and gravity on airflow disturbance is neglected, and the uniform distribution of air inlet temperature is assumed, so the numerical calculation results of air side heat transfer coefficient are smaller than the experimental results. With the increase of air velocity, the water vapor content in the center surface is more and more affected by the inlet, and the water vapor content increases, which indicates that the latent heat transfer is insufficient. With the increase of water flow velocity in the inner pipe, the wind speed gradually decreases. Therefore, when the heat exchange recovers heat, it can reduce the wind speed on the air side, thus reducing the power consumption of the fan and saving energy.

The data in Table 1 show that the drying phenomenon is alleviated to some extent with the increase of pipe spacing, especially for the upper second pipe pass, but the influence on the lower first pipe pass is not obvious. With the increase of tube spacing $p'$, the average falling film factor decreases. When $p'$ is greater than 30 mm, the falling film factor is less than 1, which reduces the advantages of full liquid type. At the same time, the outlet temperature of cold water increases, that is, the heat transfer amount decreases.

Table 1. Influence of different tube spacing on heat transfer

| Tube spacing $p'$ (mm) | The first tube side dry spot percentage (lower part)(%) | Second tube side dry spot percentage (upper part)(%) | Average falling film factor | Cold water outlet temperature (℃) |
|------------------------|------------------------------------------------------|---------------------------------------------------|-----------------------------|----------------------------------|
| 20                     | 64.1                                                 | 10.8                                              | 1.72                        | 8.17                             |
| 30                     | 70.4                                                 | 8.4                                               | 0.07                        | 8.03                             |
| 40                     | 66.7                                                 | 6.6                                               | 1.03                        | 7.93                             |
| 50                     | 54.2                                                 | 3                                                 | 0.86                        | 8.43                             |

Figure 1. is the temperature distribution curve of the center of refrigerant and water in the heat transfer tube of the heat exchanger. It can be seen from fig. 1 that the curve generally shows a downward trend, which shows that when refrigerant condenses in the heat exchanger, the temperature of fluid in the inner tube decreases with the decrease of refrigerant temperature, and the temperature of water in the inner tube is higher than that of refrigerant. This is because with the decrease of the internal temperature of the heat transfer pipe, the temperature difference between the heat transfer pipe and the outside air begins to decrease, and the heat dissipation is also small.

![Figure 1. Temperature curve of refrigerant and water](image-url)
The turbulent kinetic energy value increases and changes dramatically, and the turbulent kinetic energy is large, which has a strong disturbance effect on the fluid, enhances the convective heat transfer performance between the fluid in the pipe and the pipe wall, and enhances the heat transfer of the fluid. Along the clockwise direction of the tube wall circumference, the thickness of the liquid film on the tube wall gradually decreases, reaching the minimum value near 100 ~ 120, and then the thickness of the liquid film gradually increases slightly until the bottom of the heat transfer tube. The actual heat transfer coefficient is much larger than the calculated heat transfer value. It can be seen that the falling film evaporation outside the tube is mainly convection heat transfer. Combined with the previous analysis, it can be concluded that convection occurs due to the normal velocity, which makes the heat transfer achieve the effect of convection heat transfer.

4.2. Influence of physical parameters on heat transfer

It is a transient process that the liquid film changes with time from impacting the top of the heat transfer tube to spreading completely. Therefore, the setting of the time step also has a certain influence on the calculation results. There is no diffusion effect between the isosurface of the mixture fraction, and there is also a great deficiency. The database obtained by the two-dimensional flame surface model equation not only has the mixture fraction and the reaction progress variables as the look-up scalar, but also has the corresponding scalar dissipation rate, which can reflect different combustion mechanisms. When the refrigerant flow rate is sufficient, dry spots appear in the cold water inlet section of only some tubes at the bottom, while the falling film area with good heat transfer is located far away from the inlet section. Therefore, there should be an optimal ratio between the falling film area and the full liquid area, that is, there is an optimal number of full liquid tubes. The inlet state of air is closely related to the flow of air, while the calculation of pressure difference is more susceptible to the flow state of fluid.

Different flow rate outside the pipe, that is, different Reynolds number of liquid outside the pipe. The flow rate is calculated and expressed by the relation between flow rate and Reynolds number. At the same temperature, the density and viscosity of liquid are the same, and Reynolds number and flow rate express the same physical quantity.

\[
Re = \frac{4\Gamma}{\rho v}
\]  

(8)

Figure 2 shows the liquid film thickness at different Reynolds numbers and compares it with Nusselt solution. When Reynolds number is small, the simulation value has a good similarity with Nusselt, while Reynolds number is high, which is quite different. This is mainly due to whether viscosity term is considered. When Reynolds number is large, the minimum thickness of liquid film moves backward, not at 90 degrees. The larger the Reynolds number is, the more obvious the viscosity effect is.

![Figure 2. Local liquid film thickness at different Reynolds numbers](image-url)
At the same circumferential angle, the liquid film thickness of small diameter horizontal pipe is greater than that of large diameter horizontal pipe. The bending resolution and the narrowest area resolution are between 0.1-1, and when the bending resolution and the narrowest area are divided, the finer the subdivision is and the better the subdivision quality is. With the increase of inlet wind speed, both sensible heat transfer and latent heat transfer increase. Along the air flow direction, due to the condensation of water vapor, the mass fraction of water vapor gradually decreases. When the top of the columnar crystal begins to branch, it enters the frost growth period. At the same time, due to the interaction of dentifrice crystals, a network frost layer is gradually formed, and when the frost layer surface is almost flat, it enters the full growth period of frost layer.

4.3. Influence of head-on wind speed on heat transfer coefficient

Under the condition that the inlet air temperature of the heat exchange is constant at 28°C, the heat transfer and flow resistance performance of SK heat transfer tubes under different inlet air flow rates and relative humidity are experimentally studied. Because of the stagnation area on the leeward side of the pipeline, the fin area can not be effectively utilized, and the temperature of wet air and the content of water vapor in this area are relatively low, especially on the leeward side of the second row of pipelines. When the pipe diameter is 15 mm, the liquid film continues to become thinner, and a small "dry spot" appears at the bottom of the second horizontal pipe. Because of the latent heat of phase change, the total heat transfer coefficient is far greater than the convective heat transfer coefficient, and it also increases with the increase of wind speed, but the ratio of the two is basically unchanged, and when the relative humidity of wet air is 0, the ratio remains around, as shown in Figure 3.

![Figure 3. Influence of head-on wind speed on the ratio of total heat transfer coefficient to sensible heat transfer coefficient](image)

Because the liquid film is affected by gravity and the surface tension of the gas-liquid interface in the falling process, the liquid is ellipsoidal; The local heat transfer coefficient of a pipe with a diameter of 0.0127 m is always larger than that with a diameter of 0.0254 m in the whole angle range, which cannot explain the change of local heat transfer coefficient by the impact zone. The total heat transfer coefficient is the largest and the outlet temperature of cold water is the lowest, that is to say, the heat transfer is the best at this time, so there is an optimal full liquid discharge number n=2 in this case. The higher the degree of flow turbulence, the better the heat transfer. At the same time, we can see that the heat transfer effect of the heat transfer tube is obviously higher than that of the smooth tube, and the coefficients are 1.01, 1.31 and 1.41 times of that of the round tube, which shows that the heat transfer tube can obviously enhance the heat transfer.

4.4. Heat exchange quantity

With the increase of spray density, the coverage and disturbance of liquid film are gradually increased, and the heat transfer coefficient is improved. When the spray density continues to increase, the thickness of the liquid film covered by the flow outside the pipe also increases, and the thermal
resistance of the liquid film increases, which is not conducive to the heat transfer and prevents the further improvement of the heat transfer coefficient. Through microscopic analysis on the outside of falling film evaporation tube of heat transfer tube, it is found that normal velocity is the main reason of convective heat transfer, which can be well explained by microscopic mechanism of falling film evaporation of heat transfer tube. The smaller the diameter, the greater the curvature, the greater the normal change rate, that is, the normal acceleration, and then the stronger the convective heat transfer and the greater the heat transfer coefficient. The direction and fluctuation of air inlet flow will cause the pressure calculation to be smaller than the experimental value under the condition of this model, and the error will be larger at some points due to the large fluctuation of pressure.

Table 2 shows the heat exchange capacity of heat transfer tubes with different pipe diameters and different spray densities. The longitudinal length 1 m is taken to extract the heat exchange quantity per unit length. When the pipe diameter is 15 mm, it can be seen from the table that when the flow rate of the liquid distribution pipe is 0.205 m/s, the heat transfer amount is the largest, which indicates that the liquid film can completely cover the pipe wall at this time, and the liquid film is very thin and the thermal resistance is very small, which is beneficial to heat transfer. When the flow rate is 0.205 m/s, the heat transfer rate is smaller than that at 0.205 m/s, and the spray density is too small, so that the liquid film can not completely cover the tube wall, and "dry spots" appear, which affects the heat transfer.

| Flow velocity of liquid distribution pipe (m/s) | Heat exchange capacity of 15mm pipe diameter (W/m) | 20mm in diameter for heat exchange (W/m) |
|-----------------------------------------------|-------------------------------------------------|----------------------------------------|
| 0.327                                         | 1535                                            | 2377                                   |
| 0.205                                         | 2031                                            | 3082                                   |
| 0.083                                         | 2506                                            | 2953                                   |
| 0.729                                         | 1926                                            | 2247                                   |

This situation is related to the frosting on the surface of the heat exchange on the one hand and the working conditions of the compressor and condenser on the other hand. The convective heat transfer coefficient of flat fins under wet condition almost coincides with that under dry condition, and increases with the increase of inlet velocity, but the increase slows down. Figure 4 shows the relationship between condensation heat transfer coefficient of wet air side and wall temperature when wet air with relative humidity is present. It can be seen that the sensible heat transfer coefficient is less affected by the wall temperature and hardly changes; High speed means that inertial force increases and viscous force decreases. Moreover, high speed is helpful to scour the boundary layer and reduce the thickness of the boundary layer, which is beneficial to enhance heat transfer.

![Figure 4. Influence of wall temperature on heat transfer coefficient](image-url)
The velocity field distribution of slotted fin is more uniform than that of straight fin, and the average fluid velocity along the copper tube wall and the fin boundary directly opposite to the copper tube wall is larger than that of straight fin. Graph of sensible heat transfer and latent heat transfer with wind speed. It can be seen from the figure that with the increase of inlet wind speed, the sensible heat exchange capacity and latent heat exchange capacity both increase. With the compressor turned on and the refrigeration process going on, frosting will occur on the surface of the heat exchanger, while the condensation convection heat transfer coefficient will gradually decrease with the increase of wall temperature, which indicates that the increase of wall temperature will lead to the decrease of the difference between the dew point temperature of wet air and the wall temperature, thus causing the decrease of water vapor condensation.

5. Conclusion
In this paper, based on the mixed fraction model, three-dimensional numerical simulation of heat and mass transfer of flat heat transfer tubes under wet conditions is carried out, and the condensation heat transfer mechanism and the action mechanism of several factors affecting condensation are studied. The condensation heat transfer of wet air on the surface of cold fins was simulated and calculated by commercial CFD software FLUENT, and the internal reasons of several influencing factors affecting condensation heat transfer were preliminary revealed, which also provided a useful reference for more reasonable design of heat exchange's.

The numerical simulation results show that the mass fraction of water vapor in the air gradually decreases along the air flow direction. Because of the stagnation area on the leeward side of the pipeline, the fin area can not be effectively utilized, and the temperature of wet air and the content of water vapor in this area are relatively low, especially on the leeward side of the second row of pipelines. Therefore, it is necessary to strengthen the fin area on the leeward side.

Under the same spray density, the liquid film thickness of large diameter horizontal pipe is thinner than that of small diameter, and the liquid film thickness distribution is relatively uniform, that is, the liquid film thickness changes in a small range; At the point with the same distance from the outer wall of the pipe, the temperature of the large pipe diameter is lower than that of the small pipe diameter, and with the increase of the distance from the outer pipe wall, the rate of temperature decrease increases, indicating that the heat transfer effect of the large pipe diameter is better than that of the small pipe diameter.

With the increase of liquid distribution eccentricity, the total heat transfer coefficient first rises slightly and tends to be stable, while the further increase of eccentricity leads to local "dryness" and liquid film accumulation area, which makes the total heat transfer coefficient drop sharply. With the increase of spray density, the critical point of the sharp drop of total heat transfer coefficient will gradually shift to large eccentricity.

References
[1] Li Shanshan, Li Guodong, Zhang Dashuai, et al. Numerical simulation of pipeline sediment transport characteristics based on hybrid model[J]. Journal of Northwest Sci-Tech University of Agriculture and Forestry (Natural Science Edition), 2017(01):231-240.
[2] Li Yuesheng, Liang Jialin, Gan Yunhua, et al. Numerical simulation of flow and heat transfer characteristics of spiral plate heat exchanger based on periodic flow model[J]. Energy Conservation Technology, 2017, 035(004): 319-325.
[3] Liu Xie, Zhong Wenqi, Li Jie, et al. Three-dimensional numerical simulation of ultra-supercritical boiler combustion air distribution optimization[J]. Journal of Southeast University (Natural Science Edition), 2018, 48(005): 794-800.
[4] Ma Haotian, Fan Lijia, Li Sitong, et al. Evolution of viscoelastic parameters of asphalt mixture before and after aging based on 2S2P1D model[J]. Highway and Transportation Science and Technology, 2020, v.37; No.304(04):27-34.
[5] Shao Shuai, Chen Xi, Tang Kai, et al. Numerical simulation of heat transfer characteristics of
low-temperature pulsating heat pipes[J]. Vacuum and Cryogenics, 2018, 024(001):48-53.

[6] Wang Tian. Numerical simulation of falling film flow and heat transfer characteristics of LiBr solution outside horizontal tubes with different diameters[J]. Refrigeration Technology, 2018, 38(04):75-79.

[7] Wu Xinghui, Yang Zhen, Chen Ying, et al. Numerical simulation of phase change microcapsule fluid heat transfer characteristics based on discrete phase model[J]. CIESC Journal, 2020, 071(004):1491-1501.

[8] Yuan Zhongxian, Liu Zhongqiu, Wu Bo. Research on heat transfer characteristics of finned tube gas-liquid heat exchanger under variable conditions [J]. Refrigeration and Air Conditioning (Sichuan), 2018, 32(05): 24-30.