Analysis of factors affecting cooling performance of cooling tower

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Abstract. Based on the 3D model of cooling tower, the Fluent simulation model was used to compare with the experimental results to analyze the feasibility of the simulation and the reliability of the results. Will the wind loss and the water temperature as evaluation index, the main analysis analyzed the gas-liquid two phase velocity ratio, air inlet Angle and spray density on the influence of cooling tower cooling performance, and the combination, analyzed the situation of different gas-liquid two phase velocity ratio, air inlet Angle and the spray density of different influence on the performance of cooling tower, respectively. At the same time, combined with the orthogonal experiment, the optimal range of these three factors affecting the cooling tower performance is obtained. It has certain reference significance for the further research and application of cooling tower.

1. Introduction

Cooling tower is an important part of industrial circulating water system, and its cooling performance directly affects the energy consumption of industrial system [1]. Therefore, the improvement of cooling tower performance plays a vital role in industrial production, so it is urgent to explore the factors affecting the cooling tower performance. At present, many scholars have studied the performance of multiple cooling towers. Some studies analyzed the influence of cooling medium [2] or surrounding environment [3] on cooling performance of cooling towers based on experimental methods, and some studies optimized cooling performance of cooling towers based on theory [4,5] to reduce energy consumption. However, due to the tedious operation of the experimental method, a large number of experiments and data statistics are needed. The theoretical method is relatively ideal, considering the influence of complicated factors in reality, the results are quite different from the actual results. There is an urgent need for convenient and accurate research methods. In recent years, CFD (Computational Fluid Dynamics), with its advantages of short period and low cost, has become a common research method for theories and experiments. Based on the CFD method, the physical parameter changes of the natural ventilation cooling tower that cannot be obtained by experiment can be obtained well [6]. In this paper, Fluent was used to conduct 3D simulation of mechanical ventilation cooling tower of self-built industrial circulating water system [7], and three factors affecting cooling performance of cooling tower were analyzed. Through orthogonal experiment, the range of these three parameters of cooling tower under better cooling performance was obtained. Based on the Fluent method, it is relatively easy to simulate the environment in the actual application of the cooling tower. Various factors existing in the actual situation can be added. Moreover, it is convenient and fast to calculate by computer.
Based on the mathematical model and physical model of the cooling tower, this paper establishes a cooling tower model that conforms to certain requirements and conducts verification. Then the 3D modeling is carried out, and the simulation is carried out by inputting different water flows and water temperature of the inlet tower. At the same time, the cooling tower experiment device (Figure 1) was used for the test, and the parameters were input through the operation platform, and the experimental results were collected [7]. Finally, by comparing the simulation results with the actual experimental results, the variation trend of the water temperature of the established cooling tower model and the difference between the model and the actual temperature are obtained. The factors influencing the cooling performance are analyzed and summarized. The trend of simulation results is obtained. The trend is analyzed and the conclusion is drawn.

Figure 1. Experimental equipment of cooling tower.

2. 3D numerical simulation of cooling tower

2.1. Mass model

Mass equation:

$$\nabla \cdot (\rho \mathbf{v}) = 0$$

(1)

Where \( \mathbf{v} \) is the gas velocity, m/s; Denotes gas density, kg/m\(^3\).

Momentum equation:

$$\nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \left( \frac{\mu}{3} \nabla \mathbf{v} + \nabla \mathbf{v}^T \right) + \rho g + F$$

(2)

Where \( p \) is the gas pressure, Pa; The effective dynamic viscosity of the gas, kg/(m \( \cdot \) s); \( G \) is the acceleration of gravity, m/s\(^2\); \( F \) is the resistance of the gas, N/m\(^3\).

Energy equation:

$$\nabla \cdot \left( \rho \mathbf{v} \int_{T_{0,ref}}^T c_{p,i}dT \right) = \nabla \cdot \left( k_g \nabla T - \sum_k J \kappa_d \frac{\mu}{3} \nabla \mathbf{v}^T \right)$$

(3)

Where, \( T \) is the air temperature, K, \( T_{ref} = 298.15 \) K; \( h = \int_{T_{0,ref}}^T c_{p,i}dT \) Is the enthalpy of component i, \( J \cdot kg^{-1}; c_{p,i} \) is the specific heat capacity of air, kJ/(kg \( \cdot \) K); \( k_{eff} \) is the effective thermal conductivity, W/(m \( \cdot \) K); \( J \) is the diffusion flux of component i, kg/(m\(^2\) \( \cdot \) s).

k equation for turbulent kinetic energy:

$$\nabla \cdot (\rho k) = \nabla \cdot (\alpha_k \mu_{eff} \nabla k) + \mu_{k} S^2 - \rho \varepsilon$$

(4)

Turbulent dissipation equation:

$$\nabla \cdot (\rho \varepsilon) = \nabla \cdot \left( \alpha_k \mu_{eff} \nabla \varepsilon \right) + 1.42 \mu_k S^2 - 1.68 \rho \frac{\varepsilon^2}{k} - R_e$$

(5)

Where, \( \mu_k = 0.0845 \rho \frac{k^2}{\varepsilon} \) is the dynamic viscosity of turbulence, kg/(m \( \cdot \) s); \( \mu_k = 0.0845 \rho \frac{k^2}{\varepsilon} \) is the modulus of the average strain tensor; \( \alpha_k, \alpha_k \) is the inverse effective prandtl number, and is about 1.93 when the flow field is high Reynolds number. \( R_e \) is an additional term introduced to consider the flow field of large curvature and fast strain region.
The temperature of cooling water can be expressed as:

\[ m_c c_p \frac{dT_w}{dt} = h \frac{A_w}{m_w}(T_w - T_a) \]  

(6)

Where, \( m_w \) is the mass of cooling water, kg; \( C_p,w \) is the specific heat capacity of cooling water, kJ/(kg \cdot K); \( T_w \) and \( T_a \) are the temperature of cooling water and air respectively, K. \( h \) is the heat transfer coefficient of cooling water, kW/(m\(^2\) \cdot K); \( A_w \) is the contact area of gas-liquid phase, m\(^2\).

Calculation formula of the interaction between cooling water and air:

\[ \frac{dv}{dt} = F_d (v - v_w) + \frac{g(\rho_w - \rho)}{\rho_w} v + F \]  

(7)

\[ F_d = \frac{18 \mu C_D Re}{\rho_w d_w^2} \frac{1}{2a} \]  

(8)

Where \( v_w \) is the velocity of cooling water droplets, m/s; \( \rho_w \) is the density of water, kg/m\(^3\).The first term on the right of the formula represents the drag force of the water drop, and \( F \) is the resistance generated by pressure difference.\( d_w \) is the diameter of water droplet, m;\( Re \) is the relative Reynolds number.

The porous media model is equivalent to adding source terms to the momentum equation describing the flow field.This source term is mainly composed of viscous loss term and inertial loss term, as shown in the following equation:

\[ S = - \sum_{j=1}^{3} D_{ij} \mu v_j - \frac{1}{2 \rho} \sum_{j=1}^{3} C_{ij} v_i^2 \]  

(9)

Where \( i \) is in the x, y and z directions;\( D \) and \( C \) are the given resistance coefficient matrix.

2.2. Physical model

The physical model of cooling tower is established according to the mathematical model.The fan used in the simulated mechanical ventilation cooling tower in this paper is YWF4D-600S-137/70-G external rotor axial-flow fan.The distributor is made of a DN40 main channel and a number of DN8 branch pipes welded together, and the branch pipes are arranged in an array of 12 x 20 holes with a diameter of 2mm as a water jet hole.The packing in the cooling tower is made of trapezoidal oblique wave packing with cross-section, the size is 720mm x 720mm x 250mm.The air inlet surface of the fan shell is a circle with diameter of 705mm, the outlet surface expands to a circle with diameter of 750mm, and the overall height of the fan part is 300mm.The cooling tower was modeled in three dimensions by using the ANSYS workbench, and the tower body of the cooling tower was divided into four parts: water collection area, spray area, packing area and rain area, as shown in figure 2.

![Figure 2. Geometric model of cooling tower.](image)

Because of the complex shape of cooling tower, non-structural tetrahedral meshes with good topological topology are mainly used in the division of calculation areas [8], while the water-collecting area, sprinkling area, packing area and rain area of cooling tower are divided into structured grids.The cooling tower is divided into three grid schemes: 1339287, 1428207 and 1790727.The total pressure value of the fan in cooling tower calculated by grid model with grid number of 1428207 and grid number of 1790727 is less than 4.5%.Considering that the discrete phase model needs to be coupled to calculate the gas-liquid two-phase flow field, a grid model with grid number of 1790727 is selected to simulate the cooling tower performance.
2.3. Verification analysis of 3D numerical calculation model of cooling tower

It can be seen from table 1 that there is a certain error between the simulated cooling performance parameters of the cooling tower and the experimental measurement values. As the cooling effect of the cooling tower is affected by the surrounding environment [9]: the temperature around the cooling tower test device is about 288K, which is significantly lower than the internal temperature of the cooling tower. The fluid in the cooling tower is transferred heat through the wall and the surrounding atmosphere, while in the numerical simulation, it is assumed that the tower wall is an adiabatic wall surface. Therefore, the calculated cooling water outlet tower temperature is slightly higher than the experimental water outlet tower temperature.

Table 1. The experimental and simulation temperature of the cooling tower.

| water-carrying capacity (m³/h) | feed water temperature(K) | out of the tower water temperature(K) |
|--------------------------------|---------------------------|---------------------------------------|
| observed value                 | analog value              |                                       |
| 8.09                           | 301.58                    | 300.55                                | 300.696                              |
| 8.15                           | 300.36                    | 299.24                                | 299.590                              |
| 8.21                           | 301.23                    | 299.91                                | 300.369                              |

Error analysis of simulation results and experimental results by using data in table 1:

\[ \varepsilon_1 = \frac{800.696 - 300.55}{300.55} \times 100\% = 0.486\% \]

\[ \varepsilon_2 = \frac{299.590 - 299.24}{299.24} \times 100\% = 1.170\% \]

\[ \varepsilon_3 = \frac{300.369 - 299.91}{299.91} \times 100\% = 1.530\% \]

\[ \varepsilon = \frac{0.486\% + 1.170\% + 1.530\%}{3} = 1.062\% \]

It can be seen from the table that although the influence of the surrounding environment on the cooling performance of the cooling tower is not considered in the simulation, the temperature value of the simulated cooling water is consistent with the change trend of the temperature value of the cooling tower measured in the experiment and the difference is not very big. After calculation, the average error is about 1%. Therefore, the simulated temperature value of cooling water is relatively reasonable and has certain reference significance.

3. Factors influencing cooling performance of cooling tower

The cooling tower works by means of the gas entering the high-temperature liquid. When the gas passes through the high-temperature liquid, it takes away the temperature and steam, so as to reduce the liquid temperature. In evaluating the performance of cooling tower, the water temperature of cooling tower is generally taken as the index to measure the performance of cooling tower [10, 11]. In large circulating water systems, the loss of various amounts of water will directly affect the economic benefits of cooling towers [12]. Therefore, in this paper, the wind blow loss is included into the index to evaluate the performance of the cooling tower. Taking the wind blow loss and tower outlet temperature as the evaluation indexes, the gas-liquid two phase velocity ratio, air inlet Angle and spray density are comprehensively analyzed and summarized, and the range of these three parameters that can make the cooling tower performance better is finally obtained.

3.1. Gas-liquid two phase velocity ratio

In the internal environment of the cooling tower, it is the environment where the gas and liquid two-phase flow exist. The flow rate of the gas and liquid two-phase flow will affect the frequency of heat transfer. In Fluent, the gas-liquid two-phase velocity rate ratio parameter was changed to obtain the corresponding value of wind blowing loss and temperature change, so as to obtain the curve diagram of gas-liquid two-phase velocity rate ratio of the influence of wind blowing loss and temperature on cooling tower (figure 3). After analyzing the curve in the figure, we get: as the gas-liquid two phase velocity ratio increases, the wind loss of the cooling tower increases. The temperature of cooling water decreases first and then increases: when the gas-liquid two phase velocity ratio is less than 1.7, the temperature of cooling water decreases with the increase of gas-liquid two phase velocity ratio; When
the gas-liquid two phase velocity ratio is greater than 1.7, the temperature of cooling water increases with the increase of gas-liquid two phase velocity ratio.

Figure 3. Cooling performance parameters of different gas-liquid two phase velocity ratio.

Figure 4. Effect of different air inlet Angle on wind loss.

Figure 5. Effect of different air inlet Angle on temperature.

Figure 6. Effect of different sprinkle density on wind loss.

Figure 7. Effect of different sprinkle density on temperature.

3.2. Air inlet Angle
The air inlet Angle affects the time of air contact with water and ultimately affects heat exchange. By using the software to summarize the data of different air inlet Angle of different gas-liquid two phase velocity ratio, the cooling performance parameters of the cooling tower at different air inlet Angle of different gas-liquid two phase velocity ratio were obtained (figure 4,5). In terms of the same gas-liquid two phase velocity ratio, the reduction of air inlet Angle can greatly reduce the wind loss of cooling tower, but reduce the temperature drop of cooling water. As for the whole curve, when the gas-liquid two phase velocity ratio is less than 1, the air inlet Angle has little influence on the wind blow loss. As the gas-liquid two phase velocity ratio increases, the influence of the air inlet Angle on the wind blow
loss increases. When the air inlet Angle is greater than 60 degrees, the wind blow loss of cooling tower is obvious. However, when the air inlet Angle is less than 60 degrees, the wind loss of cooling tower can be effectively reduced and the cooling water temperature is not affected much.

3.3. Sprinkle density
The spray water level is at the upper end of the cooling water outlet of the cooling tower. The purpose of the spray water is to conduct heat exchange with the cooling water to reduce the temperature of the cooling water. Different densities of the spray water will lead to different degrees of heat exchange. The simulation results of spray water with different spraying densities with different gas-liquid two phase velocity ratio were summarized, and the cooling performance parameters of cooling tower under different gas-liquid two phase velocity ratio and different cooling water spraying densities were obtained (figure 5). It can be seen from the broken line diagram that: when the gas-liquid two phase velocity ratio is less than 2, the change of spray density has little effect on the wind blow loss. When the gas-liquid two phase velocity ratio is greater than 2, the wind blow loss decreases with the increase of spray density. The decrease of spray density will increase the temperature drop of cooling water to some extent, but if the spray density is too small, the temperature will rise, as shown in figure 6, 7.

3.4. Comprehensive analysis of influencing factors
It can be seen from section 3.1 to 3.3 that cooling performance of cooling tower is affected by gas-liquid two phase velocity ratio, spraying density and air inlet Angle. The three factors are conducted orthogonal experiment. Based on orthogonal experiment, three horizontal values are selected for each influencing factor, as shown in table 2.

| factors                     | Gas-liquid two phase velocity ratio A (m/s) | Sprinkle density B (×10^{-4}m^2) | Air inlet Angle C (°) |
|-----------------------------|--------------------------------------------|----------------------------------|-----------------------|
| 1                           | 1.9                                        | 1.89                             | 60                    |
| 2                           | 1.733                                      | 3.77                             | 30                    |
| 3                           | 1.035                                      | 7.54                             | 90                    |

Based on orthogonal test level value of the three factors of the results (table 3), when air inlet Angle is 60°, gas-liquid two phase velocity ratio between 1.7 and 1.9, cooling tower has better cooling performance. It can be seen from figure 6, 7 that cooling performance of the cooling tower is better when the spraying area of the cooling tower is 0.04-0.1% of the cross-sectional area of the tower body.

| Test  | Wind loss (%) | Temperature (K) |
|-------|---------------|-----------------|
| A1B1C1 | 0.73          | 299.47          |
| A1B2C2 | 0             | 299.86          |
| A1B3C3 | 40.45         | 299.49          |
| A2B1C2 | 0             | 299.89          |
| A2B2C3 | 38.76         | 299.47          |
| A2B3C1 | 0             | 299.67          |
| A3B2C1 | 0             | 299.93          |
| A3B3C2 | 0             | 300.04          |
| A3B1C3 | 4.01          | 299.75          |

4. Conclusions
(1) In this paper, three-dimensional numerical simulation of the cooling tower was carried out based on Fluent, and the wind blow loss and tower outlet temperature were taken as comprehensive
evaluation indexes. Three factors affecting cooling performance of the cooling tower were mainly discussed, and the three factors were considered comprehensively and analyzed in depth.

(2) By setting the gas-liquid two phase velocity ratio parameter, the corresponding value of wind blow loss and temperature change was obtained. It can be seen from the line diagram that when the gas-liquid two phase velocity ratio was 1.7-1.9, the wind blow loss of cooling water and the temperature of cooling water were kept in a better range.

(3) On the premise of setting a certain gas-liquid two phase velocity ratio, set different air inlet Angle to get the corresponding value of wind loss and temperature change. It can be seen from the broken line graph that when the air inlet Angle is less than 60 degrees, the wind blow loss of the cooling tower can be effectively reduced and the cooling water temperature drop has little influence.

(4) On the premise of setting a certain gas-liquid two phase velocity ratio, different spraying densities were set to obtain the corresponding values of wind loss and temperature changes. According to the broken line diagram and the orthogonal experiment, it can be seen that the cooling tower has a better performance when the spraying area is 0.04-0.1% of the cross-sectional area of the tower body.

In conclusion, the study of the influence of the cooling tower performance, the optimal range of the parameters of the three factors as follows: when the air inlet Angle is under 60 °, gas-liquid two phase velocity ratio is between 1.7 and 1.9, the spraying area is 0.04-0.1% of the cross-sectional area of the tower body.

Acknowledgment

Fund Project: Shanghai Science and Technology Commission Science and Technology Research Program (13dz1201700).

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