The analysis of the influence of packing and total pressure on cooling performance of the cooling tower

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Abstract. Packing of the cooling tower, in which the heat exchange mainly, plays a decisive role in the cooling performance of the cooling tower. This thesis conducted the three-dimensional numerical simulation of the cooling tower based on CFD software FLUENT and analysed the physical characteristics of the gas-liquid two phase. The axial flow fans with two different blade profiles are simulated to make the cooling tower has different total pressure under the same air volume, concluding that the total pressure of the cooling tower has little influence on the performance of the cooling tower. Also, the influence of the packing resistance coefficient and height on the cooling performance is studied, finding that increasing the packing height is more conducive to improving the cooling performance compared with the increase of the packing resistance coefficient.

1. Introduction

The mechanical draft wet cooling tower, which removes waste heat generated in industrial manufacturing processes, is one major component in circulating cooling water system. Its cooling performance directly affects the efficiency of the circulating water system. The cooling tower also has a broad application since it can handle the water flows from only a few gallons of water per minute to hundreds of thousands of gallons per minute [1]. However, cooling tower emissions have become an increasingly common hazard to the environment and to the health [2, 3]. Therefore, the research about optimization of the cooling tower has attracted increasingly attention. Compared with the natural draft cooling tower, which optimized by pre-cooling the inlet air [4, 5], reducing backflow of the outlet air [6], constructing reasonable packing height [7] and so on, the mechanical draft cooling tower is optimized from axial flow fan, which enhance the cooling performance by controlling airflow [8]. Now the studies on the cooling tower are mainly based on experimental [9, 10] and theoretical [11, 12, 13] analysis, only a few literatures describe the optimization of the cooling tower based on simulation calculation [14]. Computational fluid dynamics, which can provide detailed, visualized and comprehensive physical characteristics of the air and water motion in the cooling tower compared to experiment and theory analysis, is not commonly used. This paper conducts three-dimensional numerical simulation of mechanical draft cooling tower based on CFD software FLUENT, and analyzes the influence of the packing and tower total pressure on the cooling performance in combination with the internal fluid flow characteristics of the cooling tower.
2. Three-dimensional mathematical model of cooling water

The air flow field in the cooling tower is assumed to be incompressible flow field, which adheres to the conservation of mass, momentum and energy.

The mass conservation equation:
\[ \nabla \cdot (\rho \mathbf{v}) = S_w \]  
(1)

Where, \( \mathbf{v} \) is the velocity, m/s; \( \rho \) is density, kg/m\(^3\); \( S_w \) is water evaporation, kg/(m\(^3\)·s).

The momentum conservation equation:
\[ \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \left( \mu_{\text{eff}} \left( \nabla \mathbf{v} + \nabla \mathbf{v}^T \right) \right) + \frac{2}{3} \nabla \cdot \left( \mathbf{v} \mathbf{v} \right) + \rho g + F \]  
(2)

Where, \( p \) is the static pressure, Pa; \( \mu_{\text{eff}} \) is the effective viscosity, kg/(m·s); \( g \) is the acceleration of gravity, m/s\(^2\); \( F \) is the resistance to the air, N/m\(^3\).

The energy conservation equation:
\[ \nabla \cdot \left( \rho \int_{T_{\text{ref}}}^{T} c_p dT \right) = \nabla \cdot \left( k_{\text{eff}} \nabla T - \sum_i h_i J_i + \mu_{\text{eff}} \left( \nabla \mathbf{v} + \nabla \mathbf{v}^T \right) \right) + \frac{2}{3} \nabla \cdot \left( \mathbf{v} \mathbf{v} \right) \]  
(3)

Where, \( T \) is the temperature, K; \( T_{\text{ref}}=288.16 \) K; \( h_i = \int_{T_{\text{ref}}}^{T} c_p dT \) is the enthalpy of component \( i \), J·kg\(^{-1}\); \( c_p \) is the specific heat capacity, kJ/(kg·K); \( k_{\text{eff}} \) is the effective heat conductivity coefficient, W/(m·K); \( J_i \) is the diffusion flux of component \( i \), kg/(m\(^2\)·s).

The temperature expression of water:
\[ m_w c_{p,w} \frac{dT_w}{dt} = h A_w (T_a - T_w) \]  
(4)

Where, \( m_w \) is the water quality, kg; \( c_{p,w} \) is the water specific heat capacity, kJ/(kg·K); \( T_w, T_a \) is the temperature of water and air, K; \( h \) is the heat transfer coefficient of water, kW/(m\(^2\)·K); \( A_w \) is the contact area between water and air, m\(^2\).

The interaction between water and air:
\[ \frac{dv_w}{dt} = F_p (v - v_w) + \frac{g (\rho_w - \rho)}{\rho_w} + F \]  
(5)

\[ F_p = \frac{18 \mu}{\rho_w d_w^2} \frac{C_D \Re}{24} \]  
(6)

Where, \( v_w \) is velocity of water droplets, m/s; \( \rho_w \) is water density, kg/m\(^3\); the first term on the right-hand equation is the drag force exerted on the water droplet, \( F \) is the resistance generated by the pressure difference; \( d_w \) is water droplet diameter, m; \( \Re \) is the relative Reynolds number.
The flow field in the packing was simulated by porous model in FLUENT, which is equivalent to adding the source term to the momentum equation of the flow field. The source term is mainly composed of viscous loss and inertial loss items, which is written as:

\[
S_i = -\left( \sum_{j \neq i} D_{ij} \mu v_j + \sum_{j \neq i} C_{ij} \frac{1}{2} \rho |v_j|^2 \right)
\]

(7)

Where, \( i \) is the direction of \( x, y, z \); \( D_{ij}, C_{ij} \) is the given resistance coefficient matrix. The velocity of the air and water is relatively large, so the pressure drop can be approximately proportional to the square of the velocity, ignoring the first item on the right side of the equation.

3. Grid model and boundary setting of cooling tower

The simulated mechanical cooling tower is the one used in the self-built circulating water system. Its overall size is 720mm × 720mm × 800mm, which includes the axial flow fan, water recycling area, spray area, packing area and water collecting pool. Use Workbench software model the three-dimensional cooling tower, and mesh the fan flow field and other fields in the tower with unstructured mesh and structured mesh respectively. When the grid number reaches 1790727, the calculated total pressure of the cooling tower tends to be stable, which achieves the grid independence.

In this cooling tower, the volume of water droplets in the spray and rain areas accounts for 0.15% of the total volume, therefore, the heat transfer process between the water and air can be described by discrete phase model in FLUENT, in which the air is regarded as continuous phase and the water is regarded as discrete phase. The fan speed is set to 1350rpm, which calculated by multiple reference frame model, and the flow field in the cooling tower simulated by RNG k-ε turbulence model.

The inlet and outlet of the cooling tower are set to be velocity inlet and pressure outlet, and the other walls of the cooling tower are set to be no slip adiabatic wall boundary since it is assumed that the cooling tower has no heat exchange with environment. The temperature of the inlet circulating water is 300.36K. Use the SIMPLE algorithm coupling the pressure and velocity field of the tower, and calculate the turbulent kinetic energy, dissipation rate and energy by the second order upwind scheme.

4. Simulation results and analysis

4.1. Verification analysis of cooling tower numerical model

The simulated calculation and experimental measurements of the outlet water temperature of the cooling tower are shown in Table1. In addition to the water flow and air volume, the surrounding environment also can affect the cooling performance of the cooling tower [15]. Since the temperature around the cooling tower was about 288K, which caused the heat transfer from the internal tower to the environment atmosphere through the walls, resulting in a decrease of the fluids temperature in the cooling tower, while the tower walls are assumed to be adiabatic walls in the numerical simulation, so the calculated outlet water temperatures are higher than the experimental values. Although the environmental factors are not considered in the simulation, the outlet water temperatures are relatively reasonable compared with experimental values, therefore, the numerical simulation results are reliable.
Table 1. The experimental and simulation temperature of circulating water

| Water flow /m³/h | Inlet water /K | Outlet water /K | Experimental value | Simulation 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            |

4.2. The effects of packing on cooling performance of the cooling tower

4.2.1. Packing resistance coefficient. The packing in the cooling tower has inertial resistance to the gas-liquid two phases, and the resistance is related to the flow rate and packing type. Using two different sets of packing resistance coefficients that resistance coefficient 2 is two times resistance coefficient 1, the performance parameters of the cooling tower simulated by FLUENT are shown in Fig. 1.

![Graph showing cooling performance with two packing resistance coefficients](image)

Figure 1. Cooling performance of the tower with two packing resistance coefficients

![Diagram of air turbulent kinetic energy distribution in packing cross section](image)

Figure 2. Air turbulent kinetic energy distribution in packing cross section

It can be seen from the Fig. 1 that the increase of packing resistance can reduce the wind loss and the temperature of cooling water outflow, but the effect is not very large: the changing degree of water outflow temperatures is not more than 2.3% and the reducing extent of wind loss is less than 5.5%.
Figure 3. Air effective heat conductivity distribution in packing cross section

Figure 4. The temperature changes of the same water particle in the cooling tower

The increase of the packing resistance coefficient decreases the flow velocity of air, reduces the turbulence fluctuation of the flow field, and then increases the convective heat transfer of the flow field in the tower, as shown in Fig.2 and Fig.3. The velocity of the air flowing through the packing with a larger resistance coefficient is smaller, which indirectly increase the contact time between the gas and liquid in the spray, so the increase of resistance coefficient slightly increases the temperature drop of water particles in the spray, as shown in Fig.4, the temperature changes of one water particle in the tower when the air volume is 8600m³/h and the water flow is 8.15 m³/h.

4.2.2. Packing height. Increase the packing height from 250mm to 500mm and simulate the working conditions of the cooling tower. The cooling performance of the cooling tower with two different packing heights is shown in Fig.5.

Compared with the packing resistance coefficient doubling, the increase of the packing height can effectively reduce the outflow temperature of the water, but greatly increase the wind loss of the cooling tower: the reducing degree of water outflow temperatures is about 39%−64%, but the maximum increase in wind loss is up to 8.7 percentage points.

It can be seen from the Fig.2, 3 and Fig.6, the difference of effective heat conductivity in the same packing cross section of the cooling tower with two filling height is small, therefore, the increase of the packing height equivalent to extend the gas-liquid two phase flow path, increase the convective heat transfer time, so as to improve the temperature drop of outflow water.
4.3. The effects of total pressure on cooling performance of the cooling tower
The performance parameters of axial flow fan include air volume, total pressure, efficiency, etc. The blade profile of the rotor blade plays a decisive role in the performance parameters of the axial flow fan. The performance parameters of cooling tower are related to air volume, cooling water flow, packing and so on. In this paper, the cooling tower is ventilated by two different axial flow fans with fan-shaped type and airfoil type respectively. Under the condition of the same air volume and fan speed, the cooling tower with different rotor blades has different total pressure. According to the simulation results of FLUENT, when the cooling tower uses the same air volume and cooling water flow, the influence of total pressure on the cooling performance of the cooling tower is shown in Fig.7. It can be seen that the wind loss of the cooling tower is slightly due to the total pressure of the cooling tower, which is mainly affected by the mass ratio of gas-liquid two phases: The wind loss of the cooling tower increases with the increase of the gas-liquid two phase mass ratio, and the wind loss increases with the cooling tower total pressure increasing. The greater the total pressure difference, the greater the wind loss.
Figure 7. Wind loss varies with the difference of tower total pressure

5. Conclusion
The three-dimensional numerical simulation of the cooling tower is conducted based on FLUENT. Combined with the physical characteristics of the air and water in the tower, it can be concluded that the total pressure of the cooling tower has little influence on the cooling performance of the cooling tower, which is mainly affected by the flow velocity of the air and water. The increase of the packing resistance coefficient cannot significantly improve the cooling performance of the cooling tower because the function of the fill is to extend the stay time of the water and increase the heat exchange area, so as to increase the heat transfer, therefore, increasing the packing height is more conducive to improving the cooling performance of the cooling tower.

Acknowledgments
This work was financially supported by Science and technology committee of Shanghai (13dz1201700) fund.

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