Study on Temperature Distribution Characteristics of Condensate in Marine Condenser

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Abstract. According to the structure and working principle of the marine condenser, the fluent computing platform is used to establish the numerical model of the flow field related to the condenser, and the simulation results are analysed. The corresponding arrangement scheme of condensate temperature measuring points is proposed to be applied to the practical engineering problems of condensate supercooling control of the condenser, so as to improve the economy and safety of steam turbine unit operation.

1. Introduction
Condenser is an important cooling equipment of steam turbine generator set, which plays an important role in cooling steam exhausted from steam turbine into water and maintaining constant back pressure of steam turbine. In recent years, the numerical simulation of tube-shell heat exchanger in China has focused on shell side, as shown in reference [1-3], and the structure is mainly aimed at segmental baffles. Meanwhile, references [4] and [5] have carried out numerical research on a new type of tube-shell longitudinal flow heat exchanger.

When the ship is sailing in the ocean, the temperature of cooling water required by the condenser changes obviously, which has a certain influence on the condensate temperature of the condenser. According to the structure and working principle of marine condenser, various control equations and calculation models suitable for numerical simulation of condenser are discussed in this paper. Considering the influence of the temperature distribution characteristics of cooling water along the pipe length on the condensation amount, heat exchange coefficient and heat exchange amount of steam, a two-dimensional simplified numerical model of the formation process of condenser condensate is carried out, and a condensate temperature distribution characteristic diagram is obtained.

2. Physical model

2.1 Simplification of Model
Due to the complicated phenomena of flow and heat transfer in large condensers, the formation process of condensed water is simplified as that saturated steam at a certain temperature is liquefied into saturated water at the same temperature when it contacts cold cooling water pipes, and then the saturated water at this temperature is further cooled by cooling water pipes with its temperature reduced, thus resulting in the supercooling degree of condensed water. Since this process is not only complicated but also involves the two-phase flow problem in the condensation heat exchange process, the simulation in this paper simplifies the problem into: the saturated water at the same temperature as the saturated steam is cooled by the cooling water, and the temperature decreases to form the supercooling degree problem.
The two-phase problem is converted into the equivalent single-phase problem for research, as shown in Figure 1 below.

In addition, the following further treatment is required:
1) The cooling water tube bundle area is treated as a group, and the physical field of the tube bundle area is simulated by a porous medium model with distributed resistance and distributed mass sink;
2) Non-bundle area is full of condensed water.

2.2 Mathematical Model
According to the characteristics of Fluent, when conducting two-dimensional numerical simulation research, numerical analysis research is conducted from the three-dimensional calculation model. In the three-dimensional rectangular coordinate system, the steam flow and condensation heat transfer process with distributed mass sinks can be described by continuous equation, momentum equation and turbulence equation. This paper mainly studies the first two equations.

2.2.1 Governing equation.
- Continuity equation,
  \[ \text{div}(\rho U) = S_n \]  
  (1)

- Energy equation,
  \[ \text{div}(\rho TU) = \text{div}\left(\frac{\lambda}{c_p} \text{grad}T\right) + S_r \]  
  (2)

2.2.2 Source Item.
Because the actual physical process is simplified, the phase change heat transfer problem of steam is simplified to the single phase convection heat transfer problem of saturated water at the same temperature.

The equivalent amount of saturated water flowing in at the same temperature:
\[ S_n = \frac{\alpha_s A(t_r - t_s)}{\pi d^2 lr} \]  
(3)

- In non-bundle area,
  \[ S_n = 0 \]  
(4)
\[ S_0 = 0 \quad (5) \]

- In bundle area,
\[ S_i = \frac{\alpha^* A_i}{\pi d^2} \left( t_i - t_w \right) \left( h_e - h_g \right) \quad (6) \]

2.2.3 Boundary conditions
Since the incoming steam is simplified to condense into water, a mass distribution source term with a certain distribution form can be added above the tube bundle area, i.e. \( S_m \). Alternatively, a velocity distribution inlet with a certain form can be arranged at the inlet, and the form is as follows,
\[ v_w = \frac{S_m}{S_w \rho_w} = \frac{\alpha^* A_i}{\pi d^2} \left( t_i - t_w \right) \left( \frac{x+l}{2} \right) \left( \frac{t_{in} - t_{out}}{l} \right) \quad (7) \]

Among them, \( v_w \) is the velocity distribution of saturated water inlet and \( S \) is the cross-sectional area of condenser inlet (as mentioned earlier, for the two-dimensional numerical solution simulation in Fluent, it is equivalent to stretching the two-dimensional model by 1 meter to become a three-dimensional numerical simulation problem). The outlet is set as pressure outlet boundary condition, and the others are wall condition. At the same time, in order to do better engineering application, pressure inlet can also be set, and compared with flow inlet.

In addition, we can also see from equation 14 above, the distribution form of \( v_w \) is the same as that of the mass source term \( S_m \). That is when the value of \( x \) is the smallest, the value of \( v_w \) is also the largest. In other words, the quality of heat exchange at the cooling water inlet is relatively large.

3. Numerical simulation

3.1 Example Model and Grid Partition
According to the above analysis, we can simplify it to the simulation model shown in the following Figure 2.
The three parts of the calculation area are meshed as shown in Figure 3 below. The middle part is a porous medium area. As this part plays an important role in the research, the mesh can be inconsistent with the non-bundle area according to the calculation requirements.

Figure 3. Grid division.

3.2 Simulation Results of Steady State Working Conditions

According to the actual situation of the problem, Fluent was used to carry out numerical simulation research on simplified models under several typical working conditions respectively, and the temperature distribution characteristics of condenser condensate were obtained.

Figure 4 shows the simulation results of condensate water temperature distribution under different cooling water temperatures, where a and c are the calculation results of constant cooling water temperatures of 18.5℃ and 4℃, respectively, and heat exchange quantity has certain distribution along the length direction of cooling water pipes. The inlet temperatures of B and D are 18.5℃ and 4℃, respectively. The temperature has a certain distribution along the length direction of the cooling water pipe, and the heat exchange amount is a fixed value along the length direction of the cooling water pipe.
Figure 4. Condensate water temperature distribution chart under different cooling water temperature conditions.

It can be seen from the results that considering the linear distribution of cooling water temperature and heat transfer coefficient along the length direction of the cooling water pipe, the temperature of condensate water at the outlet is not uniform along the whole length direction of the pipe.

3.3 Numerical Simulation Results under Off-design Conditions

As shown in Figure 6 below, the inlet and outlet temperatures of cooling water under the four working conditions are different, and the energy has certain distribution along the length direction of the cooling water pipe, and the heat exchange amount is the same.
From the results, it can be seen that under variable working conditions, as long as the cooling water has a certain linear distribution along the length direction of the cooling water pipe, the temperature of the condensed water at the condenser outlet is also inconsistent, and the supercooling degree at the leftmost end and rightmost end is inconsistent. Therefore, the model is reasonable.

4. Conclusion
Since the cooling water has a linearly increasing temperature distribution along the length of the pipe, theoretically the temperature in the condensation water area should also be substantially linearly distributed. Therefore, the closer the condenser wall temperature changes with the tube length to the outlet of the cold circulating water, the higher the wall temperature, which also leads to a linear distribution of the temperature in the condensed water collection area.

The temperature of the central area of the condensation zone can generally represent the temperature of the entire condensation zone, and the temperature measuring point can be arranged near the midpoint of the length direction of the hot well below the condenser, i.e. within the central area of the condensation water collection zone.

However, in the actual condenser, the temperature difference in the condensation water area will not be particularly obvious during the falling process of the water in the condensation water collection area through the sputtering and temperature equalization of the metal mesh. Therefore, the arrangement range of condenser condensate water temperature measuring points can be expanded as long as they are generally arranged in the central area in the length direction of the thermal deaeration system of the hot well.

The condensation water temperature measuring point at the condenser outlet is the temperature measuring point before deaeration of the hot well. In the condenser temperature control program, the temperature measuring value of the measuring point will be used for feedforward control of condensation water supercooling degree control of the thermal deaeration system of the hot well.

Nomenclature
\( S_m \) mass source term of the tube bundle area, that is, the amount of condensed steam
\( \alpha \) total heat transfer coefficient of steam to the cooling pipe wall

\( l \) total length of the condenser cooling water pipe

\( d \) diameter of condenser

\( S_r \) energy source term in tube bundle area

\( r \) latent heat released by steam condensation

\( t_s \) steam temperature

\( t_c \) cooling tube wall temperature

\( A \) total heat exchange area in the condenser

\( h_s \) enthalpy of saturated water at the same temperature of steam

\( h_x \) enthalpy value of condensed water when supercooling exists

\( v \) circulating water flow (cooling water)

\( t \) average temperature of cooling water

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