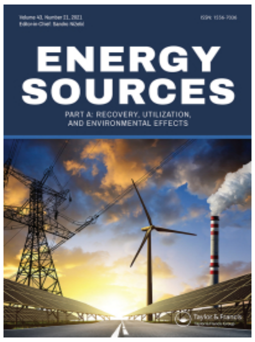

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Correction algorithm for calculating heat transfer in air-cooling condenser based on analyzing steam condensation locations

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ABSTRACT

A correction algorithm based on analyzing the steam condensation locations is proposed to address the problem of large errors when calculating the heat transfer of the air-cooling condenser (ACC) in Fluent. By building a detailed geometric model of the ACC and using radiator boundary conditions to simplify the heat-sinking tube bundle, Fluent software was used to calculate the heat transfer of the ACC under four winter operating conditions, and then, the calculation results were further corrected by applying the correction algorithm. The results show that after using the correction algorithm, the errors between calculation results and experiment data are reduced from 4.20~36.98% to 0.01~1.79%. When the electric load of the air-cooling generator set or the ambient temperature was low, the condensation velocity increased, for which there would be a local steam-free area in the heat-sinking tube bundle of the ACC, leading to large errors when using the radiator model. At this point, the correction algorithm based on the analysis of steam condensation position can serve to improve the degree of accuracy. Meanwhile, this correction algorithm can be further expanded to use in the simulating calculation of an indirect air-cooling generator set, and it is able to correct the heat transfer calculation result of the air-cooling tower by analyzing the heat transfer condition of circulating water in the heat-sinking tube bundle, so that reliable data can be provided to guide the anti-freezing of the indirect air-cooling generator set.

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KEYWORDS
Air-cooling condenser; steam condensation location; correction algorithm; flow heat transfer calculation; fluent

Introduction

Air-cooling condenser (ACC) is the core component of the cooling system in an air-cooling generator set, and its heat transfer performance will directly affect the back pressure of the generator set, which in turn affects its operating economy and safety. Since the ACC uses external air as the cooling medium, its flow and heat transfer characteristics are closely related to the environmental conditions, so the heat transfer characteristics of the ACC under different environmental conditions have been widely studied by researchers in the field.

At present, the most reliable way of research on ACC is field research. Du et al. (2011) used the neural network model to predict the operating pressure of the ACC in different working conditions based on the data obtained from the field experiment of a direct air-cooling generator set in North China. Luo et al. (2021) established a scaled-down model of direct air-cooling fan array to

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study the zoning scheme and clustering effect of fan array through experiments and proposed a control strategy that can effectively reduce fan power consumption. Marincowitz, Owen, and Muiyser (2019) analyzed the wind resistance performance of the windscreen by using a laboratory-based experimental apparatus consisting of a scaled fan row. Liu et al. (2013) conducted experiments of adjusting parameters in different zones of the ACC fan array to test the working performance in a 2×330 MW direct air-cooling generator set and found that the effects of fan speed on the back pressure and coal consumption vary in each fan region of the generator set, and the most significant parameter affecting the generator set performance was the fan speed. Chen et al. (2019) conducted experimental research on finned tube bundles with different geometric shapes and derived heat transfer correlations for finned tube bundles with different shapes. Ge et al. (2011) used infrared thermal imaging technology to monitor the surface temperature of the ACC of three typical direct air-cooling generator set in Northern China. The results showed that the upstream unit in the ACC was more likely to freeze in winter. Zhao et al. (2022) used the digital twin model to analyze the historical data of a direct air-cooling generator set and then proposed a set of fan frequency control logic accordingly, which helped the unit save 535.526 tons of standard coal in 2 weeks.

The results obtained from the above field studies are reliable and accurate, but the various costs of the field experiments are high, and ACC operation under some extreme operating conditions cannot be simulated due to the limitations faced during the normal operation of the ACC. In this context, numerical simulation has been extensively used in the study of ACC operation because of its lower cost and better flexibility. At present, researchers always use mechanism models to simulate the different operating conditions of the power plant. Feng and Luo (2019) established a mechanism model based on the number of transfer units (NTU) method for a 660-MW power plant, calculated the optimal back pressure, and discussed the antifreeze performance of the isolation valves. Zhu et al. (2018) established a static model based on the NTU method, considered the fan operating status, and found that the ACC may not meet the heat dissipation requirement when the air temperature is relatively high. Zhang et al. (2021) proposed a system mathematical model of the ACC and introduced two types of fan control methods to cope with the ambient temperature fluctuation. Zhu et al. (2021) established a direct air-cooling condenser dynamic model and a detailed turbine-feedwater heater system model and then proposed a variable condenser pressure operating method for the air cooling power plant. The aforementioned models are based on the ACC operating mechanism, and these models are one-dimensional model, which is able to compose a complex system and is suitable for optimal research. However, a one-dimensional model cannot precisely calculate the off-standard and extreme operating conditions, because the ambient influence is a three-dimensional element, such as the ambient wind, and the empirical formula cannot accurately describe fluid flow changes such as eddy current.

The computational fluid dynamics (CFD) method is an effective tool for the three-dimensional flow and heat transfer study, which is widely used by researchers. Bekker, Meyer, and van der Spuy (2023) analyzed the wind resistance performance of the wind wall and wind skirt by using the CFD software OpenFOAM. Wang et al. (2020) studied the effects of the ambient wind speed on the ACC by using the CFD method. Deng et al. (2020) used the CFD method to calculate the steam condensate situation in the finned tube under the cold weather. Chen et al. (2016) analyzed the effects of the louver opening degree on the ACC's antifreeze performance by using the numerical simulation method. Guo et al. (2017) established the flow and heat transfer models of the cooling air couped with the circulating water by using the CFD method and analyzed the freezing risk at different positions in the ACC. Chen et al. (2021) used the steam enthalpy to describe the water phase state change and simulated the performance of the subregional modulation upon the fan array. In the aforementioned simulation studies of the ACC, the principal method for simplifying the heat-sinking tube bundle is to ignore the geometry of the finned tube and replace it by the heat transfer coefficient, resistance coefficient, and condensation temperature. This treatment method is relatively accurate in normal operating conditions; however, when the ambient temperature is below 0°C, there will be large errors because of accelerated steam condensation.

To solve the problem of large simulation errors in winter operating conditions after simplifying the heat-sinking tube bundle of the ACC, a correction algorithm based on the analysis of steam condensation locations in the ACC unit tube is proposed. This method can correct the heat transfer calculation results of the ACC in winter operating conditions by calculating the steam condensation situation in the heat-sinking tubes and then improve the preciseness of the ACC simulating analysis. In addition, the correction algorithm can also provide support for the correction of the heat transfer calculation of the indirect air-cooling generator set when there is a freezing risk of the circulating water in the tube under winter conditions.

The ACC geometric model and mesh generation

The ACC discussed in this article belongs to a 4 × 660 MW coal-fired power plant, which has two ACC islands side by side. Each ACC island has 128 ACC units in 8 rows and 16 columns, where each column is composed of five downstream units and three upstream units. Select the ACC island on the windward side as the object of geometric modeling, because the leeward ACC island is less affected by the ambient wind.

The geometric model

The geometric model of the ACC is shown in Figure 1. According to the design parameters of the ACC and the blueprint of the powerhouse, the ACC and its surrounding buildings were modeled in detail, mainly restoring the support columns and steel brackets under the ACC, the outer wind-blocking wall, the inner ACC unit, and the steam distribution pipe extending from the main plant to the top of the ACC. The main plant next to the ACC includes the steam engine room, boiler room, deaerator room, and coal bin.

Since the object of flow heat transfer calculation is the air around the ACC, it is necessary to extract the air zones near the ACC and delete the solid zones in the geometric model. As shown in Figure 2, the size of the air region near the ACC is chosen as 1 km × 1 km × 0.6 km, and a buffer area is left around the ACC to reduce the turbulence intensity near the air region boundaries to improve the stability of the calculation.

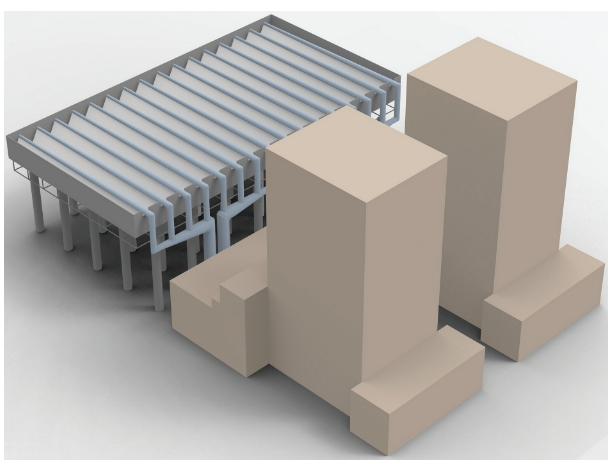

Figure 1. Geometric model of the ACC.

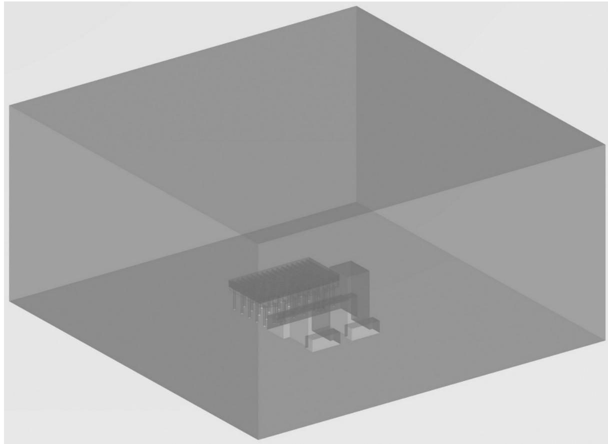

Figure 2. Air zone around the ACC.

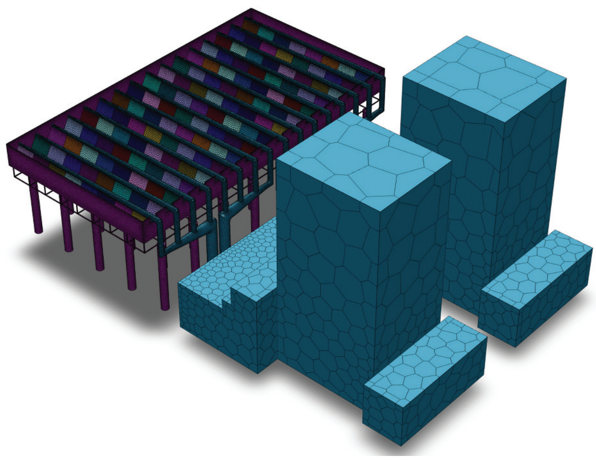

Figure 3. Mesh of the ACC model.

Mesh generation

The dimensional span of the ACC is large, in which the spacing between the steam distribution pipe and the connection to the ACC unit is around 0.30 m; however, the height of the main plant reaches 120 m. In order to reduce the overall mesh number of the ACC model while ensuring the accuracy of the calculation, the ACC model is non-uniformly meshed by using Fluent Meshing software, and the mesh type is unstructured polyhedral (Figure 3).

The results of mesh-independence verification are shown in Figure 4. When the mesh number is greater than 5 million, the calculated value of the total heat transfer of the ACC begins to stabilize, and when the mesh number is not less than 8 million, the fluctuation of the heat transfer of the ACC has been reduced to less than 1%. It can be considered that when the number of mesh is greater than or equal to 8 million, continuing to encrypt the mesh will not have a remarkable impact on the calculation results, and the mesh independence is successfully verified. Therefore, the amount of mesh in the air region of the ACC is set to 8 million.

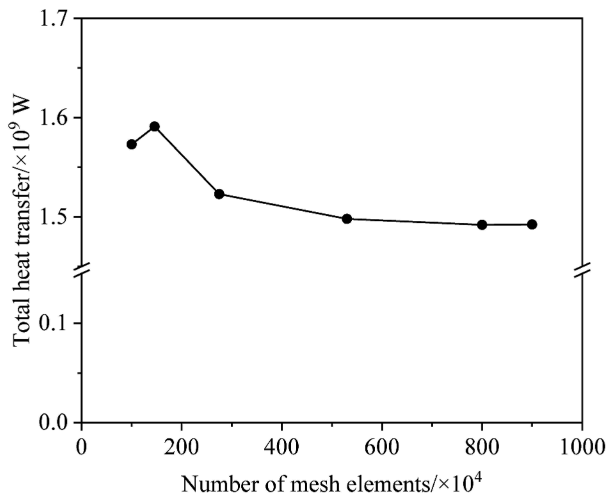

Figure 4. Mesh-independence verification.

Simulation model and correction algorithm

Turbulence model

The standard k-ε two-equation model was applied to work out the characteristics of the turbulent flow of air for the ACC in its air flow process. This model was proposed by Launder and Spalding (1974), which adds the ε turbulent kinetic energy dissipation velocity equation to the k turbulent kinetic energy equation to form the k-ε two-equation model. The airflow process in the ACC can be approximated as incompressible flow, and there is no item of the turbulence source in the model, so the k-ε equations are shown as Eqs. (1) and (2). The values of the coefficients are as follows: $Pr_k = 1.00$, $Pr_\varepsilon = 1.30$, $C_{1\varepsilon} = 1.44$, and $C_{2\varepsilon} = 1.92$ (Rezaei and Seif 2022).

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{Pr_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \tag{1}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{Pr_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon} G_k \frac{\varepsilon}{k} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{2}$$

In the equations, ρ stands for the density, kg/m^3; k for the turbulent kinetic energy, m^2/s^2; t for the time, s; u_i and u_j for the velocities, m/s; x_i and x_j for the spatial locations, m; μ for the dynamic viscosity, Pa·s; μ_t for the coefficient of the turbulent dynamic viscosity, Pa·s; Pr_k for the turbulent Prandtl number for the k-equation; G_k for the turbulent kinetic energy increase caused by the average velocity gradient; ε for the turbulent kinetic energy dissipation velocity, m^2/s^3; Pr_ε for the turbulent Prandtl number for ε equation; $C_{1\varepsilon}$ and $C_{2\varepsilon}$ for the constant coefficients.

Solving algorithm

Compared with Semi-Implicit Method for Pressure Linked Equations (SIMPLE), the Semi-Implicit Method for Pressure Linked Equations Consistent (SIMPLEC) algorithm used as a solving algorithm has a better convergence in the process of working out the solving algorithm for the simulation model of ACC. The algorithm is based on the iterative idea of "assumption-correction," and the main solution process is as follows:

(1) Initializing to assign an initial value to the variables in the equation;
(2) Working out the velocity field by substituting the initial pressure field in the momentum equation;
(3) Correcting the pressure field by substituting the velocity field in the continuity equation;
(4) Solving the turbulence equation and the rest of governing equations;
(5) Determining whether the iteration converges; if it converges, stop the iterating; if it does not converge, use the calculated value of this iteration as the initial value of the next iteration, and continue iterating from step 2.

Treatment of the heat-sinking tube bundle

As the arrangement of fins in the heat-sinking tube bundle is relatively dense, it is necessary to apply an equivalent model to simplify its geometric structure. The radiator boundary conditions are provided in the Fluent software, which can save a lot of computational resources by applying these boundary conditions to equate the complex geometry of the heat-sinking tube bundle to a zero-thickness plane in equivalence. For the radiator boundary conditions, the idea of an all-parameters-based model was applied to abstract the flow heat transfer characteristic of the heat-sinking tube bundle as resistance coefficient k_L (related to the air velocity v_a) and heat transfer coefficient h, and to define the steam condensation temperature inside the heat-sinking tube bundle as the heat transfer temperature T_s. The values of the aforementioned parameters are shown in Table 1.

Correction algorithm for calculating heat transfer

In the process of simplifying the heat-sinking tube bundle by using the radiator boundary conditions, its heat transfer temperature is defined as the steam condensation temperature inside the heat-sinking tube bundle. In the normal operation conditions, the ACC unit is basically in the two-phase section of gas–liquid mixture, so it is reasonable to define the heat transfer temperature as the steam condensation temperature. However, on winter operating occasions, ambient temperatures are low, and the amount of steam condensation in the downstream unit increases, which instead leads to a reduction in the flow of steam into the upstream unit. Along with low ambient temperatures, the upstream unit will experience early condensation of steam, and there will be a certain length of vacuum section inside the upstream unit. Since the heat transfer temperature of the entire ACC unit is defined as the steam condensation temperature within the radiator boundaries, the heat transfer amount calculated using this boundary will be higher than the actual value, resulting in a wider error in calculation.

To solve the problem discussed earlier, a correction algorithm based on the analysis of steam condensation locations in the ACC unit is proposed. As shown in Figure 5, i and j represent different ACC units; Q_{d_i} and Q_{u_j} are the heat transfer of the downstream and upstream ACC units, respectively; q_s is the total steam mass flow rate; n_{unit} is the number of the active ACC units; r is the latent heat of the steam; q_{d_i} and $q^c{}_{d\_i}$ are the steam inlet mass flow rate and condensate mass flow rate of single downstream ACC unit, respectively; $Q_{d\_i\_modify}$ and $Q_{u\_j\_modify}$ are the corrected heat transfer of the downstream and upstream ACC units, respectively; q_{u_j} and $q^c{}_{u\_j}$ are the steam inlet mass flow rate and condensate mass flow rate of single upstream ACC unit, respectively; d_i is the distance between each downstream ACC unit and the target upstream ACC unit in the same column; d_t is the total distance between all downstream ACC units and the target upstream ACC unit in the same column. For the heat transfer correction process, first, calculate q_{d_i} and $q^c{}_{d\_i}$, and then compare their

Table 1. Parameter values of the radiator boundary conditions.

Parameter	Unit	Value
k_L	-	$27.12v_a^{-0.45}$
h	W/(m²·K)	3835.21
T_s	°C	Changed with the dump steam pressure

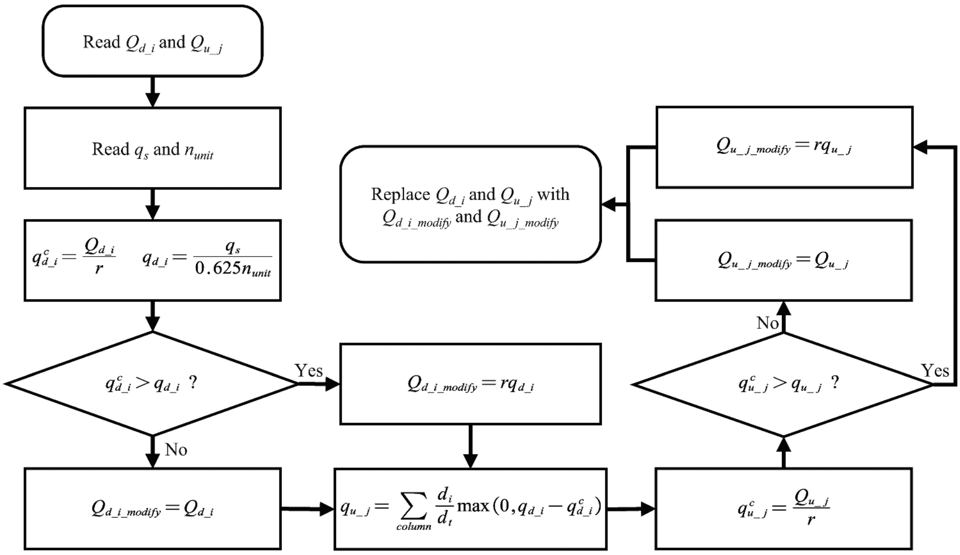

Figure 5. Correction process of the correction algorithm.

values. If $q^c{}_{d\_i} > q_{d\_i}$, it means that the condensate mass flow rate is bigger than the inlet steam mass flow rate, which is unreasonable, so the corresponding Q_{d_i} need to be corrected as $Q_{d\_i\_modify}$; if $q^c{}_{d\_i} \leq q_{d\_i}$, it means that the corresponding Q_{d_i} is relatively accurate. Second, summarize the downstream unit calculation results, distribute the remaining non-condensed steam to the upstream unit by distance (d_i) weighting, and then calculate q_{u_j} and $q^c{}_{u\_j}$. Third, repeat the heat exchange correction process to upstream units and get $Q_{u\_j\_modify}$. Finally, replace Q_{d_i} and Q_{u_j} with $Q_{d\_i\_modify}$ and $Q_{u\_j\_modify}$, the correction process is finished.

Results and discussion

Experiment data

To evaluate the outcome of the simulation correction algorithm described in the "Correction algorithm for calculating heat transfer" section, part of the experiment data of this air-cooling system under actual winter operating conditions were obtained from the air-cooling generator set mentioned in the "Introduction" section, and four operating points were selected from these data as the boundary conditions for Fluent simulating calculations. The local weather conditions during this experiment data acquisition were good, clear with breezes, so the influence of ambient wind was ignored in the Fluent calculation process, and the air circulation in the ACC mainly relied on the axial flow fans below the ACC unit. The detailed information of the experiment is shown in Table 2.

Table 2. Detailed information of the experiment.

		Value			
Parameter	Unit	Point 1	Point 2	Point 3	Point 4
Electric loading	MW	649.89	467.61	530.24	271.57
Ambient temperature	℃	−4.92	0.60	−11.64	−3.45
Dump steam temperature	℃	42.06	44.22	37.60	43.81
Dump steam pressure	kPa	8.23	9.21	6.49	7.92
Fan frequency	Hz	48	50	24	23
Air-cooling unit condition	-	All put into operation	Shut down the rows 1 and 6	All put into operation	Shut down the rows 1 and 6

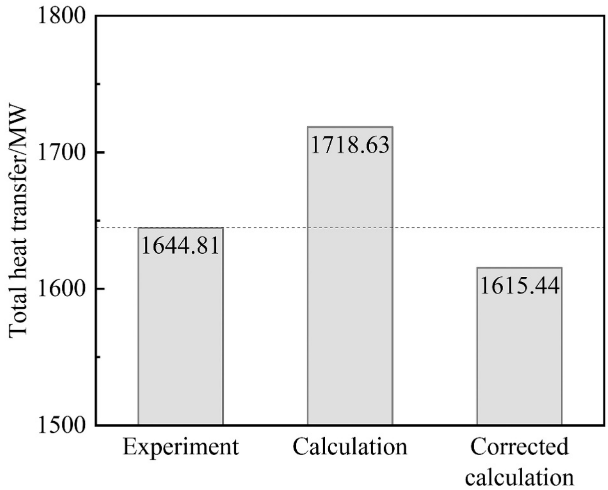

Figure 6. Experiment, calculation, and corrected calculation results under operating point 1.

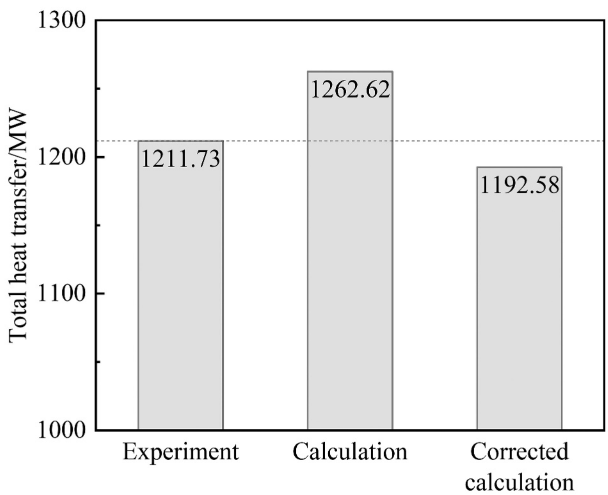

Figure 7. Experiment, calculation, and corrected calculation results under operating point 2.

Correction algorithm performance evaluation

Figures 6–9 show the comparisons between the experiment data and the simulation results before and after the correction process. It illustrates that before the correction process, the calculated heat transfer is generally higher than that in the experiment, and its relative error is 4.49, 4.20, 11.94, and 36.98% at points 1–4, respectively. After the correction process, the relative error between the simulation results and the experiment data is decreased to 1.79%, 1.58, 0.47, and 0.01% at points 1–4, respectively, and the corrected result is generally lower than the experiment data. It shows that the correction algorithm has a good correction performance under winter conditions and can effectively improve the accuracy in the heat transfer calculation of the ACC unit.

When comparing the boundary conditions of points 1 and 3, the electric loading and ambient temperature of point 3 are lower than those of point 1, which leads to the higher calculation error of point 3 before the correction. This is because that when the electric loading is reduced, the steam mass flow of the ACC unit is reduced and due to the decrease in the ambient temperature, the steam

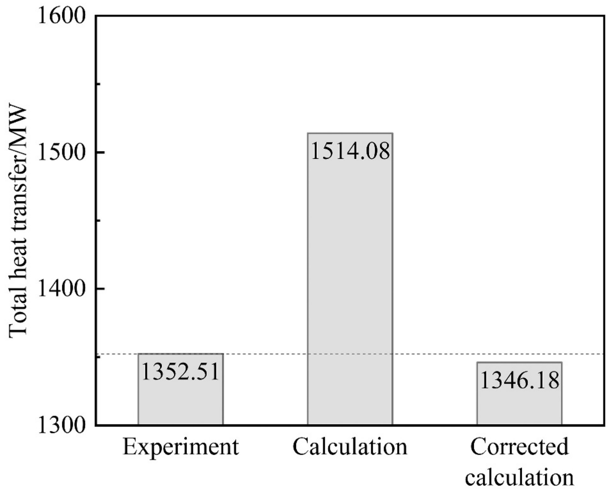

Figure 8. Experiment, calculation, and corrected calculation results under operating point 3.

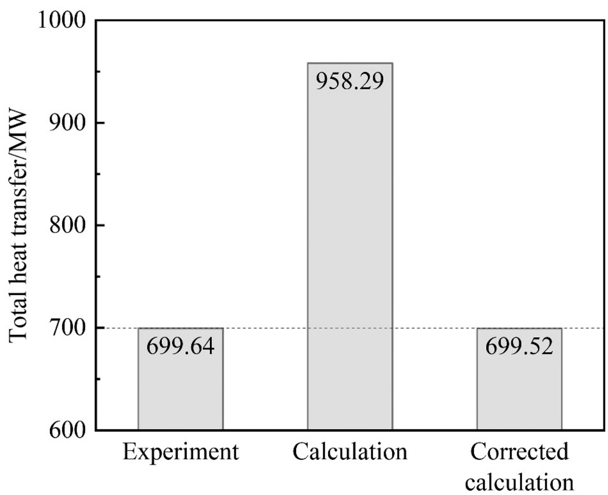

Figure 9. Experiment, calculation, and corrected calculation results under operating point 4.

condensation process of the ACC unit is relatively accelerated, which leads to the appearance of liquid or vacuum sections inside the ACC unit. The same conclusion can be drawn after comparing the boundary conditions and results of points 2 and 4 that the electric loading and ambient temperature are lower in point 4, so the calculation error of point 4 is 36.98% before the correction, which is much higher than that of point 2 (4.2%).

After correcting the calculation results, the relative error between the corrected result and experiment data of point 1 is reduced from 4.49 to 1.79%, and the relative error of point 3 is reduced from 11.94 to 0.47%. It can be found that after the correction, the calculation error is smaller when the electric loading and ambient temperature are lower, this is because that the heat transfer of the ACC unit is closer to the steam latent heat when the steam condensation process is accelerated. This is the same between points 2 and 4; after the correction, the relative errors of points 2 and 4 are 1.58% and 0.01%, which indirectly proves the validity of the calculation logic in the correction algorithm.

For points 1 and 2, the calculation errors before and after correction are relatively close. This can be explained as the decrease in electrical load is offset by the increase in ambient temperature. However, the calculation error of points 3 and 4 cannot be explained by this law, because they have a larger difference in the dump steam temperature. To quantitatively analyze the impact of steam condensation speed on calculation errors, a parameter named σ_{cond} was proposed to represent the steam condensation speed in Eq. (3). σ_{cond} is the proportion of excess heat transfer capacity, which represents the excess condensation speed of ACC under current boundary conditions. The bigger σ_{cond}, the faster the steam condensation. According to the calculation result in Figures 6–9, σ_{cond} of points 1–4 are 6.39, 5.88, 12.47, and 37.00% respectively. So, the close calculation error of points 1 and 2 is because that their σ_{cond} are relatively similar, the remarkable different calculation error of point 3 and point 4 is because there is a large gap between their σ_{cond}. Moreover, it can be found that the calculation errors of the ACC without the correction are proportional to σ_{cond}, and the corrected calculation errors of the ACC are inversely proportional to σ_{cond}, which means the steam condensation speed has a direct effect on the calculation error of the ACC, and it directly proves the validity of the calculation logic in the correction algorithm.

$$\sigma_{\text{cond}} = \frac{Q - Q^*}{Q^*} \tag{3}$$

where σ_{cond} stands for the proportion of excess heat transfer capacity, %; Q for the heat transfer of ACC without the correction, MW; Q^* for the corrected heat transfer of ACC, MW.

In conclusion, the proposed correction algorithm can effectively improve the accuracy of ACC heat transfer calculation. The ambient condition will affect the steam condensation speed in the ACC unit, and when the steam condensation process is accelerated, the calculation error without the correction is increased and the corrected calculation error is decreased, which proves the validity of the calculation logic in the proposed correction algorithm.

Conclusion

A correction algorithm based on the analysis of steam condensation locations in the ACC unit tube is proposed; after comparing the performance between ordinary method and the correction algorithm, the conclusions are as follows:

(1) When using the simplified heat-sinking tube bundle model (such as radiator) to calculate the heat transfer condition of the ACC in winter, there will be a large error when the ambient temperature is lower than 0°C. It is because that when the ambient temperature is lower, the steam condensation is accelerated, and the actual heat transfer process is deviated from the standard operating conditions of the simplified model.

(2) A correction algorithm based on the steam condensation situation analysis is proposed to improve the heat transfer calculation accuracy of the ACC. Compared with the ordinary heat transfer calculation method, the correction algorithm can realize the error reduction up to 36.97% (from 36.98 to 0.01%, at operating point 4).

(3) When the ambient temperature decreases, the correction algorithm will show better performance. When the ambient temperature decreased from −4.92 to −11.64°C, the error reduction is increased from 2.70 to 11.47%; and when the ambient temperature decreased from 0.60 to −3.45°C, the error reduction is increased from 2.62 to 36.97%.

(4) The correction algorithm can be further expanded to the simulating calculation of air-cooling tower in indirect air-cooling operating set. An effective analysis of the condensation amount in local areas of the heat-sinking tube bundle can achieve the correction of the calculated heat transfer of cooling towers when there is a risk of circulating water freezing inside the heat-sinking tube bundle in winter, which can provide powerful data support for improving the operational safety and economy of indirect air-cooling operating set.

(5) For the future work, it is necessary to further combine CFD calculation with one-dimensional mechanism model, enhance the accuracy of CFD calculation under various operating conditions, and increase the practicability of CFD calculation in the process of engineering design.

Disclosure statement

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