Performance Research on Mechanical Draft Wet Cooling Tower under Variable Operating Conditions

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***Abstract*—Based on the enthalpy difference theory and the characteristics of the mechanical draft cooling tower, a mathematical method of the cooling tower performance is derived to analyze the influence of operating parameters on tower outlet water temperature. The results show that the influence of atmospheric pressure and dry-bulb temperature on the tower outlet water temperature is negligible. The wet-bulb temperature is the main environmental factor affecting the cooling tower performance. Cooling water flowrate, condenser heat load, failure cooling area and draft resistance all have a positive correlation with tower outlet water temperature. While the air flowrate of the fan increases, the tower outlet water temperature will decrease. The above conclusions will help to accurately predict the changing trend of tower outlet water temperature under variable operating conditions, and provide guidance for the adjustment of cooling tower operation under variable conditions.**

***Index Terms*—cooling performance, cooling tower, mathematical model, tower outlet water temperature, variable operating condition**

I. Introduction

The cooling tower is an indispensable cold-end equipment in thermal power plants. The performance of the cooling tower directly determines the circulating water temperature, and thus affects the condenser vacuum. Therefore, the operating performance of the cooling tower is of great significance to the economy of the generator set [1]. Compared to natural draft cooling towers, mechanical draft towers have the advantages of low initial investment, small floor area, and short construction period, and they have been widely applied in high-temperature and high-humidity areas, industrial parks, and peak utilization gas turbines [2], [3]. The research shows that the improvement of the generating unit thermal efficiency is positively related to the reduction of the tower outlet water temperature. The cooling tower kept in the best working condition can improve the power generation efficiency [4]-[6]. With the change of generator load and environmental parameters, the cooling tower operating conditions are constantly changing [7]. If the mechanical draft cooling tower always works in the design operation mode, it will cause the cooling tower fan and circulating pump power consumption to not match with the steam turbine micro power increase. Therefore, the cooling tower operation mode needs to be targeted and reasonably optimized [8], [9].

So far, the main research object is still the natural draft cooling tower. The research direction is numerical calculation and model test [10]-[13], the influence of the ambient crosswind on the performance of the cooling tower and the countermeasures [14]-[17].

Heat and mass transfer inside a natural draft wet cooling tower (NDWCT) have been investigated numerically under different operating and crosswind conditions [10]. The three-dimensional CFD model has utilized the standard k–e turbulence model as the turbulence closure. The current simulation has adopted both the Eulerian approach for the air phase and the Lagrangian approach for the water phase. The film nature of the water flow in the fill zone has been approximated by droplets flow with a given velocity. The required heat and mass transfer have been achieved by controlling the droplet velocity. At that specific droplet velocity, effects of the following operating parameters on the thermal performance of the NDWCT have been investigated: droplet diameter, inlet water temperature, number of nozzles, water flow rate and number of tracks per nozzle. As a result, the effect of crosswind velocity on the thermal performance has been found to be significant. Crosswinds with velocity magnitude higher than 7.5 m/s have enhanced the thermal performance of the NDWCT.

Chen and Sun *et al*. [13] have performed a hot model test of natural draft wet cooling towers (NDWCTs) to investigate the effect of cross walls on the thermal performance of NDWCTs under crosswind conditions. The hot model test can simulate the actual operation of a prototype tower by operating a model tower at steady state conditions while varying the temperature and flow rate of the incoming hot water along with the crosswind velocity. Cross walls of two shapes at different setting angles were installed in the rain zone and tested under various operating conditions. The results show that crosswinds degrade the NDWCT performance below a critical crosswind velocity, but improve the performance

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above critical crosswind velocity. Increasing water flow rate and inlet water temperature can raise critical crosswind velocity. Installing cross walls can improve the NDWCT performance. At low crosswind velocities, the solid wall leads to better NDWCT performance than the porous wall. However, the opposite effect is obtained at high crosswind velocities. At all crosswind velocities, the cross wall at a setting angle of 0° results in higher performance than that at 45°, regardless of cross wall shapes. Moreover, the cross wall at 45° degrades the NDWCT performance under high crosswind conditions.

Based on CFD code FLUENT, three-dimensional numerical analyses were carried out for natural draft wet cooling tower under crosswind conditions by Zhao and Sun *et al*. [16]. Sensitivity analyses to parameters such as ambient crosswind velocity profile and water droplet equivalent diameter validated the adopted numerical model. The effect of crosswind on wet cooling tower inner and outer aerodynamic field and tower internal heat and mass transfer performance were investigated numerically. The results show that crosswind causes the increase of air inflow relative departure degree and induces horizontal air mass flow rate which improves rain zone heat and mass transfer but reduces tower vertical air mass flow rate, and then produces an unfavorable effect on fill zone and increases outflow water temperature. The analyses about air inflow relative departure degree show that improving the air inflow aerodynamic field can reduce the unfavorable effect of crosswind on the circumference distribution of air inlet air radial velocity and then improve the total cooling performance of wet cooling tower under crosswind conditions.

In the coming period, the gas-fired power generation industry will usher in a period of rapid development, and the most commonly used mechanical draft cooling towers for gas-fired generating units should obtain their accurate operating characteristics as soon as possible. At present, there are relatively few studies on mechanical draft cooling towers [18]-[25].

Rahmati [18] deals with an experimental investigation of thermal performance of mechanical draft wet cooling towers by changing various parameters such as hot water temperature, water flow rate, air mass flow rate and stage numbers of packing. Naik [19] proposes a simple analytical model for calculating the amount of water taken up by the ambient air in a cross-flow wet cooling tower. An expression is derived using the condenser and the cooling tower effectiveness, to estimate the water evaporation loss of the cooling tower in terms of known inlet parameters. A constrained multiple parameter inverse identification technique is proposed for a mechanical cooling tower to meet a required heat rejection rate from hot water and also ensuring minimum power consumption [20].

Rao and More [21] explores the use of an improved Jaya algorithm called self-adaptive Jaya algorithm for optimal design of mechanical draft cooling tower from economic facets. The proposed self-adaptive Jaya algorithm determines the population size automatically and it is proved better as compared to the other optimization methods with respect to achieving the optimal value of the objective function at less computational effort. A feedback model has been proposed in order to control the performance of a mechanical draft cooling tower under varying heat load conditions suiting diverse applications such as solar power generation, HVAC and diesel engine [22].

In order to know the aerodynamic characteristics of the cooling tower and its changing regulation, the aerodynamic characteristics of the airflow around air inlet of counterflow mechanical draft cooling tower were studied through physical model experiment, and the formula for its resistance calculation was given [23]. It was demonstrated that, the calculation result of the resistance of the airflow around air inlet using the code formula tended to be inaccurate. The study results can provide reference for the design of cooling tower.

In the cold district of the North China, plume usually appears around the outlet of mechanical draft cooling tower, which would have adverse impact on surrounding environment. Wang and Feng *et al*. [24] studied the formation mechanism and the prevention method of the plume around mechanical-draft cooling tower, and found that the using of dry-wet joint cooling towers is one of the effective measures to eliminate the plume.

The spacing distance between two parallel mechanical draft cooling tower rows was designed too large according to the relevant Chinese Design Codes in a 4×600 MW Thermal power plant. A mathematical model experiment was made to analyze the influence of local practical environment factor and spacing distance of tower row on cooling capacity, evaluate the environmental wind's influence on reflux and disturbance of exhaust wet air in different cooling tower row layouts, and optimize the cooling tower row layout [25]. It was concluded that as its long axis parallels the dominate summer wind direction, the spacing distance has no influence on wet air reflux and spacing distance can be decreased from 51 m to 21.6 m, and thereby the site area of the plant is reduced with guaranteed cooling capacity.

This paper proposes to establish a thermal calculation model for mechanical draft cooling towers under variable conditions, and comprehensively studies changes in cooling performance with environmental parameters, generator load, and circulating water parameters, and provides theoretical basis for optimizing the operation of mechanical draft cooling towers.

II. Cooling Tower Mathematical Model

The cooling tower performance mathematical model consists of aerodynamic calculation and thermal calculation. The aerodynamic calculation is mainly the balance calculation of the cooling tower draft resistance and the total pressure of the axial fan. The thermal calculation is mainly the balance calculation between the cooling capacity and the cooling task of the tower.

A. Aerodynamic Calculation

1) Draft resistance

$$H_{tot} = \sum\left(K_j V_j^2 \rho_m / 2\right) \quad (1)$$

where H_{tot} is the total draft resistance of the cooling tower, K_j is the resistance coefficient of each component of the cooling tower, including the air inlet, support, filling, water distribution system, water eliminator, air duct, air outlet, etc., ρ_m is the cooling tower average air density.

2) Fan pressure

$$H_{fan} = f\ (Q_a) \quad (2)$$

where H_{fan} is the total pressure of cooling tower fan, Q_a is the air flowrate of cooling tower fan.

B. Thermal Calculation

1) Cooling capacity

$$N_c = A\lambda^n \quad (3)$$

where N_c is the cooling capacity of the cooling tower, λ is air to water ratio, A and n are the fitting coefficients by filling test.

2) Cooling task

Under given conditions of atmospheric parameters, tower inlet and outlet water temperatures, and the air to water ratio, the cooling task of the cooling tower can be expressed as (4) according to the Merkel enthalpy difference theory, and can be simplified according to the Simpson formula (5) as follows:

$$N_t = \int_{t_2}^{t_1} \frac{c_w dt}{i'' - i} \quad (4)$$

$$N_t = \frac{c_w \Delta t}{6}\left(\frac{1}{i_2'' - i_1} + \frac{4}{i_m'' - i_m} + \frac{1}{i_1'' - i_2}\right) \quad (5)$$

where N_t is the cooling task of cooling tower, c_w is the specific heat of water, Δt is the water temperature difference in the cooling tower, i_1'', i_2'' and i_m'' are the saturated air specific enthalpies corresponding to the tower inlet water temperature t_1, tower inlet water temperature t_2 and the average water temperature t_m, i_1, i_2 and i_m are the specific enthalpies of the tower inlet air, outlet air and the average state air.

In summary, the thermal calculation of the cooling tower is to obtain a balance between the cooling capacity and the cooling task, that is, N_c=N_t. Note that when solving, you must ensure that these three conditions of $i_1'' > i_2$, $i_m'' > i_m$ and $i_2'' > i_1$ are satisfied at the same time, in order to obtain the only true solution.

III. Research Method

In thermal power plants, condensers, cooling towers and circulating water pumps are the main equipment of the cold-end system. When the thermal power generating units are working under different operating conditions, the coupling effect between the three sets of equipment will eventually reach a dynamic balance. Therefore, when investigating the operating characteristics of the cooling tower, not only the cooling tower itself but also the relevant parameters of the condenser and the circulating water pump should be considered. Regardless of the makeup water and open cooling water, the cooling water flowrate in the cooling tower is the same as that in the condenser. Under stable conditions, the tower inlet and outlet water temperatures are the condenser outlet and inlet water temperatures, respectively. The water temperature drop in the cooling tower is equal to the water temperature rise in the condenser. Cooling water temperature difference has nothing to do with the atmospheric parameters, cooling tower performance, but only with the cooling water flowrate and condenser heat load.

This article uses the mechanical draft cooling tower of a gas turbine power plant in Jiangsu province as the research object, and uses the cooling tower performance calculation model established in the previous section to analyze the changing conditions of various influencing factors. The design parameters of the mechanical draft cooling tower of the power plant are as follows: atmospheric pressure is 100.528 kPa, dry bulb temperature is 25.95 ℃, wet bulb temperature is 23.58 ℃, the tower inlet water temperature is 35.96 ℃, the tower outlet water temperature is 27.46 ℃, the cooling water temperature difference is 8.5 ℃, and the cooling water flowrate is 3500 t/h, single tower plane size is 17 m × 17 m, tower air inlet height is 4.4 m, total height is 13.4 m, fan blade diameter is 9144 mm, design air flowrate is 252×10^4 m^3/h, total fan pressure is 175.56 Pa, and the filling used for the cooling tower is a PVC film type with a height of 1.25 m.

IV. Results and Discussion

From the above analysis, we can see that when the cooling tower structure and the filling type is given, the cooling tower performance is related to atmospheric pressure, dry bulb temperature, wet bulb temperature, cooling water flowrate, condenser load, effective cooling area, draft resistance and fan air flowrate. The following analysis will mainly focus on the above eight factors affecting the cooling performance. The reference conditions are the design conditions of the cooling tower, in which the atmospheric pressure is 100.528 kPa, the dry bulb temperature is 25.95 ℃, the wet bulb temperature is 23.58 ℃, the tower inlet water temperature is 35.96 ℃, the tower outlet water temperature is 27.46 ℃, the cooling water temperature difference is 8.5 ℃, and the cooling water flowrate is 3500 t/h.

A. Atmospheric Pressure

Based on the design condition, while the parameters such as dry bulb temperature, wet bulb temperature, cooling water flowrate, and cooling temperature difference remain unchanged, and only under the condition of changing atmospheric pressure, the law of cooling tower inlet and outlet water temperature changing with atmospheric pressure is given by calculation and analysis of variable operating conditions.

As shown in Fig. 1, within the range of normal changes throughout the year, the atmospheric pressure increase will cause the tower inlet and outlet water temperature to rise, but the change will be very small. For example, when the atmospheric pressure increases from 98.028 kPa to 102.028 kPa, the tower outlet water temperature increases from 27.40 ℃ to 27.50 ℃, and only increases by 0.10 ℃. This shows that atmospheric pressure has a very small effect on the cooling tower performance, which is negligible.

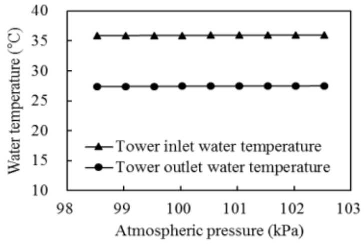

Fig. 1. Influence of atmospheric pressure on the tower inlet and outlet water temperature.

B. Dry Bulb Temperature

Based on the design condition, while the parameters such as atmospheric pressure, wet bulb temperature, cooling water flowrate, and cooling temperature difference remain unchanged, and only under the condition of changing dry bulb temperature, the law of cooling tower inlet and outlet water temperature changing with dry bulb temperature is given by calculation and analysis of variable operating conditions.

As shown in Fig. 2, when the atmospheric pressure and the wet bulb temperature are constant, the dry bulb temperature will have a very small effect on the tower inlet and outlet water temperature. For example, when the dry bulb temperature rises from 23.95 ℃ to 39.95 ℃, the tower outlet water temperature drops slightly from 27.46 ℃ to 27.44 ℃, which only changes by 0.02 ℃. This shows that the dry bulb temperature has negligible effect on the cooling performance.

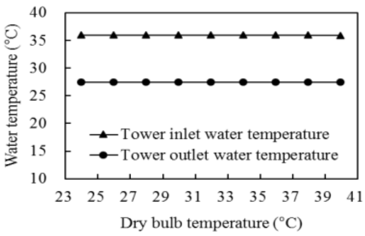

Fig. 2. Influence of dry bulb temperature on the tower inlet and outlet water temperature.

C. Wet Bulb Temperature

Based on the design condition, while the parameters such as atmospheric pressure, dry bulb temperature, cooling water flowrate, and cooling temperature difference remain unchanged, and only under the condition of changing wet bulb temperature, the law of cooling tower inlet and outlet water temperature changing with wet bulb temperature is given by calculation and analysis of variable operating conditions.

As shown in Fig. 3, when the atmospheric pressure and dry bulb temperature are constant, the increase of the wet bulb temperature will cause the tower inlet and outlet water temperature to rise, and the two are approximately linear.

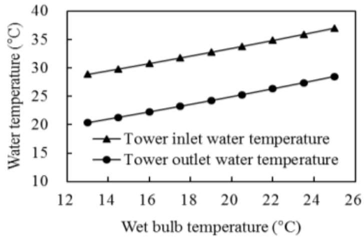

Fig. 3. Influence of wet bulb temperature on the tower inlet and outlet water temperature.

For example, when the wet bulb temperature increases from 13 ℃ to 25 ℃, the tower outlet water temperature rises from 20.36 ℃ to 28.51 ℃, increasing by 8.15 ℃, which shows that the wet bulb temperature has a greater impact on the cooling performance. Compared with atmospheric pressure and dry bulb temperature, the wet bulb temperature is the main factor affecting the tower outlet water temperature, and can be used as the main basis for the adjustment of cooling tower operation.

D. Cooling Water Flowrate

Based on the design condition, while the parameters such as atmospheric pressure, dry bulb temperature, and wet bulb temperature remain unchanged, and only under the condition of changing cooling water flowrate, the law of cooling tower inlet and outlet water temperature changing with cooling water flowrate is given by calculation and analysis of variable operating conditions.

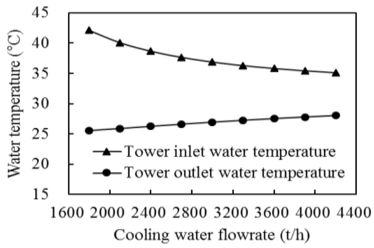

Fig. 4. Influence of cooling water flowrate on the tower inlet and outlet water temperature.

As shown in Fig. 4, when the atmospheric parameters and the condenser load are constant, as the cooling water flowrate increases, the tower inlet water temperature decreases, the tower outlet water temperature increases, the cooling water temperature difference decreases, and the change trend gradually becomes slower. In addition, the cooling water flowrate has a greater influence on the tower inlet water temperature than that on the tower outlet water temperature. For example, when the cooling water flowrate is increased from 1800 t/h to 4200 t/h, the tower inlet water temperature decreases from 42.10 ℃ to 35.12 ℃ and decreases by 6.98 ℃. The tower outlet water temperature rises from 25.57 ℃ to 28.04 ℃ and increases by 2.47 ℃. It can be seen that the cooling water flowrate is an important factor influencing the cooling tower performance. Although the cooling water flowrate has a relatively small effect on the tower outlet water temperature, it can greatly reduce the tower inlet water temperature, i.e., the water temperature at the condenser outlet, thereby increasing the vacuum of the condenser. Therefore, it can be used as an important means of cooling tower operation adjustment by adjusting the circulating pump operating mode to change the water flowrate.

E. Condenser Heat Load

Based on the design condition, while the parameters such as atmospheric pressure, dry bulb temperature, wet bulb temperature and cooling water flowrate remain unchanged, and only under the condition of changing condenser heat load, the law of cooling tower inlet and outlet water temperature changing with condenser heat load is given by calculation and analysis of variable operating conditions.

As shown in Fig. 5, when the atmospheric parameters and the cooling water flowrate are constant, with the increase of the condenser heat load, the tower inlet and outlet water temperature will both increase, and the cooling water temperature difference will gradually increase, and it will basically show a linear change trend. However, the condenser heat load has a greater influence on the tower inlet water temperature than that on the tower outlet water temperature. For example, when the condenser heat load increases from 60% to 140%, the tower inlet water temperature rises from 31.36 ℃ to 40.24 ℃, increasing by 8.88 ℃, and the tower outlet water temperature rises from 26.26 ℃ to 28.34 ℃, increasing by only 2.08 ℃.

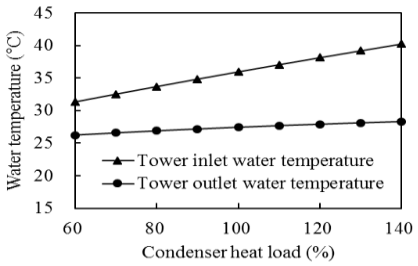

Fig. 5. Influence of condenser heat load on the tower inlet and outlet water temperature.

F. Cooling Area

After long-term operation of the cooling tower, the water splash device will damage or falling off, and the filling will be fouled or blocked, resulting in increased failure cooling area, reduced effective cooling area, and finally reduced cooling tower performance.

Based on the design condition, while the parameters such as atmospheric pressure, dry bulb temperature, wet bulb temperature, cooling water flowrate and condenser heat load remain unchanged, and only under the condition of changing cooling area, the law of cooling tower inlet and outlet water temperature changing with cooling area is given by calculation and analysis of variable operating conditions.

As shown in Fig. 6, when the atmospheric parameters, cooling water flowrate, and condenser heat load are constant, with the increase of the proportion of failure cooling area, the tower inlet and outlet water temperature are both increasing, and have a linear trend. For example, when the percentage of failure cooling area increases from 0 to 16%, the tower inlet water temperature rises from 35.96 ℃ to 37.16 ℃, and the tower outlet water temperature rises from 27.46 ℃ to 28.66 ℃, increasing by 1.20 ℃. It can be seen that the failure of the cooling area will have a significant adverse effect on the cooling performance. Therefore, in the daily operation, it is necessary to strengthen the supervision and maintenance of the core components of the cooling tower, timely repair or replace the damaged splash device and filling, keep more effective cooling area, and ensure that the cooling tower works in the best condition.

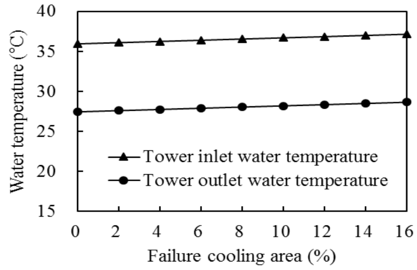

Fig. 6. Influence of failure cooling area on the tower inlet and outlet water temperature.

G. Draft Resistance

For new gas turbine power plants, there are generally strict environmental noise control requirements. As a main noise source, the cooling tower often has a noise reduction device installed at the air inlet and outlet, which will increase the cooling tower draft resistance, and reduce cooling performance.

As shown in Fig. 7, when the atmospheric parameters, cooling water flowrate, and condenser load are constant, with the increase of draft resistance, the tower inlet and outlet water temperature both show a rising trend, which will gradually accelerate. For example, when the draft resistance is increased from 175 Pa to 205 Pa, the tower inlet water temperature rises from 36 ℃ to 37 ℃, and the tower outlet water temperature rises from 27.5 ℃ to 28.5 ℃, by an increase of 1 ℃. And when the draft resistance increases from 205 Pa to 230 Pa, the tower inlet water temperature rises from 37 ℃ to 39.5 ℃, and the tower outlet water temperature rises from 28.5 ℃ to 31 ℃, increasing by 2.5 ℃. It can be seen that the increased draft resistance has an adverse effect on the cooling performance. Therefore, in the preliminary design stage of the power plant, it is necessary to consider the additional resistance caused by adding noise reduction devices to the mechanical draft cooling tower, and the fan should reserve full pressure margin. And if the margin was not taken into account at the beginning, the type and installation position should be properly considered when adding the noise reduction device in the later stage, so as to minimize draft resistance and reduce adverse effects on cooling performance.

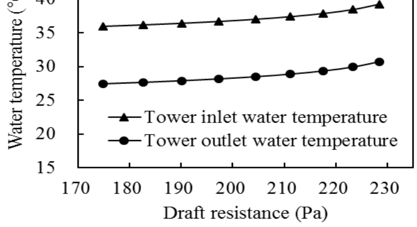

Fig. 7. Influence of draft resistance on the tower inlet and outlet water temperature.

H. Fan Air Flowrate

Unlike natural draft cooling towers, the air flowrate of mechanical draft cooling tower can be actively controlled and regulated. Generally, the fan air flowrate can be changed by using an inverter fan or adjusting the blade angle, and the cooling capacity of the cooling tower can be adjusted according to the cooling requirements.

As shown in Fig. 8, when the atmospheric parameters, cooling water flowrate, and condenser load are constant, with the increase of fan air flowrate, the tower inlet and outlet water temperature both show a decreasing trend, which will gradually slow down. For example, when the fan air flowrate increases from 126×10^4 m^3/h to 252×10^4 m^3/h, the tower inlet water temperature decreases from 41 ℃ to 36 ℃, and the water outlet water temperature from 32.5 ℃ to 27.5 ℃, decreasing by 5 ℃. And when the air flowrate increases from 252×10^4 m^3/h to 328×10^4 m^3/h, the tower inlet water temperature drops from 36 ℃ to 34.7 ℃, and the tower outlet water temperature drops from 27.5 ℃ to 26.2 ℃, lowering by 1.3 ℃. It can be seen that an increase of the fan air flowrate will improve the performance of the cooling tower, but as the air flowrate increases, the effect achieved will gradually decrease, and the fan power consumption will continue to increase. Therefore, when adjusting the fan air flowrate and tower cooling capacity through fan frequency regulation or blade angle adjustment, the relationship between fan power consumption and water temperature reduction should be comprehensively taken into account in order to maximize the benefits.

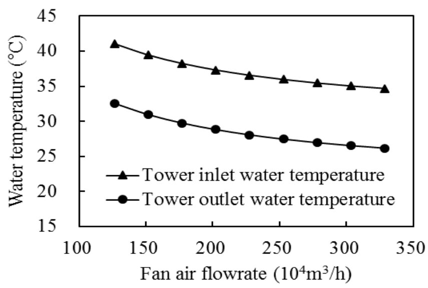

Fig. 8. Influence of fan air flowrate on the tower inlet and outlet water temperature.

V. Conclusions

A mathematical model of mechanical draft cooling tower under variable operating conditions was established to investigate the influence of various operating parameters on the cooling performance. The results show that the atmospheric pressure and dry bulb temperature have a tiny effect on the tower performance, which can be neglected. And the wet bulb temperature is the main environmental factor that affects the tower performance and can be used as the main basis for the adjustment of the cooling tower with seasonal changes.

Cooling water flowrate, condenser heat load, failure cooling area and draft resistance all have a positive correlation with tower outlet water temperature. While the air flowrate of the fan increases, the tower outlet water temperature will decrease. The above conclusions will help to accurately predict the changing trend of tower outlet water temperature under variable operating conditions, and provide guidance for the adjustment of cooling tower operation under variable conditions, so as to maximize the benefits of power generation.

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