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Crosswinds Effect on the Thermal Performance of Wet Cooling Towers Under Variable Operating Conditions

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Abstract. In order to quantitatively analyze the influence of the variable operating parameters on the cooling performance of natural draft wet cooling towers (NDWCTs), a hot model test system was set up with adjustable ambient temperature and humidity, circulating water flowrate and temperature. In order to apply the hot model test results to the real tower, the crosswind Froude number is defined. The results show that the crosswind has a negative effect on the thermal performance of the cooling tower, and there is a critical crosswind velocity corresponding to the lowest cooling efficiency. According to the crosswind Froude number similarity, when the ambient temperature decreases, or the circulating water flowrate and temperature increase, the cooling tower draft force will increase, and the critical crosswind velocity will increase correspondingly.

1. Introduction

Natural draft wet cooling towers are widely used to cool the circulating water in thermal power plants. Existing studies have shown that the environmental crosswind could reduce the cooling tower performance, and can even cause the unit trip in extreme cases. Russell [1] pointed out that the crosswind can greatly affect the cooling tower performance through the dry tower and industrial cooling tower research. Grange et al. [2] performed prototype and model tower tests on natural draft cross-flow wet cooling towers. The results show that crosswinds can adversely affect cooling performance, and crosswinds will become favorable when the crosswind velocity exceeds a certain value. Bender et al. [3] tested the model tower in the wind tunnel. The results show that crosswinds could seriously affect the air flow in the tower, and would lead to an increment by 45% in the windward side. Al-Waked et al. [4] found that when the crosswind velocity was 7.5 m/s, the tower outlet water temperature was increased by 1.7 K. And the main reason was nonuniform distribution of the air flow in the tower caused by crosswinds. Gao et al. [5] found that the crosswind would adversely affect the cooling water temperature difference and the cooling efficiency by hot model tests, both of which could be reduced by a maximum of 6% and 5%. Zhao et al. [6] established a three-dimension numerical model of the cooling tower. It was found that the crosswind increased the lateral air flowrate and enhanced the cooling performance of the rain zone, but the longitudinal air flowrate was reduced, which was not conducive to heat and mass transfer in the fill zone, and finally reduced overall performance of the cooling tower. Zhou et al. [7] performed a numerical analysis on wet cooling towers. The results show that the crosswind has a negative effect on the water temperature of the tower, and would lead to a maximum water temperature at the crosswind velocity of 6 m/s, which is 1.34 ℃ higher than that without crosswinds.

In summary, crosswinds effect on the thermal performance of wet cooling towers were studied by means of hot model tests and numerical methods respectively [5, 6]. However, the former literature [5] only discussed the adverse effect of the crosswind on the cooling tower performance, and did not further explore the changing law of the crosswinds effect under various variable conditions. The latter literature [6] only uses the numerical calculation to study the influence of the varying circulating water parameters. In view of this, this paper intends to study the influence and mechanism of the crosswind on the thermal performance of the wet cooling tower when the parameters such as ambient temperature, circulating water flowrate and tower inlet water temperature are changed through the hot model test, so as to guide the actual operation of the cooling tower.

2. Model test

The model cooling tower is made of plexiglass, and the schematic diagram of the entire test system is shown in Figure 1. When the model test begins, the circulating water is heated to a given temperature in the lower tank, pumped to the upper tank by the circulating pump, and then it flows into the tower. Finally, it falls into the water basin after being cooled, and flows back into the lower tank, to complete a cycle. The detailed description of the hot model test system can refer to the previous literature [8].

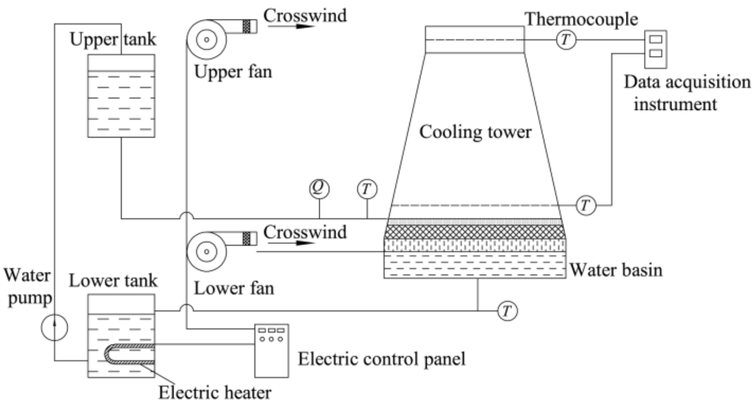


Figure 1. Schematic diagram of the hot model test system

During the test, the ambient temperature is selected as 16, 20 and 24 ℃, the tower inlet water temperature is selected as 40, 50 and 60 ℃, the circulating water flowrate is selected as 4, 6 and 8 L/min, and the crosswind velocity is selected as 0.0, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8 m/s.

In this test, the main parameters to be measured include atmospheric pressure, dry and wet bulb temperature, crosswind velocity, circulating water flow rate, water and air temperature at the inlet and outlet of the tower. The parameters and measuring instruments are detailed in literature [8].

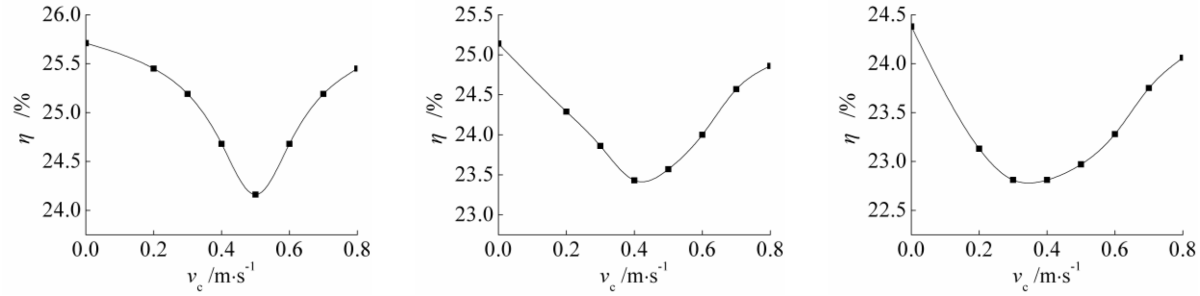
3. Results and discussion

3.1. Cooling efficiency

Cooling efficiency η is often used to indicate the thermal performance of NDWCTs. η is defined as $\eta=(t_1-t_2)/(t_1-\tau)$, where t_1 and t_2 are the tower inlet and outlet water temperature respectively, τ is the wet bulb temperature of the inlet air.

3.2. Crosswinds effect on the cooling efficiency under different ambient temperatures

This section discusses three conditions with the ambient temperature θ_1=16 ℃, 20 ℃ and 24 ℃, the circulating water flowrate Q and the tower inlet water temperature t_1 are set as 6 L/min and 50 ℃ respectively, and the relative humidity φ is maintained at 58 %.



(a) θ_1=16℃ **(b) θ_1=20℃** **(c) θ_1=24℃**

Figure 2. Crosswinds effect on cooling efficiency under different ambient temperatures

Figure 2 shows crosswinds effect on the cooling efficiency at different ambient temperatures. When the crosswind velocity v_c=0 m/s, η=25.7%, 25.1% and 24.4% under three conditions with θ_1=16℃, 20℃ and 24℃. It can be seen that the higher θ_1 is, the lower η will become. This is because when the ambient temperature increases, the temperature difference between the air in the tower and the circulating water will decrease, the contact heat dissipation will decrease and finally the cooling performance will reduce. Therefore, the summer temperature is high, the cooling tower performance is poor, and the winter temperature is low, and is favorable to the cooling performance.

Figure 2 also shows that the trend of crosswinds effect on cooling efficiency is basically the same at different ambient temperatures. In the absence of crosswind, η is higher. When the crosswind increases, η will decrease first and then increase, and there exists the minimum value of η.

Based on the above, a new concept is given to describe this characteristic, that is, for a certain type of cooling tower at a certain structural parameters, environmental parameters and circulating water parameters, v_c corresponding to the minimum η is defined as critical crosswind velocity v_{cr}. v_{cr} corresponds to the minimum η under crosswind conditions, that is, when v_c is lower than v_{cr}, η will gradually reduce, and when v_c is higher than v_{cr}, η will gradually improve.

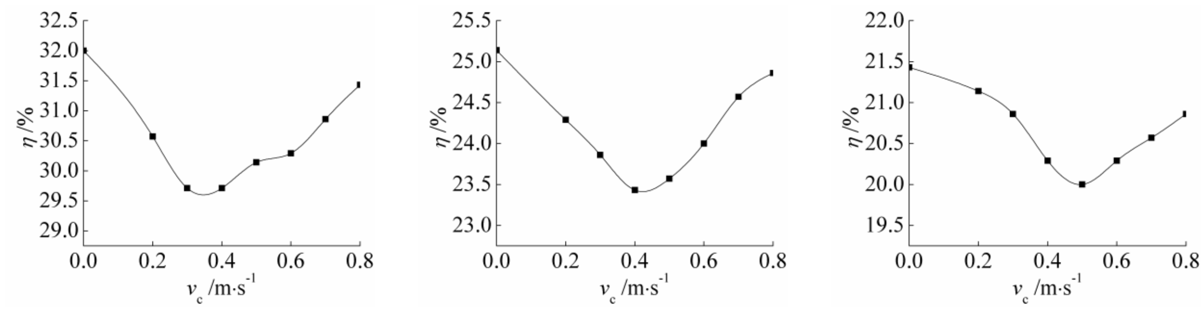
Figure 2 also reflects the effect of the ambient temperature on the critical crosswind velocity. It can be seen that when θ_1 is 16 ℃ and 20 ℃, v_{cr} is 0.5 m/s and 0.4 m/s, while the corresponding v_{cr} at θ_1=24 ℃ is between 0.3 m/s and 0.4 m/s. This shows that the higher θ_1 is, the smaller v_{cr} will become, and the cooling tower is more susceptible to the adverse effect of environmental crosswinds, that is, the anti-crosswind capacity of cooling tower in the winter is stronger than that in the summer.

3.3. Crosswinds effect on the cooling efficiency under different circulating water flowrates

This section discusses three conditions with Q=4 L/min, 6 L/min and 8 L/min. And t_1=50 ℃, θ_1=20 ℃ and φ=58 %.

Figure 3 shows crosswinds effect on η at different circulating water flowrates. When v_c=0 m/s, η=32.0%, 25.1% and 21.4% under three conditions with Q=4 L/min, 6 L/min and 8 L/min. Obviously, when the other conditions are constant, the smaller Q is, the higher η will become.

It can be seen that there is a critical crosswind velocity in a variety of variable circulation water conditions. It is worth noting that the critical crosswind velocities corresponding to variable circulating water flowrate conditions are not the same. When Q=4 L/min and 6 L/min, the corresponding v_{cr} are 0.3 m/s and 0.4 m/s. And at the case of Q=8 L/min, the corresponding v_{cr} is between 0.5 m/s and 0.6 m/s. It can be seen that v_{cr} will change along with the change of Q, and the larger Q is, the bigger v_{cr} will become. This shows that in the cooling tower operating process, the greater Q is, the stronger the cooling tower will be to withstand the crosswinds effect, but the circulating pump power consumption will increase correspondingly. Therefore, in the actual operation of the cooling tower, it should deal with the relationship between the two factors, so that the cooling tower can meet the needs of cold end while achieving higher operating performance.



(a) *Q*=4L/min **(b) *Q*=6L/min** **(c) *Q*=8L/min**

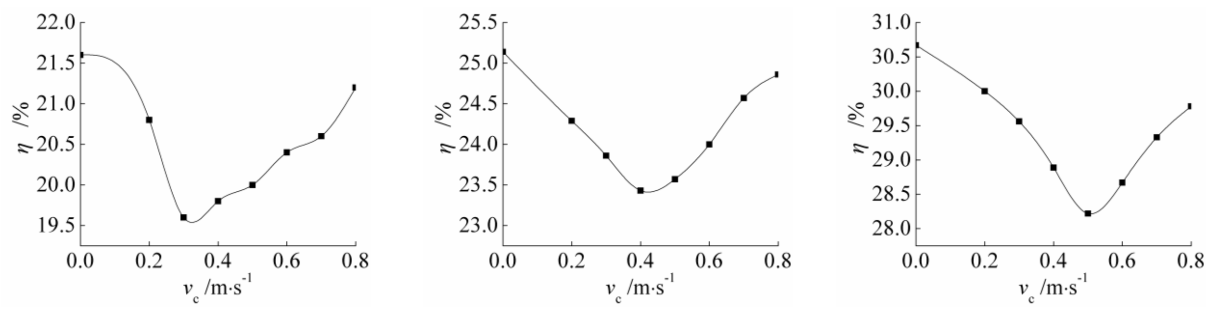
Figure 3. Crosswinds effect on cooling efficiency under different circulating water flowrates

3.4. Crosswinds effect on the cooling efficiency under different tower inlet water temperatures

This section discusses three conditions with t_1=40 ℃, 50 ℃ and 60 ℃. And other operating parameters are constant, with Q=6 L/min, θ_1=20 ℃ and φ=58 %.

Figure 4 shows crosswinds effect on the cooling efficiency at different tower inlet water temperatures. When v_c=0 m/s, η=21.6%, 25.1% and 30.7% under the three conditions with t_1=40℃, 50℃ and 60℃. Obviously, when the other parameters are constant, the higher t_1 is, the higher η will become.

It can be seen from Figure 4 that there is a critical crosswind velocity v_{cr} at different tower inlet water temperatures, corresponding to the minimum η under crosswind condition, similar to the variable ambient temperature and circulation water flowrate conditions above.



(a) t_1=40℃ **(b) t_1=50℃** **(c) t_1=60℃**

Figure 4. Crosswinds effect on cooling efficiency under different tower inlet water temperatures

The critical crosswind velocity v_{cr} corresponding to the operating conditions t_1=40 ℃, 50 ℃ and 60 ℃ is 0.3 m/s, 0.4 m/s and 0.5 m/s, respectively. It can be seen that the higher t_1 is, the bigger v_{cr} will become. This indicates that a higher t_1 makes it easier to eliminate the adverse effect of crosswinds. But on the other hand, the higher t_1 also can deteriorate the condenser performance. Therefore, in the actual operation of the cooling tower, it should first ensure the safe and economical operation of the condenser, on this basis, it can be appropriate to improve the tower inlet water temperature. If you want to eliminate crosswinds effect, you should seek other effective wind protection measures.

3.5. Inferences about the critical crosswind velocity and dimensionlessness of the crosswind velocity

Fr_c is defined as the crosswind Froude number, and that is $Fr_c = v_c/\sqrt{\Delta\rho g H_e/\rho}$. When a hot model test conforms to the kinematic similarity and thermo-dynamic similarity in the same time, the crosswind Froude number similarity will be satisfied naturally. According to the definition, Fr_c reflects the relative relationship between the crosswind inertia force and the tower draft force, which characterizes the crosswind effect on the cooling performance. Each Fr_c represents a cooling tower operating state under the effect of a crosswind, and the cooling tower operating state corresponding to v_{cr} is recorded as Fr_{cr}.

According to Fr_c similarity, v_c should proportionally vary with the tower draft force to keep the same cooling tower operating state. As mentioned above, when θ_1 decreases, Q and t_1 increases, the draft force of the cooling tower will increase, v_c will increase correspondingly, which is required to achieve the same air flow state in the tower. And that is the fundamental reason for the change of critical crosswind velocity.

The crosswind velocity v_c is dimensionless to the ratio of the crosswind velocity v_c to the air velocity v_f above the fill, denoted as the dimensionless crosswind velocity V_c. It can be found that η achieves minimum value when V_c=4 at all cases, and the cooling performance becomes worst, that is, the dimensionless critical crosswind velocity $V_{cr}= v_{cr}/v_f$=4. This conclusion has a strong theoretical and practical significance, that is, for a cooling tower, if you can get the air velocity above the fill, you can get the critical crosswind velocity corresponding to the worst cooling performance of the tower operating conditions.

4. Conclusion

In this paper, the crosswinds effect on the cooling performance of cooling tower is studied based on hot model test when the ambient temperature, circulating water flowrate and tower inlet water temperature changes. Specific conclusions are as follows:

1) The crosswind has a negative effect on the cooling tower thermal performance. There is a critical crosswind velocity v_{cr} corresponding to the lowest cooling efficiency, that is, when the crosswind velocity is lower than v_{cr}, the cooling performance will gradually reduce, and when the crosswind velocity is higher than v_{cr}, the cooling performance will gradually improve.

2) Cooling tower operation satisfies the crosswind Froude number similarity. When the ambient temperature decreases, the circulating water and the tower inlet water temperature increases, the cooling tower draft force will increase, the crosswind velocity will increase correspondingly, which is required to achieve the same flow state in the cooling tower. And that is the fundamental reason for the change of critical crosswind velocity.

3) At the dimensionless critical crosswind velocity V_c=4, the cooling efficiency η achieves the minimum value, and the cooling tower has the worst performance. For a cooling tower, if you can get the air velocity above the fill, you can get the critical crosswind velocity corresponding to the worst cooling performance of the tower operating conditions.

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