

Experimental Research on Optimizing Inlet Airflow of Wet Cooling Towers under Crosswind Conditions

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Abstract. A new approach of installing air deflectors around tower inlet circumferentially was proposed to optimize the inlet airflow and reduce the adverse effect of crosswinds on the thermal performance of natural draft wet cooling towers (NDWCT). An inlet airflow uniformity coefficient was defined to analyze the uniformity of circumferential inlet airflow quantitatively. Then the effect of air deflectors on the NDWCT performance was investigated experimentally. By contrast between inlet air flow rate and cooling efficiency, it has been found that crosswinds not only decrease the inlet air flow rate, but also reduce the uniformity of inlet airflow, which reduce NDWCT performance jointly. After installing air deflectors, the inlet air flow rate and uniformity coefficient increase, the uniformity of heat and mass transfer increases correspondingly, which improve the cooling performance. In addition, analysis on Lewis factor demonstrates that the inlet airflow optimization has more enhancement of heat transfer than mass transfer, but leads to more water evaporation loss.

1. Introduction

Natural draft counter-flow wet cooling tower is widely used to cool the circulating water in thermal power plants and nuclear power plants. Circulating water from the condenser is injected from the nozzles and goes successively through spray zone, filler zone and rain zone to transfer heat and mass to the air, and then returns to the condenser. The cooling tower performance decides directly the condenser vacuum and influences the generating efficiency [1], so it is of great importance to research and improve the cooling performance. There are mainly three methods of cooling tower thermal calculation, namely Poppe, Merkel and e-NTU. Kloppers et al. [2] found that the results of Merkel and e-NTU are nearly the same while the accuracy of Poppe is the highest. Fisenko et al. [3] proposed a cooling tower performance mathematical model including both the droplet cooling in spray zone and the film cooling in fill zone. The deviation between the calculated results and experimental results is smaller than 3%, but the model is not applicable to frozen conditions and windy conditions. Hawlader [4] and Williamson [5] respectively used algebraic method and k - ϵ turbulence model to build two-dimensional axisymmetric cooling tower numerical model and study the influence of the nonuniformity of air water flow and heat and mass transfer on the cooling tower performance. Smrekar [6] measured the air flow field above the spray zone and proposed the optimal spray mode which can ensure the uniformity of the heat transfer inside tower and minimize the available energy loss. Muangnoi [7] found through the available energy analysis that the available energy provided by



circulating water is more than that obtained by air due to entropy generation. The available energy loss in top of the heat and mass transfer zones is larger while bottom smaller. Other than the cooling tower structure factor, environmental factors especially the cross wind also have strong impact on cooling tower performance [8-10]. Derksen [11-13] found through wind tunnel test and numerical calculation that crosswind can strongly affected the air flow field and proposed that windbreaks should be installed on the upper air inlet to reduce the air from upwind side, thus ensure the uniformity of inlet air. According to Zhai et al. [14], the main reason of the crosswind negative effect is that crosswind changes the pressure distribution of the inlet and outlet and breaks the uniformity of inlet air, and windbreaks can weaken the negative effect of crosswind. Al-Waked et al. [15-16] used fixed velocity droplet flow to simulate the film flow in fill zone and found through numerical calculation that the outlet water temperature is increased by 1.7 °C when the crosswind velocity is 7.5 m/s. The primary cause is proposed to be the nonuniformity of the air flow field caused by crosswind. Research also shows that installing porous windbreaks both inside and outside rain zone can lower the outlet water temperature by 0.5~1 °C. Gao et al. [17] found through model experiment that when Froude number is 0.174 the cooling temperature difference and efficiency coefficient have the minimum value. Zhao et al. [18-19] built a 3D numerical model applicable to cooling towers under crosswind effects and found that crosswind increases the inlet air relative deviation, generates cross air flow and strengthens rain zone performance, meanwhile weakening heat and mass transfer in the fill zone, lowering the water temperature difference of fill zone and increasing the outlet water temperature. It's proposed that installing cross wall in rain zone will improve the tower performance. Zhou et al. [20-21] use high-accuracy Poppe model in fill zone and Discrete Phase Model in spray zone and rain zone, and obtain the 3D numerical solution of wet cooling tower. Results show that crosswind has negative effects on outlet water temperature which gets the highest value when the crosswind velocity is 6 m/s, 1.34 °C higher than zero crosswind conditions. Installing cross wall can lower the outlet water temperature by 0.32 °C.

In conclusion, previous researches consider through qualitative analysis that crosswind breaks the uniformity of cooling tower inlet air flow and reduces the inlet air quantity, thus weakening the cooling performance. Besides, no better solution than windbreaks is proposed. In this paper, a kind of new method is introduced, namely air deflector. Air uniformity coefficient is defined to be the performance index evaluating the inlet air flow uniformity. Through hot model test, the impact of air flow optimization on cooling tower performance is studied, the mechanism of which is analyzed.

2. Model experiment

2.1. Test criterion

To be more valid and accurate, and guide design, operation and optimization of the real tower, the hot model test must satisfy the following similarity criteria, including the geometric, kinematic, dynamic and thermal similarity.

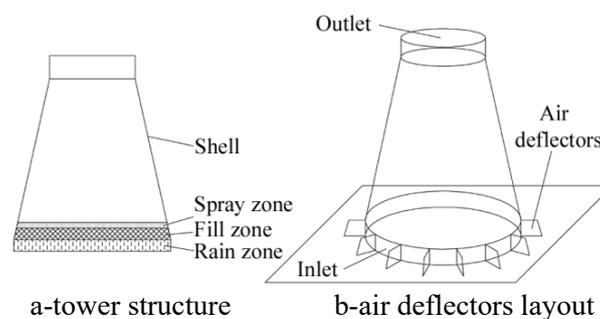


Figure 1. Schematic structure of the model tower.

2.1.1. Geometric similarity. The model NDWCT used in this paper is made with a scale of 1:100 to the prototype tower, the dimension of the prototype tower is 37 m × 68 m × 85 m (top outlet diameter × bottom diameter × height), the height of the tower inlet is 5 m, and the fill area is 3200 m². The dimension of the model tower is about 370 mm × 680 mm × 850 mm, and the height of the tower inlet is 50 mm. Fig. 1 shows the schematic structure of the model tower. There is an optional variable frequency fan at the top of the tower to make up for the lack of model tower pumping force. Wind tunnel experiments of the tower and its internal components were performed to ensure resistance similar with the prototype tower.

2.1.2. Kinematic similarity. The air velocity ratio of the model should be equal to that of the prototype, that is,

$$\left(\frac{v_{to}}{v_{cw}}\right)_P = \left(\frac{v_{to}}{v_{cw}}\right)_M \quad (1)$$

where v_{to} is the outlet air velocity, v_{cw} is the crosswinds velocity at the top outlet, P and M represent the prototype and model tower respectively.

2.1.3. Thermo-dynamic similarity. It is impossible for the model test to conform to both Reynolds criterion and Froude criterion at the same time. This experiment is hot model test, through the heat and mass transfer between the inlet air and the circulating water, making the formation of the density difference between the air inside and outside tower, resulting buoyancy driving force, and on this basis to study the thermal performance of the cooling tower under various crosswind conditions. In this model test, the driving force of buoyancy and the inertial force of crosswinds are the main factors to be concerned, while the viscous force is less important. Therefore, it is the density Froude number similarity to be satisfied, that is,

$$Fr_{\Delta} = \left(\frac{v_{to}}{\sqrt{\frac{\Delta\rho_a g H_e}{\rho_i}}}\right)_P = \left(\frac{v_{to}}{\sqrt{\frac{\Delta\rho_a g H_e}{\rho_i}}}\right)_M \quad (2)$$

where Fr_{Δ} is density Froude number, $\Delta\rho_a$ is the density difference between the inlet and outlet air, ρ_i is the density of the inlet air, g is the acceleration of gravity, H_e is the effective height.

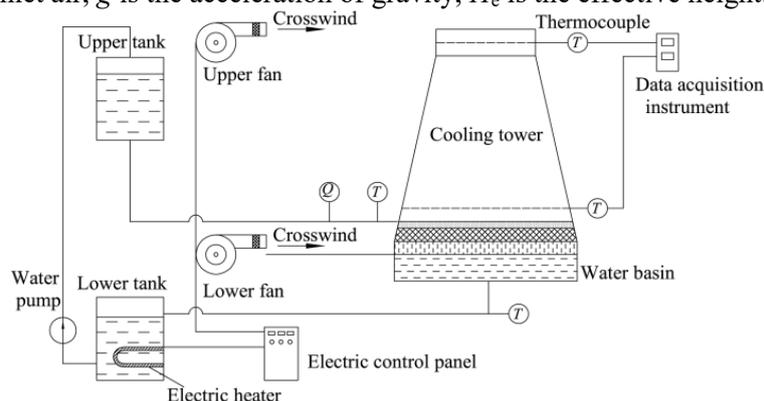


Figure 2. Schematic diagram of the hot model test system

2.2. Experimental equipments

The entire cooling tower models are made of transparent plexiglass, which is shown in Fig. 2. In the Experiment-performed, firstly, circulating water in the heating tank is heated to a setting temperature, secondly, the water is pumped into the buffer tank by using the circulating water pump. Circulating water will automatically flow into the cooling tower, then through spray zone, fill zone and rain zone in sequence and have convective heat and mass transferred with the air from the bottom to top. The

cooled circulating water falls into the water basin and flows into the heating tank, a circuit is completed.

In the hot model test, air deflectors are installed at the tower inlet, which are right-angled trapezoid with thickness of 1mm, 36 pieces in total, uniformly distributed along the circumference of the tower inlet. adjacent air deflectors are spaced by 10° , and its detailed dimensions and layout are as shown in Fig. 3. In the following text, BO and AO represent before and after the inlet airflow optimization condition.

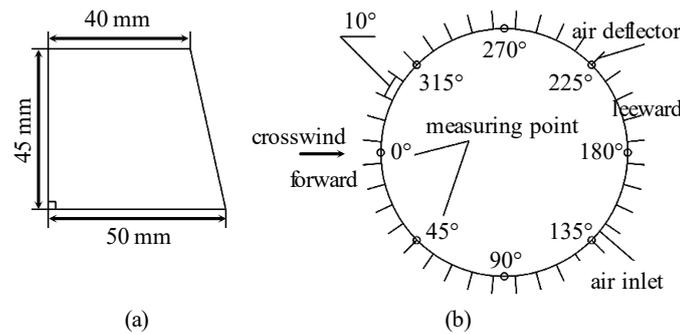


Figure 3. Arrangement mode for air deflectors. (a) air deflector size, (b) distribution of air deflectors and inlet air velocity measuring points

3. Experiment content

In the experiment, the tower inlet air velocity is measured to quantitatively analyze the inlet air uniformity along the circumference of the cooling tower. The layout of eight measuring points is as shown in Fig. 3(b) and spaced by 45° , all of which are in a half height of the tower inlet. At the same time, temperatures of the circulating water and air in and out of the tower in different side before and after optimization are measured to get various performance parameters of the cooling tower under various operating conditions, then the difference of inlet air of the cooling tower and thermal performance parameters are analyzed to clarify the effects of crosswind and air deflectors on the performance of the cooling tower.

The circulating water temperature is set as 40°C , and circulating water flow rate is 8 L/min. Circulating water temperature can be set by an electronic control panel, its volume can be adjusted through regulating valve on the circulating water line. An induced draft fan is installed away from the experiment table to get the hot and humid air out of the tower, in order to keep constant temperature and humidity. Due to the influence of crosswind is mainly concentrated in the air inlet and outlet of cooling tower [10, 14], frequency conversion fans are on the height of tower inlet and outlet to simulate environment influence on the cooling tower. According to the dynamic similarity criterion, crosswind velocity of the hot model test should be 1/10 of the actual velocity, six state of crosswind velocity (0.0, 0.2, 0.4, 0.0, 0.2 and 1.0 m/s) are selected in the lower fan, measured in the half height of windward side of the cooling tower (practice for $z = 2.5$ m height). The higher fan crosswind velocity (practice for $z = 85$ m) should be determined according to the formula depicting the natural crosswind velocity distribution above the ground [15], that is,

$$\frac{v_{cw}}{v_{cw,ref}} = \left(\frac{z}{z_{ref}}\right)^{0.2} \quad (3)$$

where $v_{cw,ref}$ is a reference crosswind velocity at the reference height $z_{ref} = 10$ m. The crosswind velocity in the higher fan is twice as the lower fan, and the corresponding crosswind velocity in the higher is 0.0, 0.4, 0.8, 1.2, 1.6 and 2.0 m/s. In the following text, the crosswind velocity is indicated by the higher fan crosswind velocity. More cross-section flow field tests guarantee the reliability of the results. The test of flow field in the section shows that the model velocity have roughly the same with actual conditions, which ensured the reliability of the result.

In the experiment, atmosphere pressure, dry-and-wet-bulb temperature, wind velocity in the side and inlet, circulating water, the temperature of the circulating water and air in and out of the tower, etc. are measured. All of these monitored parameters and measuring instruments are listed in Table 1.

Table 1. Monitored parameters and measuring instruments

Item	Measuring instrument	Accuracy
Atmospheric pressure	Hot-wire manometer (KA31)	0.01 kPa
Crosswind and inlet wind velocity	Hot-wire anemoscope (KA31)	0.01 m/s
Inlet dry and wet bulb temperature	Psychrometer	0.1 °C
Outlet air temperature	Copper-constantan thermocouple	0.1 °C
Inlet and outlet water temperature	Mercury thermometer	0.1 °C
Inlet and outlet air humidity	Hygrometer (HI8564)	0.1%
Circulating water flow rate	Variable area flow meter	0.01 L/min

4. Results and Discussion

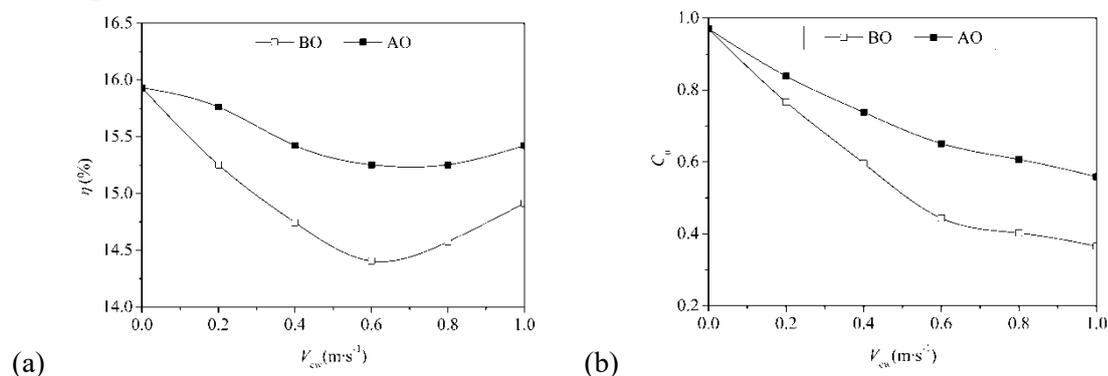
4.1. Cooling efficiency

Cooling efficiency η is often used to indicate the thermal performance of NDWCT. η is determined from,

$$\eta = \frac{T_{wi} - T_{wo}}{T_{wi} - T_{awb}} \quad (4)$$

where T_{wi} and T_{wo} are the inlet and outlet water temperature respectively, T_{awb} is the wet bulb temperature of the inlet air.

As shown in Fig. 4(a), before the optimization of the inlet airflow, the cooling efficiency is increased at first, and then reduced by the increasing environment crosswind. The cooling efficiency drops from 15.93% to 14.41%, a decline of nearly 10 %, when v_{cw} increases from 0 to 0.6 m/s, η rebounds when v_{cw} continues to increase. After optimizing the air intake with wind deflectors, the overall trend of cooling efficiency is similar to that before optimization, but has been significantly weakened by the crosswind. Compared with optimized air intake, the cooling efficiency of different crosswind conditions improves significantly, its biggest decline is 4.27% by the influence of crosswind. Before and after optimization, the change of the cooling efficiency is determined by the intake performance of the cooling tower.



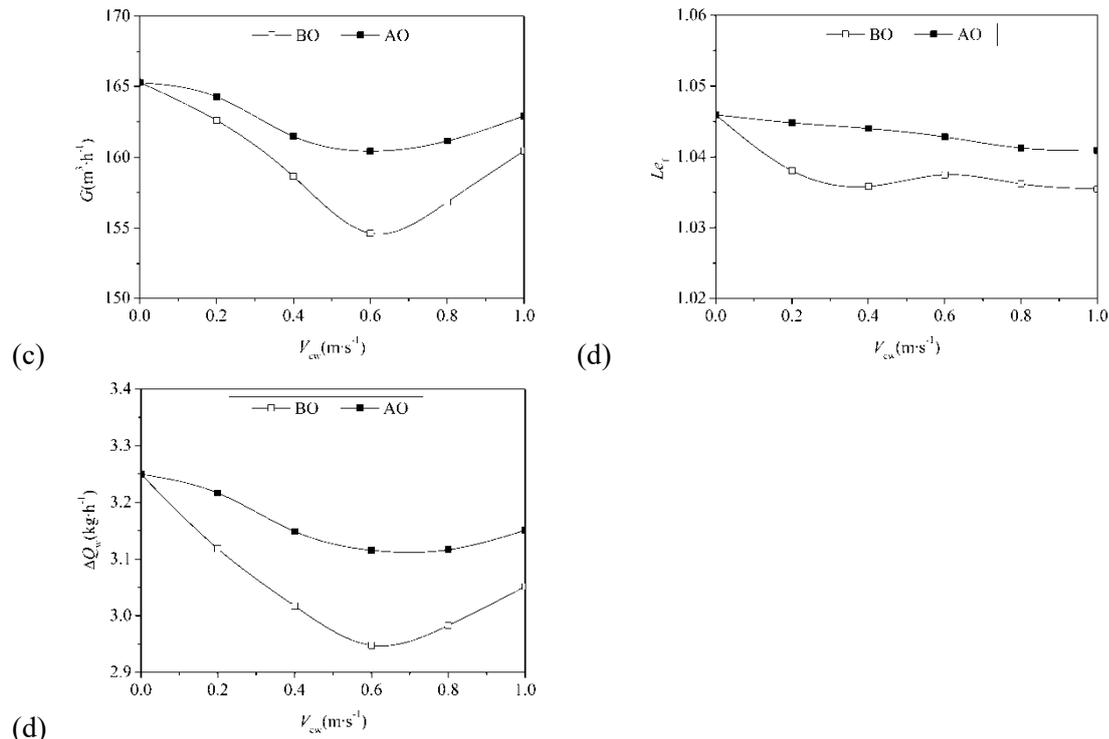


Figure 4. Crosswinds effect on NDWCT performance before and after inlet airflow optimization. BO and AO represent the performance before and after inlet airflow optimization respectively. (a) cooling efficiency, (b) airflow uniformity coefficient, (c) airflow rate, (d) Lewis factor, (e) evaporation loss

4.2. Airflow rate and airflow uniformity coefficient

Airflow rate G is an index of cooling performance and bigger G represents better performance. According to the balance of heat transfer between air and water, G has the equation of

$$G = \frac{c_w \rho_w Q (T_{wi} - T_{wo})}{K \rho_a (i_{ao} - i_{ai})} \quad (5)$$

where G has the unit of m^3/s , c_w is the specific heat of water, $\text{kJ}/(\text{kg} \cdot ^\circ\text{C})$. ρ_w is water density, kg/m^3 . Q is flow rate of circulating water. ρ_a is air density. i_{ai} and i_{ao} is specific enthalpy of air in and out of tower respectively, kJ/kg . K is the evaporation coefficient that is decided by temperature of outlet water.

In order to analyze the uniformity of circumferential inlet airflow quantitatively, a new parameter of C_u named airflow uniformity coefficient is introduced to with the formula as follows:

$$C_u = \frac{\frac{1}{n} \sum_{i=1}^n v_{a,i}}{\sqrt{\frac{1}{n} \sum_{i=1}^n v_{a,i} + \frac{1}{n} \sum_{i=1}^n (v_{a,i} - \frac{1}{n} \sum_{i=1}^n v_{a,i})^2}} \quad (6)$$

In Eq. (6), n is number of test points that is taken as 8 here. $v_{a,i}$ is the velocity of inlet air at the test point of i , m/s . C_u related to average velocity of inlet airflow and standard error demonstrates the degree of deviation of inlet airflow.

As the definition of Eq. (6), the range of C_u is 0~1. In theory, if there is not crosswind, inlet airflow is totally even circumferentially i.e. $v_{a,i}$ is equal everywhere, with $C_u=1$. But existence of crosswind disturbs the uniformity of inlet airflow, making $C_u < 1$ as a result. If crosswind gets extremely large that

results in a great difference of inlet air velocities around tower, the C_u can be almost 0. At the condition of certain airflow rate, bigger C_u represents more uniform heat and mass transfer and better cooling performance, in opposite, smaller C_u shows bigger difference of heat and mass transfer and more points of weak heat exchange that deteriorates the global cooling efficiency.

Before the optimization, it can be seen in Fig. 5(a), 4(b) and 4(c) that the velocities of circumferential inlet airflow are almost the same without crosswind, at the condition of that, $C_u=0.97$ and G reaches the maximum of $165.27 \text{ m}^3/\text{h}$. While crosswind increases inlet airflow of windward and reduces that of leeward sharply, making circumferential inlet airflow deviates from the no crosswind condition and totally reducing C_u and G . As v_{cw} up to 0.6 m/s , outflow is observed at leeward, C_u reduces to 0.44 , and G reaches the minimum of $154.64 \text{ m}^3/\text{h}$, which is 6.43% lower than the maximum. When v_{cw} exceeds 0.6 m/s , the uniformity of inlet airflow gets worse, nevertheless airflow rate presents of recovery trend, e.g. $C_u=0.3$, $G=160.45 \text{ m}^3/\text{h}$, at the point of $v_{cw}=1.0 \text{ m/s}$.

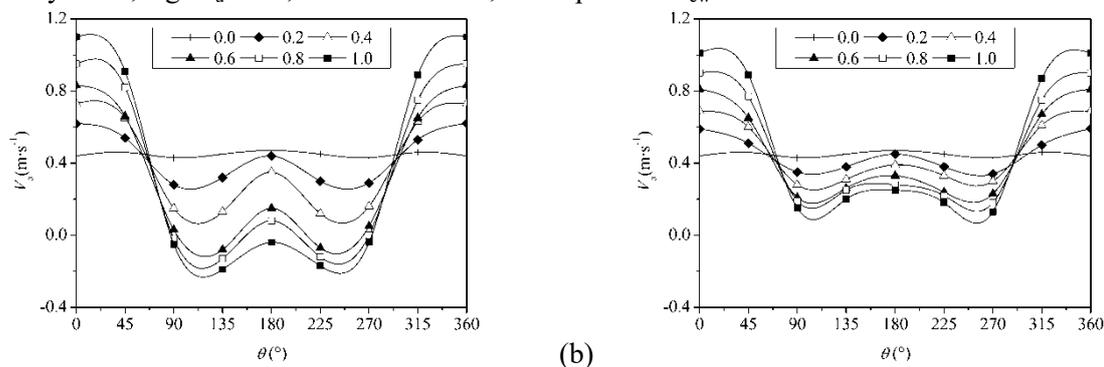


Figure 5. Crosswinds effect on circumferential distribution of the NDWCT inlet air velocity. (a) before inlet airflow optimization, (b) after inlet airflow optimization

After installing air deflectors at tower inlet, as showed in Fig. 5(b), 4(b) and 4(c), the general changing trend is the same as that of before optimization, but the deviation of inlet airflow of windward and leeward is obviously lower than that of no crosswind condition. However, outflow is not observed at the studied range of crosswind velocities and airflow uniformity coefficient increases universally, airflow rate has a relatively big rise as well. When $v_{cw}=0.6 \text{ m/s}$, $C_u=0.65$, $G=160.43 \text{ m}^3/\text{h}$.

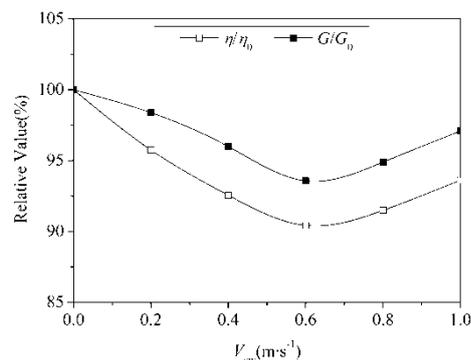


Figure 6. Comparison between the relative variation of η and G under crosswind conditions

4.3. Relative variation of η and G

Fig. 6 shows the comparison between the relative variation of η and G under crosswind conditions, in which, η_0 and G_0 of no crosswind case are used as benchmarks. It can be seen that the change of η/η_0 is bigger than G/G_0 , e.g. when $v_{cw}=0.6 \text{ m/s}$, η decreases 9.57% , while G only lessens 6.43% , which indicates that the reduction of G is not the only reason of the drop of performance but also attributed to

the circumferential nonuniformity of inlet airflow that discomfit the heat and mass transfer in tower. Fig. 7 compares the relative variation of η and G before and after inlet airflow optimization. From an opposite sight ,because of the optimization, increase of η is also bigger than G , e.g. when $v_{cw}=0.6$ m/s, η increases 5.88%, while G only raises 3.74%. This means that the air deflectors not only increase airflow rate but also enhance the uniformity of inlet air and equalize heat and mass transfer. So the performance change of cooling tower under crosswind is the result of variation of G and uniformity of inlet air.

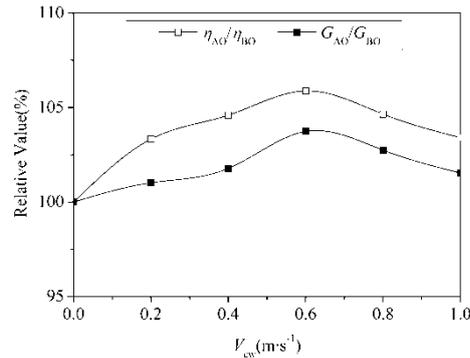


Figure 7. Comparison between the relative variation of η and G before and after inlet airflow optimization

4.4. Lewis factor and evaporation loss

Lewis factor Le_f represents the relationship of intensity of heat and mass transfer in the process of evaporation with the formula,

$$Le_f = \frac{k_h}{c_p k_m} \quad (7)$$

where c_p is constant-pressure specific heat of moisture air, kJ/(kg·°C); k_h is heat transfer coefficient, kW/(m²·°C); k_m is mass transfer coefficient, kg/(m²·s). It can be seen in equation (7) that bigger Le_f indicates more intense heat transfer while smaller Le_f implies faster mass transfer.

In the wet cooling towers, evaporation cooling is dominant and the loss of water ΔQ_w can be calculated by:

$$\Delta Q_w = G(\chi_{ao} - \chi_{ai}) \quad (8)$$

where χ_{ai} and χ_{ao} represent moisture content of air going in and out of tower respectively, kg/kg.

In the paper of [23], Le_f ranges from 0.5 to 1.3, taking 1.0 as an approximate value. Le_f of Fig.4(d) ranges 1.03~1.05, which is dovetailed nicely with [23]. Additionally, it can be seen in Fig.4(d) that Le_f enlarges after optimization which means the air deflectors relatively have more function in improving heat transfer and minifies the ratio of latent heat in the total heat load, while water loss caused by evaporation still increases. As in Fig.4 (e), owing to the optimization, water loss increases 5.69% when $v_{cw}=0.6$ m/s, which is the cost of improving cooling efficiency.

5. Conclusion

1) A new approach of installing air deflectors around tower inlet circumferentially is proposed to optimize the inlet airflow of NDWCT. Then the effect of air deflectors on tower performance under crosswind conditions is investigated through a hot model test. It is shown that crosswind has a great influence on cooling tower performance before optimization, cooling efficiency decreases firstly and then increases as the crosswind gets bigger. While after optimization, cooling efficiency raises intensely at all crosswind conditions and the change with wind gets smoothly. So installing air deflectors could ameliorate the adverse effect of crosswind on cooling performance.

2) In order to analyze the uniformity of circumferential inlet airflow quantitatively, inlet airflow uniformity coefficient C_u is defined. The model test result shows that without crosswind, inlet air is very uniform and $C_u=0.97$, air flow rate is biggest as well. Existence of crosswind deviate the inlet air, and leeward inlet flow decreases, even change into out flow, both C_u and G get lower sharply. Installing air deflectors makes inlet flow of circumference more uniform and increases C_u and G .

3) Analysis of relative change of cooling efficiency and air flow rate before and after optimization indicates two aspects of crosswind effect, firstly, crosswind reduces airflow rate, and secondly, crosswind destroys the uniformity of circumferential inlet airflow so as to make heat transfer of inner tower uneven and deteriorates cooling performance as a result. Air deflectors optimize both of the two aspects and improve cooling efficiency.

4) As Le_f increases after the optimization, air deflectors have more function on enhancing heat transfer than mass transfer and reduce the ratio of evaporation cooling; however the total water loss still gets bigger.

6. References

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