INFLUENCE OF CROSSWIND ON HELLER NATURAL DRAFT DRY COOLING TOWER AND IMPROVEMENT MEASURES

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ABSTRACT

With the risk of water resources increasingly heavier and the need of the inland development of the nuclear power, dry cooling tower in power plant with its excellent water conservation characteristics, gets more and more attentions from the countries all over the world, especially in coal-rich but water-short areas. There are mainly three dry cooling tower forms: the air-cooled condenser(ACC), the natural draft dry cooling tower with surface type condenser(Harman system) and the natural draft dry cooling tower with jet condenser(Heller system).The radiator of Heller dry cooling tower is fixed up vertically all around the tower. Its heat transfer performance is greatly affected by environmental conditions, especially the crosswinds. The study of the effects of the crosswinds to the flow and heat transfer performance is essential to the design and optimization of the air cooling tower. Hence, the effects of the crosswinds to the flow and heat transfer performance of the air cooling system are investigated by a hot state model experimental platform. A new method adding air leading plates all around the tower to eliminate or ease the adverse effect of the crosswinds is put forward. The results show that the cooling tower flow field and temperature field are in symmetry without crosswinds. The flow and heat transfer performance of Heller air cooling system in different locations will encounter varying degrees of influence under crosswinds. The total air flow rate and the total heat transfer rate are also influenced. Under high crosswinds, airflow from windward side will oppress that from tower side and leeside. Flow a round circular cylinder is also formed. At this time, radial wind speed and effective into tower wind speed are small in tower side and leeside, heat transfer effect is poorer. The worst parts of flow and heat are mainly in the tower side. The influence mechanisms of environmental crosswinds and the certainty of heat transfer deterioration parts point out the direction for the further precautions. Adding air leading plates all around the tower is a very effective windproof measure which can improve the operating conditions greatly, change negative effect to positive effect.

INTRODUCTION

The distribution of coal resources and water resources in the world is extremely unbalanced; the coal rich areas such as South Africa, Iran, Saudi Arabia and western China are all the water shortage areas [1]. It becomes the bottleneck restricting the development of local electric power industry [2]. Using the dry cooling system is an effective way to solve this problem.

Power plant dry cooling system use the ambient air as the cooling medium to condense the steam turbine exhaust, which has remarkable water saving and environmental protection effect [3]. Compared with the traditional wet-cooling tower, dry cooling tower can save about 65%-90% water consumption. There are mainly three forms of dry cooling system: Direct air cooling system(air cooling condenser), indirect air cooling system with surface condenser (also known as Harmon system) and with jet or mixed type condenser (also known as Heller system)[4].Different from wet cooling tower, the dry cooling tower take away the heat through the natural buoyancy produced by air heating in surface heat exchanger, this makes the cooling tower cooling efficiency is significantly affected by environmental conditions, especially natural crosswind[5]. Under high crosswind speed, water temperature fluctuation is very large and the turbine back pressure increase. If the power plant doesn't take effective improvements and optimization, the unit cycle efficiency will seriously reduce, or even downtime [6].

Based on actual operating experience, during the strong wind period every year (wind speed greater than 5m/s),the power generation capacity will reduce significantly because of the cooling tower efficiency decrease[7]. The radiator of Heller NDDCT is vertically arranged vertically around the periphery of the cooling tower, so its heat transfer performance will be more affected by environmental factors [8]. Especially the environmental crosswind, it will make the air into tower very uneven and reduce the tower ventilation, thereby reducing the economy of the power plant[9-11]. Therefore, it is important to study the effect of crosswind on the flow and transfer characteristics and take some improvement measures[12-13].

A.F Du and Kröger [14-15] pointed out that the impact mechanism of crosswind on the air-cooled tower is very complex and affected by many different factors such as wind speed, the shape of the air inlet, the ratio of the tower inlet diameter to the inlet height, tower shape, pressure loss coefficient, and the radiator arrangement form. A wind tunnel experiment was built by Derkson [16] to study the effect of crosswind on dry cooling tower flow field. Through the study of external flow patterns, pressure characteristics and inlet flow rate, it is found that the influence of crosswind on the inlet flow field of the tower windward side is great.

The flow field and temperature distribution of the Heller NDDCT was simulated by Tang [17] via the numerical method and analyzed the main reasons causing the thermal performance reduction. The study found that when there is crosswind, the air flows around the tower, in the tower side, the air tangential speed is very large, and the inlet pressure is small, resulting in the small air intake rate and high outer water temperature. With the crosswind speed increase, the tower leeward side will form whirlpool and secondary flow. When the crosswind speed is large enough, it will form a large flow return area in the tower bottom and a wind hood at the tower top, then increase the flow resistance.

Waked and Behnia[18] studied the effect of transverse wind speed and ambient dry bulb temperature on the heat transfer performance of dry cooling tower by numerical simulation. The results show that when the transverse wind velocity is more than 10m/s, the efficiency of dry cooling tower reduced by 30%.

Methods of mitigating crosswind effect on NDDCT are researched rarely. Improvement measures taken are mostly about building few quantities of wing walls or wind-shield walls around cooling tower[19-21].

Waked and Behnia [18] used CFD approach to stimulate of the 3D flow field of the dry cooling tower, and analyzed the thermal performance of NDDCT under transverse wind. A kind of windbreak which can reduce crosswind effect was proposed, results show that windbreaks set at tower inlet can efficiently reduce crosswind effect on the NDDCT thermal performance. Meanwhile, for the best result, reasonable size, location and materials of the windbreaks should be taken into consideration. But the wind preventing mechanism was not discussed in detail.

A cold model test of Heller NDDCT with wind-shield wall around the tower was built by Koosha[22]. Numerical simulation was used to analyse the effect of radiator layout manner on NDDCT performance under crosswind by Kroger[23-24]. They suggested reasonable layout of radiators and windbreaks to reduce adverse effect on NDDCT by crosswind, but without a further research on windbreaks improvement mechanism and optimization measure.

Waked and Behnia[25] studied the effect of wind breaks wall installation position and porosity ratio on the NDDCT flow filed and thermal performance by numerical simulation. Bender built a wind tunnel experiment by installing wind-shield wall at the NDDCT windward side. It studied the effect of different wind-shield wall shapes on dry cooling tower.

From the above studies, it can be seen that research on the methods of mitigating the crosswind effect of NDDCT especially Heller NDDCT is still few, the proposed windbreak walls still have many problems, and there is no detailed study on the improvement mechanism. In addition, previous studies used the cold model which could only investigate the aerodynamic characteristics of the tower, but could not reflect the thermal performance directly.

Therefore in this follow-up study, the Heller indirect air-cooled tower is taken as the research object, a hot model based on it is used to investigate the influence of environmental crosswind on the aerodynamic field and thermal performance of Heller NDDCT. A new method of installing air-leading plates around the air-cooled tower was put forward. Experiment result shows that a number of smooth inlet air passages are formed around the air inlet after putting air-leading plates, which improves the air inlet uniformity of the cooling tower and eliminates the adverse effect of the crosswind.

NOMENCLATURE

D	[m]	Tower diameter at inlet
g	[m/s^2]	Gravitational acceleration
G	[Kg/s]	Air quantity
H	[m]	Cooling tower effective height
t	[℃]	Temperature
t_{wi}	[℃]	Inlet water temperature
t_{wo}	[℃]	Outer water temperature
t_{ai}	[℃]	Inlet air temperature
t_{ao}	[℃]	Outer air temperature
v_z	[m/s]	Surrounding air speed at the height of z
v_s	[m/s]	Air velocity at the tower outlet
v_c	[m/s]	Crosswind speed
v_r	[m/s]	Inlet air velocity at the tower inlet
Pr	[-]	Prandtl number
Re	[-]	Reynolds number
I	[-]	Thermal efficiency improvement factor
ε_{th}	[-]	Thermal efficiency coefficient
F_Δ	[-]	Fred number
Δt	[℃]	Water temperature drop
Δt_i	[℃]	Water temperature drop of the i_{th} radiator group
ΔT	[℃]	Total average temperature difference

Subscripts

a	Air
c	Crosswind
w	Water
M	Model tower
P	Real tower
in	Tower inlet
out	Tower outlet
wb	Condition after installing wind deflector

MODEL SIMILARITY CRITERION

In the hot model test of the air cooling tower, it is necessary to satisfy the geometric, kinematic and dynamic similarity.

1. Geometric Similarity

The model test tower used for test was constructed according to the ratio of 1:170 in the original cooling tower. The original tower is 135.4m high, the bottom diameter is 119.8m and the inlet height is 15m.

2. Kinematic Similarity

The airflow in the model tower and the original tower must be similar, that is:

$$\left(\frac{V_a}{V_s}\right)_P = \left(\frac{V_a}{V_S}\right)_M \tag{1}$$

where V_a is the air velocity at the outlet of tower top, V_s is the crosswind velocity at the height of the tower outlet, which unit is m/s. The subscript P and M represent the prototype and model tower respectively.

3. Dynamic similarity

In the hot model test, the driving force of buoyancy and the inertial force of crosswinds are the main factors to be concerned, so the test must ensure the density Froude number of the model tower and the original tower are the same, that is:

$$F_\Delta = \left(v_s \Big/ \sqrt{\frac{\Delta \rho g H}{\rho}} \right)_P = \left(v_s \Big/ \sqrt{\frac{\Delta \rho g H}{\rho}} \right)_M \tag{2}$$

where ρ is the air density within the tower, Kg/m^3; $\Delta\rho = \rho_a - \rho$, ρ_a is the air density outside the tower, Kg/m^3; H is the cooling tower effective height, m; g is the gravity acceleration, m/s^2.

EXPERIMENT SYSTEM

The schematic diagram of the experiment system is shown in Fig 1.Experiment system consists of the following parts:

1. Aerodynamic system. The system can simulate crosswind environment by two fans. These two fans are at the same height as the top and bottom of the tower, respectively. It provides a frequency converter to adjust crosswind speed which the accuracy level is 0.1m/s.
2. Water circulation system. The water system contains thermostat water tank, buffer water tank, water pump and pipes. The circulating water flows from the buffer tank into the radiator top, after exchanging heat with air in the tower, then flows into the thermostat water tank from the radiator bottom. The water is heated to a given temperature by the electric heater and then pumped to the buffer water tank to complete the cycle.

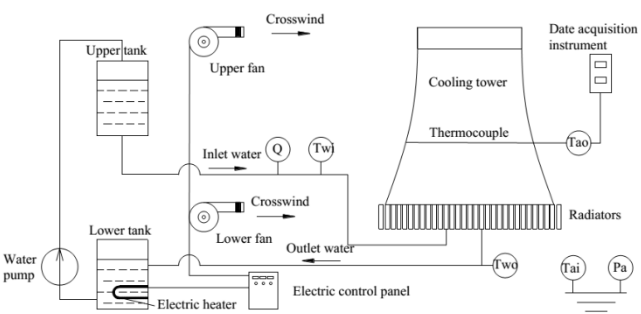


Figure 1 Diagrammatic sketch of experiment system

3. Temperature-control system. The system is composed of electric heater and a PLC (Programmable Logic Controller), it can keep the water temperature in the tank constant.
4. Data collection system. Copper-constantan thermocouple and HP data collector (Agilent34970A) was employed to measure and record air temperature in different locations within the tower model.
5. Heat sink. The radiator is divided into six groups as well as the real cooling tower; it is composed of copper radiating pipe with aluminum fins. Every radiator group has 21 pipes, the pipe length is 10cm and the internal diameter of the pipe is 0.8cm. The aluminum fin thickness is 0.5mm and fin space is 2mm.The radiator pipe of each radiator group is connected in series and in V-shaped staggered arrangement. Figure 2 and Figure 3 shows the arrangement of radiator pipe and relative position of radiator groups.

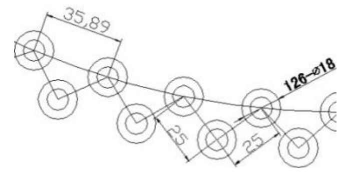


Figure 2 Arrangement of radiator pipe

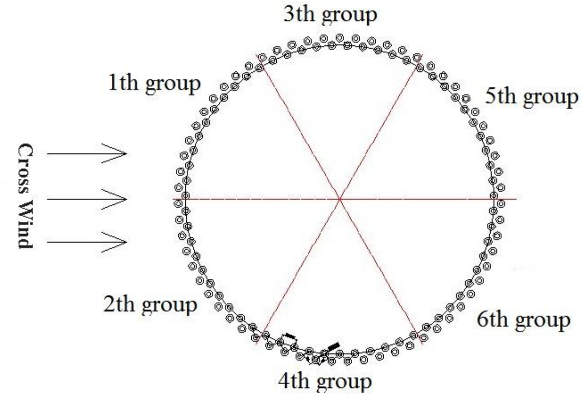


Figure 3 Relative position of radiator groups

MEASUREMENT APPARATUS AND INSTRUMENTS

In the experiment, the parameters used to reflect the cooling tower flow and heat transfer characteristics were measured, includes atmospheric pressure, crosswind velocity, circulating water flow rate, water and air temperature at the inlet and outlet of the tower. The apparatus and measuring instruments are detailed in Tab 1.

Table 1 Monitored apparatus and measuring instruments

Apparatus	Instrument	Range	Accuracy
Atmospheric dry bulb temperature	Psychomotor	0~80℃	0.1℃
Atmospheric pressure	Hot-wire manometer (KA22)	0~5Kpa	0.01Kpa
Circulating water flow rate	Flow meter	0~15L/min	0.01L/min
Inlet and outlet water temperature	K-type thermocouple	0~1300℃	0.1℃
Air velocity	Testo405-V1 thermal anemometer	0~10m/s	0.01m/s
Air temperature	Copper-constantan thermocouple	-200~200℃	0.1℃

EXPERIMENT CONTENT AND CONDITION

One substance of this experiment is to investigate the influence of crosswind on air cooling tower flow field and heat transfer performance at different circumferential positions.And then install air guide plates around the dry cooling tower model , to analysis the effect of air guide plates on cooling tower flow field and temperature field.

During the experiment, the crosswind speed and circulating water flow rate was changed to find the flow and transfer variation laws. Due to the model test tower used for test was constructed according to the ratio of 1:170 in the original cooling tower, according the dynamic similarity, the experiment crosswind speed should be 1/17 of the actual wind speed. So the experiment crosswind speed range at the height of tower air inlet is 0m/s~1.0m/s. The model flow field should meet the natural environment wind speed distribution law, that is, consider the impact of viscous resistance near the ground. The distribution rule is expressed by Equation (3):

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

Where v_z is the wind speed at height Z [*m*]*;* and z_{ref} *is* the wind speed at reference height Z_{ref} [*m*]. Then we can compute that the wind speed at the tower outlet is twice of the tower air inlet. So the experiment crosswind speed scope at the height of tower outlet is 0m/s~2m/s. The circulating water flow rate is set as 8L/min, 10L/min and 15L/min. All the experiment conditions are shown in the Table 2:

Table 2 Experiment conditions

Item	Conditions
Circulating water flow rate	8, 10, 15 L/min
Crosswind at tower inlet	0, 0.2, 0.4, 0.6,0.8,1.0 m/s
Crosswind at tower outlet	0, 0.4, 0.8, 1.2,1.6,2.0 m/s

EVALUATION INDICATOR OF NDDCT PERFORMANCE

In order to evaluate the performance of dry cooling tower accurately, this paper presents several main evaluation indexes.

The water temperature drop Δt was used to describe the effects of crosswind on dry cooling tower heat transfer performance on different positions:

$$\Delta t = t_{wi} - t_{wo} \tag{4}$$

where t_{wi} , t_{wo} is the water temperature of cooling tower inlet and outlet, respectively.

As the influence degree of crosswind on the radiator at different positions is polytropic, so the total average temperature difference ΔT is used to reflect the effects of crosswind on overall thermal performance of dry cooling tower:

$$\Delta T = \frac{1}{n} \sum_{i=1}^{n} \Delta t_i \tag{5}$$

In order to describe the crosswind effect more clearly, this paper defined a new dimensionless parameter: the thermal efficiency coefficient ε_{th} . ε_{th} is defined as the ratio of the heat dissipation amount under crosswind to the maximum heat dissipation when there is no wind:

$$\varepsilon_{th} = \frac{Q_{conv}^{U_{cw}}}{Q_{conv}^{U_{cw}=0}} = \frac{(t_{wi} - t_{wo})_{cw}}{(t_{wi} - t_{wo})} \tag{6}$$

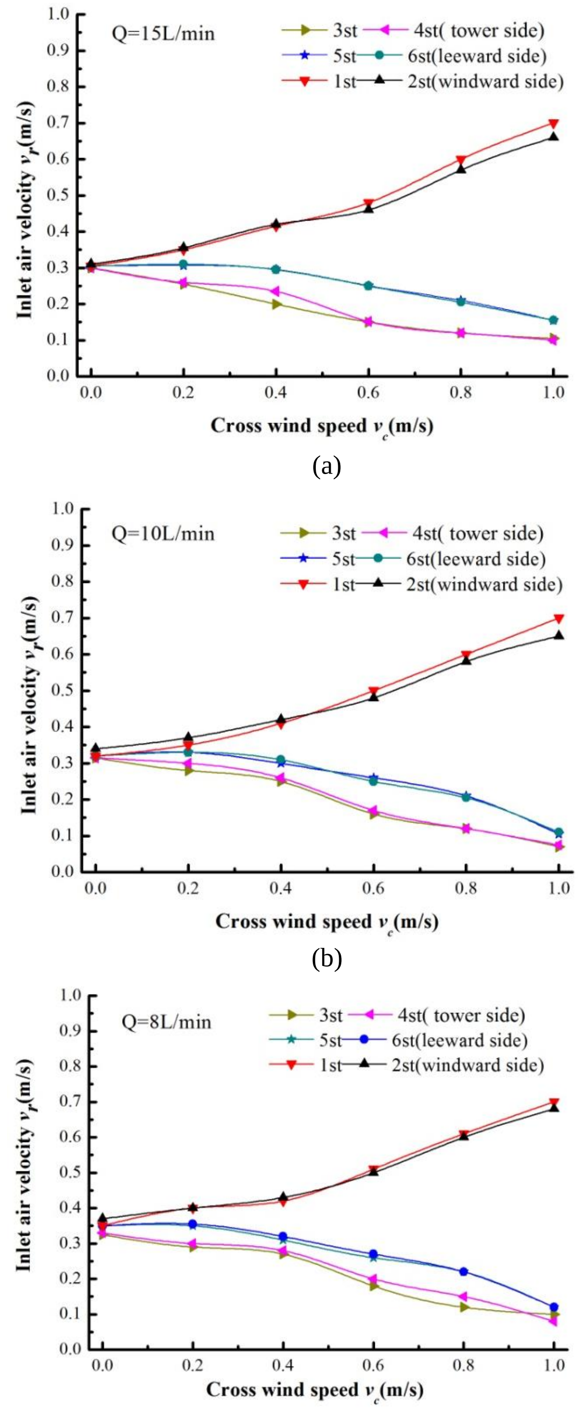
The dimensionless thermal efficiency improvement factor *I* was proposed to reflect the thermal performance change before and after arranging wind guide plate:

$$I = \frac{Q_{conv}^{U_{cw,wb}} - Q_{conv}^{U_{cw}}}{Q_{conv}^{U_{cw}=0}} = \varepsilon_{th,wb} - \varepsilon_{th} \tag{7}$$

RESULTS AND DISCUSSION

1. Crosswind Effects on flow field

Figure 4 shows the change of tower inlet wind speed with crosswind under different circulating water flow rate.



(c)

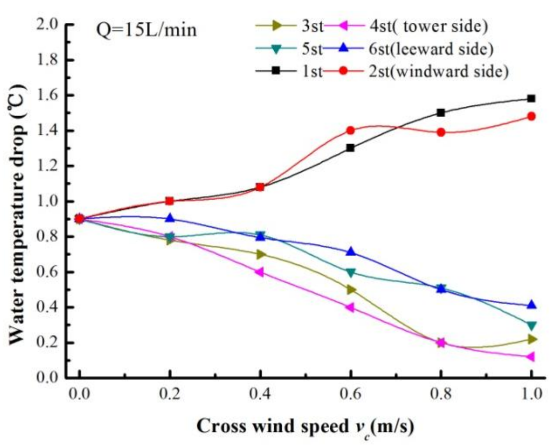
Figure 4 Crosswind Effects on flow field

When the crosswind speed rise from 0m/s to 0.4m/s, the tower inlet air velocity of windward radiator group increase from 0.3m/s to 0.42m/s, the velocity of side radiator group decrease from 0.3m/s to 0.24m/s ,while the leeward side air velocity keeps constant basically. With the crosswind speed increase from 0.4m/s to 1.0m/s, the inlet air velocity at windward increased almost 65%, but the side inlet air speed decreased by 50%, and the leeward side decreased by nearly 45%. When there is no crosswind, the inlet air flow around the tower is uniform; with the crosswind speed increase, the inlet air velocity at windward side rise continuously, the speed of tower side and leeside inlet air decrease significantly. The worst part of heat transfer around the tower is the tower side radiator group, when the crosswind speed increase to 1m/s, there is almost no air flow into the tower.

The main reason for the flow field deterioration is the increasing crosswind compress the tower side and leeside inlet air, thereby the air velocity decrease. When the crosswind speed is large enough, the “circumferential flow” occurs outside the cooling tower: although the inlet air speed is considerable, but the tangential component of the velocity is too big and the radial component is very small. So the effective inlet air flow rate is very little, resulting in flow deterioration.

2. Crosswind effects on heat transfer performance

It can be seen from Figure 5 that: (1)As the crosswind speed increases, the water temperature drop Δt of the windward radiator increase constantly, but decreases continuously of the leeward and side radiator group. (2) With the crosswind speed rise from 0m/s to 0.4m/s, the Δt in the prevailing wind surface increases by 0.2℃, decreases by 0.3℃ in the side and decreases by 0.1℃ in the leeward side. (3)With the crosswind speed rise from 0.4m/s to 1.0m/s, the Δt of the prevailing wind radiator group increases by about 0.6℃, decreases by 0.5℃ in the side group, about 0.4℃ in the leeward group.



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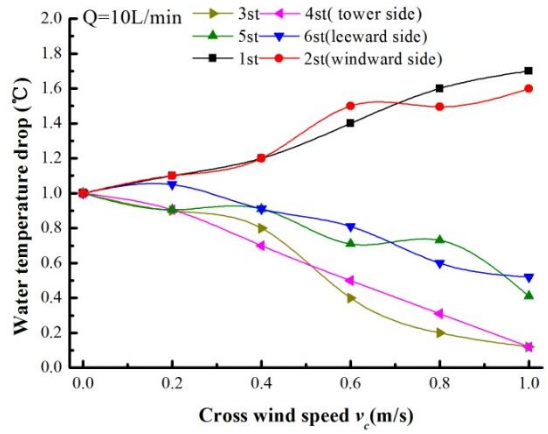

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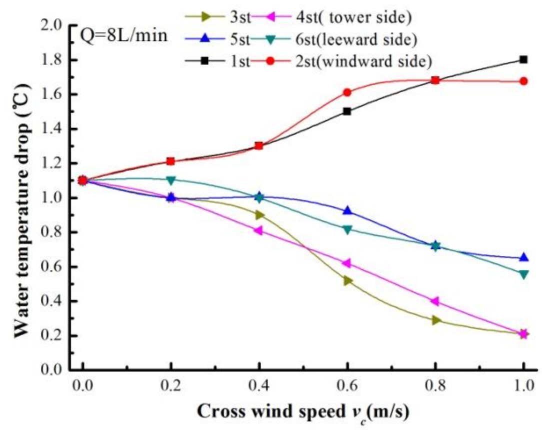

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Figure 5 Crosswind Effects on heat transfer performance

The worst parts of heat dissipation of the radiator cluster in the tower side. Especially under high crosswind speed, the Δt decreases rapidly in the side and leeward side radiator group.

The reason leading to this performance is: when there is crosswind, the inlet air flow rate increases in the prevailing wind direction of the air cooling tower, and the speed of air flow increases. The outside cold air keeps pressing into the tower from the windward radiator group, which enhance the heat transfer performance there. But meanwhile the inlet air speed of cooling tower in the side and leeward decreases, the air flow rate comes down. Because of the oppress of the high speed crosswind at the prevailing wind direction, a large amount of heated air after radiator gathers in the side and leeward, even flows out of the tower. This situation will produce back flow and the hot air may be reheated, thereby reduce the heat exchange performance of the heat radiator greatly.

3. Crosswind effect on overall thermal performance of NDDCT

Due to the influence of crosswind on the air intake condition and the heat exchange performance at different positions around the tower is different, the overall average cooling temperature drop ΔT was used to reflect the influence of crosswind to the overall heat exchange performance of

NDDCT in this paper. In the Figure 6, with the ambient crosswind speed increases, the ΔT continuously decrease. And in low wind speed, the change curve decrease smoothly, but in high wind speed, the ΔT curve downtrend is large. A reason for this performance is that in the low wind speed, the draft effect of the cooling tower is large and the influence of the inertia force caused by crosswind is small, but in the high wind speed, the crosswind inertia becomes large and the cooling tower performance becomes worse.

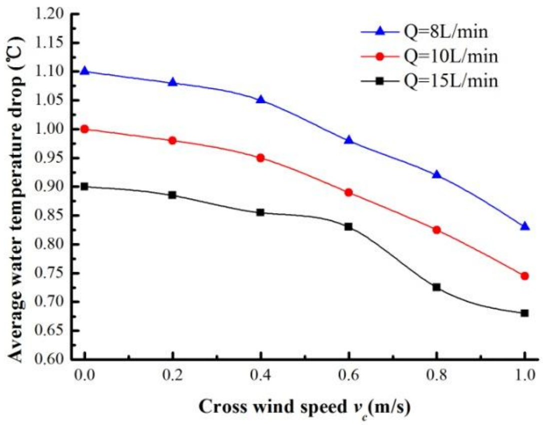


Figure 6 Crosswind effect on average cooling temperature drop

Dimensionless parameter-thermal efficiency coefficient-ε_{th} is proposed in this paper to describing the influence of environmental crosswind on total thermal performance of air cooling tower.

It can be seen from the Figure 7 that the larger the crosswind speed is, the more quickly the ε_{th} decreases. It can indicate that the crosswind has negative influence on the total thermal performance of air cooling tower. Especially in the case of high wind speed, the cooling performance deteriorates rapidly. When the crosswind speed changes from 0.4m/s to 1.0m/s, the ε_{th} is reduced by more than 20%.

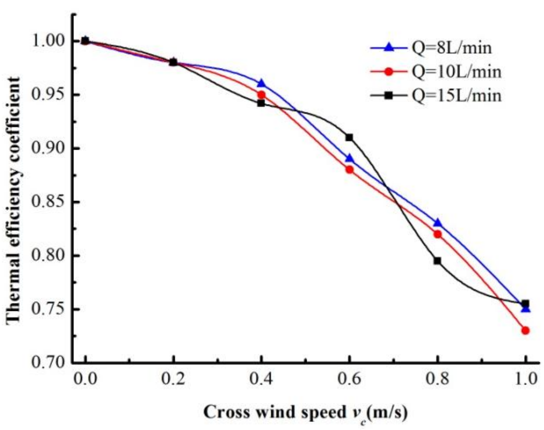


Figure 7 Crosswind effect on thermal efficiency coefficient

4. Influence of wind deflector on flow field

According to above analysis, we can see that the influence of crosswind on the cooling performance of dry cooling tower mainly concentrates on the side and the leeward. Therefore, to decrease or even eliminate the negative influence of crosswind on dry cooling tower, the air movement on the side and the leeward should be improved. The installation of air deflector around the radiator of dry cooling tower is put forward in this paper.

The type and size of air deflector adopted in the experiment is shown in Figure 8. The thickness of deflector is 1mm and the quantity is 26. The height of air deflector is levelled with air inlet. The long vertical edge is close to air inlet of air cooling tower and distributes uniformly around radiator along radial direction of the tower, as shown in Figure 9.

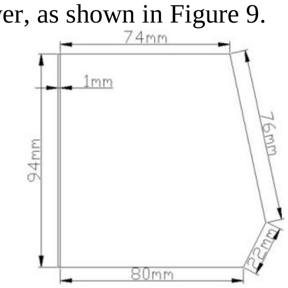


Figure 8 The shape of air deflector

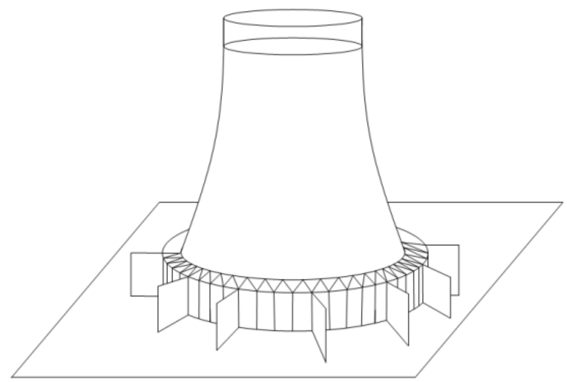
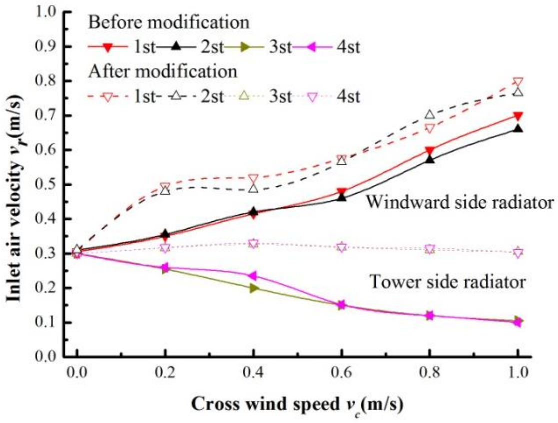


Figure 9 Schematic structure of the model tower and air deflector

Figure 10 shows the variation condition of inlet wind speed with the crosswind before and after the modification. As can be seen from the figure: 1. When the crosswind speed is low, the inlet wind velocity increases slightly compared to before modification, but the magnitude is relatively small. 2. Under high crosswind speed, the improved effect caused by wind deflector is obvious. With the crosswind speed increased from 0.4m/s to 1.0m/s, the inlet air velocity of windward radiator increased by 50%, the inlet air speed of side radiator group only decreased by 15%, and the wind speed on the leeward side only decreased by 14%. The result shows that the installation of the wind guide plate is beneficial to the inlet air velocity of the cooling tower. Especially under high crosswind speed, it can improve the air flow on the tower side and leeward side, and increase the effective tower inlet velocity.



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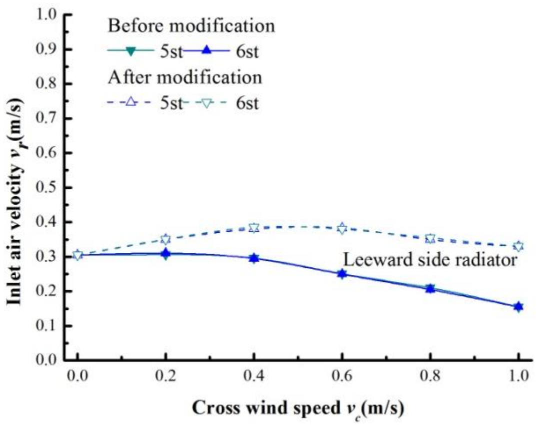

(b)

Figure 10 Influence of wind deflector on flow field

5. Influence of wind deflector on temperature field

Figure 11 shows the variation curve of Δt with the cross wind speed after installing the wind deflector, from which we can see:

(1) With the increase of wind speed, the Δt of the windward side radiator group is still increasing, and the Δt of the side surface and leeward side radiator group is still decreasing. However, relative to the results before installing wind deflector, the curve changes trend is more smoothly.

(2) When the crosswind speed increased from 0.4m/s to 1.0m/s, the Δt of the windward side radiator group increased by 0.4℃~0.5℃, the Δt of the side surface reduced by 0.1℃~0.2℃, and the leeward side reduced by about 0.2℃. The air velocity flowing into the tower at the tower side and the leeward side is increased, the outside air is continuously entered into the tower and the flow field is greatly improved, which enhances the heat transfer performance and improve the Δt downward trend obviously.

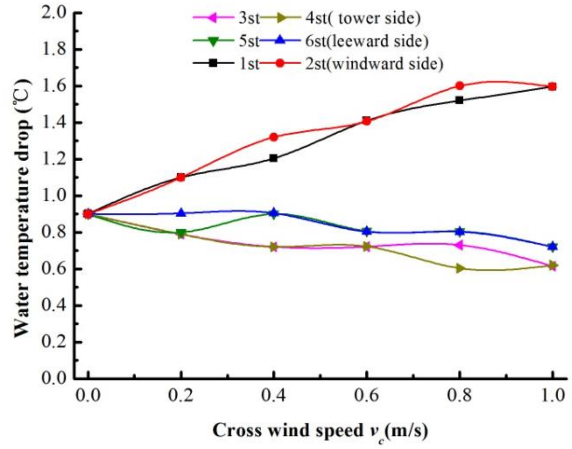

Figure 11 Influence of wind deflector on temperature field

6. Influence of wind deflector on overall thermal performance of NDDCT

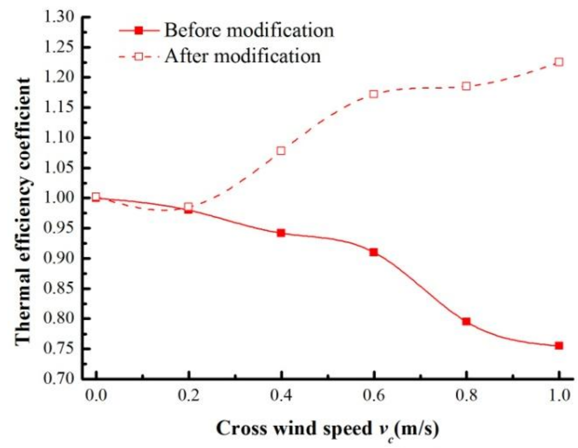

Figure 12 Influence of wind deflector on thermal efficiency coefficient

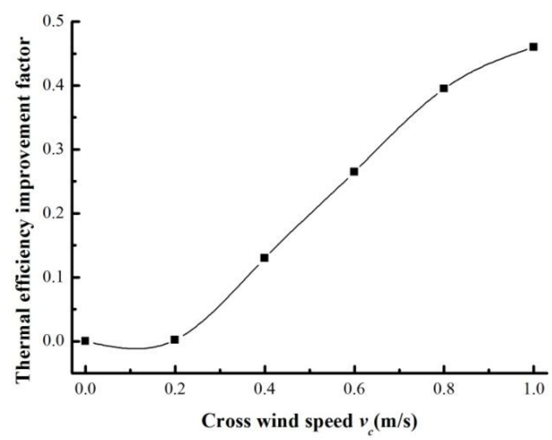

Figure 13 Influence of wind deflector on thermal efficiency improvement factor

As can be seen from Figure 12 and Figure 13, the thermal efficiency coefficient ε_{th} and thermal efficiency improvement factor I of the cooling tower all increase with the increase of crosswind speed after the installation of wind deflector. When the crosswind wind speed is 1m/s, the thermal efficiency coefficient ε_{th} increased from 0.8 to 1.2 compared to the situation without wind deflector, which increased by a factor of 50%， this is a very significant improvement.

CONCLUSION

In this paper, the hot model test of Heller NDDCT was established to analyse the influence of environmental crosswind on the flow and heat transfer characteristics of air-cooled tower Then a modify approach which installing wind guide plate was proposed and studied its improvement effect.

(1) The experiment of the NDDCT hot model before installing the wind deflector shows that: When there is no crosswind, the air flow field and heat transfer characteristics of the tower is axisymmetrical; but when the crosswind occurs, the air flow and heat transfer at different positions in the tower are affected by different degrees. Under the combined action, the overall heat transfer performance of the tower decreases with the increase of wind speed, which indicates that the crosswind has a negative effect on the air-cooled tower. The worst part of the flow and heat transfer is in the tower side area.

(2) After installing the wind deflector around the NDDCT, the experimental result shows that the wind guide plate can improve the inlet air flow rate at the tower side and leeward side, thereby enhance the heat transfer performance. After installing the wind guide plate, the thermal parameters which reflect the overall cooling performance of cooling tower, such as the total average cooling temperature difference ΔT , the thermal efficiency coefficient ε_{th} and the thermal efficiency improvement factor *I*, all increase with the increase of the crosswind wind speed. Especially in the high wind speed, the optimization result of wind guide plate on the Heller NDDCT performance is very obvious.

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