UTILIZATION OF THE LATERAL ACCELERATED CROSS-WIND TO IMPROVE THE COOLING PERFORMANCE OF A NATURAL DRAFT DRY COOLING TOWER

by

Weiliang WANG*, Junfu LYU, Hai ZHANG, Qing LIU, Guangxi YUE, and Weidou NI

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Energy and Power Engineering, Tsinghua University, Beijing, China

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Cross-wind degrades the performance of a natural draft dry cooling tower (NDDCT). Based on the basic affecting mechanism, this paper introduces a wind collecting approach. By using a wind collecting duct, the lateral flow acceleration of cross-wind is broken up, and the lateral flow kinetic energy is utilized to increase the lateral and rearward static pressure outside the radiator inlet. By adoption of a CFD model, the effect of the wind collecting approach is investigated comprehensively. It is found that the wind collecting ducts could improve the pressure distribution around the radiator bundle, reinforce the lateral air intake, and reduce the intensity of mainstream vortices, so as to enhance the ventilation rate of a NDDCT. For an outstanding performance, the two-duct wind collecting scheme is suggested, which may assure a NDDCT working in an approximately wind free manner in all investigated cross-wind range, and increase the ventilation rate by ~63% under the high cross-wind condition, which may reduce the overall coal consumption by 23500~33500 tons annually for a 660 MW coal-fired unit. The numerical results are confirmed by a hot state modelling experiment conducted in a wind tunnel.

Key words: *cross-wind, flow loss factor, NDDCT, lateral flow acceleration, ventilation enhancement, wind collecting*

Introduction

Thanks to the merits of water saving, low operation/maintenance cost and also long service time, a NDDCT, the main facility of an indirect dry cooling system [1], is increasingly used not only in coal-fired power plants, but also in concentrating solar thermal power plants [2]. It was found that ambient cross-wind obviously affects the cooling performance of a NDDCT [1]. For example, a cross-wind of 20 m/s may decrease the ventilation rate of a NDDCT by 36% [3]. And the cross-wind may increase the air temperature inside the tower by 7.5 °C [4], or decrease the heat transfer efficiency by more than 25% [5].

As the gradually increased aspiration for high efficiency, high reliability and low cost in the design and operation of power plant [6], people pay more effort on improving the

* Corresponding author, email: wang_wl@tsinghua.edu.cn

cooling performance of a NDDCT. Since CFD method is convenient to reveal the comprehensive flow field information, it is increasingly adopted in studying the performance of a NDDCT [7-9]. In order to conjointly study the NDDCT performance, a specially designed hot state test rig built in a wind tunnel is also reported [10, 11]. Besides, a flow loss factor (FLF) is proposed to quantitatively asses the cross-wind effect on the local flow field of a NDDCT in our recent study [12].

Based on the general and qualitative studies of the affecting mechanism of cross-wind on the performance of a NDDCT, a few approaches including using windbreaks and enclosure are suggested to enhance the cooling performance of NDDCT in cross-wind [13]. Numerical [14] and experimental [15] investigations found the windbreaks are effective to break the flow acceleration [16] and unfavorable pressure distribution [17]. While an enclosure arranged outside the radiators bundle is effective to avoid the formation of an unfavorable pressure distribution at the tower inlet [18]. Numerical simulation also found that combination approach of windbreaks and enclosure is effective to minimize horizontal air-flow or cross-ventilation inside the tower [19], which is also caused by cross-wind [20]. However, up to now, no competent approach has been put forward in application. The main reason is that those approaches were proposed based on experience, rather than the basic degrading mechanism of a NDDCT by cross-wind.

Our recent study shows that the mainstream vortex induced by the uneven inlet air intake is the main degrading factor for a NDDCT in presence of a cross-wind. While the flow acceleration is responsible for the pressure declining at the lateral section of the NDDCT [21]. On the ground of a comprehensive study, this paper proposes a wind collecting approach to utilize the lateral flow kinetic energy to enhance the air intake at the bottom inlet of the NDDCT. By building a CFD model of an on service NDDCT of a 660 MW unit, and constructing a corresponding hot state experiment system in a wind tunnel, the wind collecting schemes are comprehensively discussed, and the effects on the local flow field and the overall performance of a NDDCT are assessed.

Methods

Problem descriptions

The investigated NDDCT in this study is installed in a 660 MW power plant in city of Shanxi, China. The basic dimensions of the NDDCT are shown in tab. 1. On design condition of no cross-wind, as the result of the pressure difference between the inside and outside of the tower, cooling air circumferential uniformly enters the tower through between the radiator fins, so as to be heated by the cycling water inside the radiators. While under cross-wind condition, lateral low pressure areas induced by the flow acceleration emerges, resulting in a reduction of driving force and degradation of cooling performance [20]. Accordingly, a wind collecting approach is designed to collect the accelerated cross-wind at the lateral side as shown in fig. 1, where the accelerated cross-wind could be collected by the wind ducts and directed to the inlet of the back side radiators.

Figure 1(a) shows a one-duct scheme, where only one bottom wind duct. The upper edge of the open box is ~12 m above the expansion platform and the outer edge is ~35 m right to the radiator. This bottom wind duct looks like an open box, with a width of 15° in circumferential direction. Figure 1(b) exhibits a two-duct scheme, in which a middle duct is also included. The inlet of the middle duct has a width of ~15 m, and a height of 59 m. The outlet of the middle duct locates at the rear side of the bottom duct, and has a width of 15° in circumfe-

Table 1. Dimensions of the investigated NDDCT

Items	Values [m]
Total height	170
Thickness of the expansion platform	1.5
Height of the radiators	24
Height of the radiator support	2
Diameter of the outlet	84.47
Diameter of the throat	82
Diameter of the radiator bundle base	146.17
Heat exchanger type	Forgo
Heat exchanger width	2.408
Heat exchanger thickness	0.15
Fins diameter	$3.1 \cdot 10^{-3}$
Tube placement type	Staggered

rential direction. Figure 1(c) illustrates a three-duct scheme, where an upper duct is also included. The inlet of the upper duct has a width of ~16 m, and a height of ~43 m. The outlet of the upper duct locates at the rear side of the middle duct outlet, and also has a width of 15° in circumferential direction. The gap between each wind duct outlet let is also 15° in circumferential direction. The accelerated flow is directed along the streamline in each wind duct as denoted by the dotted lines.

As a NDDCT is of thin-walled structure, it cannot support the wind ducts, and thus an additional supporting is needed in application. To avoid the complex and to focus on the concept design of the wind collecting scheme, the support is not considered in the modelling.

Since the steam rate per unit power generation increases synchronously as the back pressure increases, the latent heat released in the condenser decreases slightly [22-24]. It is found that as back pressure increases within 5 kPa, the variation of exhaust heat is no more than 2%. Compared to the ventilation variation of a NDDCT (~30% correspondingly), the exhaust heat could be regarded as a constant under different cross-wind condition. Although cross-wind could affect the circumferential distribution of heat release by changing the local superficial velocity of the cooling air, as the variation of circumferentially accumulated heat rejection is negligible, the effect on the whole ventilation rate is little. Consequently, in simulation, the radiator bundle was set as a constant heat source in CFD simulation, while, in experiment, the three evenly assembled heating rods were placed at inside the radiators.

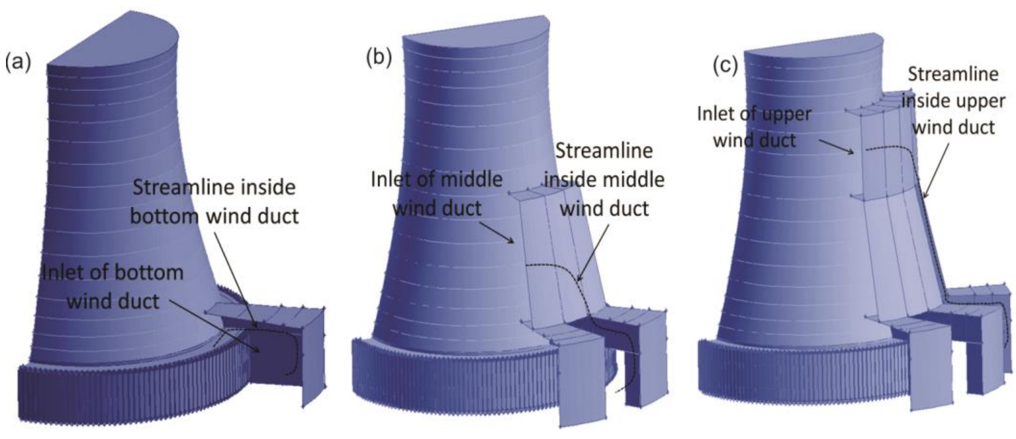

Figure 1. Configurations of different wind collecting schemes; (a) one duct model, (b) two-duct model, (c) three-duct model

The CFD modelling

Due to the symmetry of the flow field, the CFD modelling is conducted in a half-cylinder configuration, with a dimension of 1200 m (in diameter) ×1700 m (in height), which is ten times of the model scale in each dimension. As the flow path between the cross-wind inlet and the tower inlet is long enough to develop a reasonable profile, a constant velocity inlet was set at the inlet boundary of the computational domain. The outlets of the domain are all set as outflow boundary. Other wall type surfaces like the ground, tower shells and joint faces between adjacent radiators are all set as adiabatic walls with no slip. Pressure-based solver is adopted in FLUNET software, where the pressure-velocity coupling with SIMPLEC method is used.

The air-flow around the NDDCT is checked in a fully developed turbulent regime. Buoyancy force is considered by adopting Boussinesq approximation in the vertical momentum equation [25]. Standard k-ε model is chosen in the turbulent equation. The governing equations consisting of continuity, momentum and energy are well discussed elsewhere [25]. Grid independence check was conducted with grid numbers of 7535000, 8354000, 12268000, and 13771000 at the cross-wind speed of 0.5 m/s and 4 m/s, respectively. Errors of only 0.036% and 0.016% are obtained by adopting the grid number of 13371000 in two cross-wind conditions. More detailed information about CFD model was discussed in our previous publication [3].

Experiment modelling

The experimental models of the wind collecting schemes are exhibited in fig. 2, including one duct model and three-duct model. These models are scaled down by 200 times as compared to those shown in fig. 1. For the ease of processing, a gap is designed between each two neighbor ducts. Nevertheless, the inlet dimensions of each wind duct are strictly scaled down according to the dimensions introduced in fig. 1.

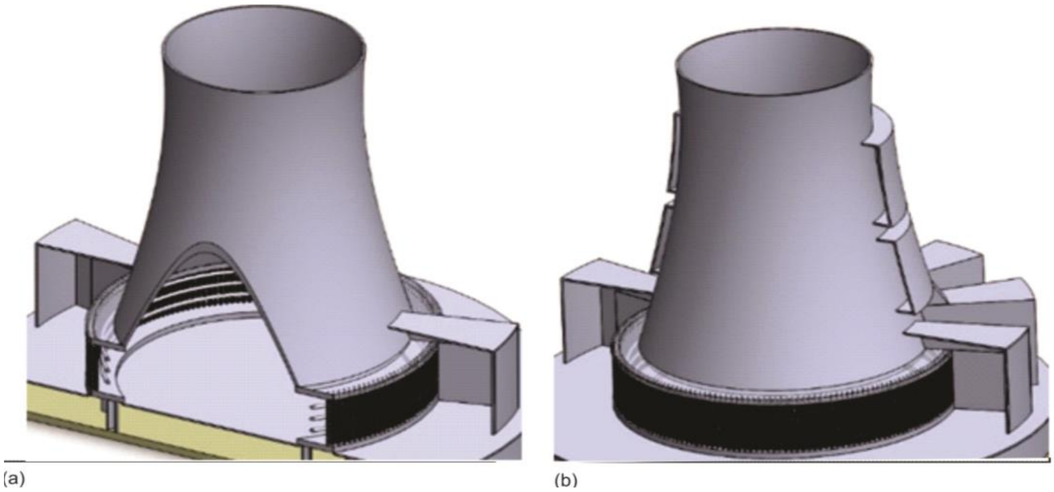

Figure 2. Experimental model of the wind collecting scheme; (a) one-duct model (b) three-duct model

The schematic diagram of the experimental system has been introduced in our previous study [11]. The system consists of a scale of 1/200 NDDCT model, a wind tunnel and a measurement system. The NDDCT model is scaled by geometry similarity. The baseline local velocity and tunnel wind are scaled according to Froude number and momentum similarity, respectively. The resistance coefficients are designed from Euler Number. Reynolds number is also considered to assure the mainstream flow in self-similar region. The NDDCT model, mainly consisting of a chimney, resistance bundle, heating rods, is placed in a wind tunnel in the experiments. The radiator resistance is mimicked by a series of parallel arranged zig-zag resistance pieces (resistance bundle). The heat rejection is simulated by three tunable electrical heating rods at the inside of the resistance bundle. The wind tunnel can supply precisely controlled cross-wind to mimic the specific environmental cross-wind.

Results and discussion

It is found that cross-wind affects the performance of a NDDCT by changing the pressure and flow fields, and degrades its ventilation mainly via the inlet of the radiator bundle [21]. Hence, the pressure contour, velocity field, and air streamline are investigated. The horizontal split of the NDDCT inlet is selected as a characteristic cross-section, and 10 m/s is selected as a characteristic velocity.

The wind collecting effects on pressure fields

The pressure contours at the middle section of the NDDCT inlet at 10 m/s under different cases are shown in fig. 3. On baseline case, cross-wind accelerates at the two sides of a

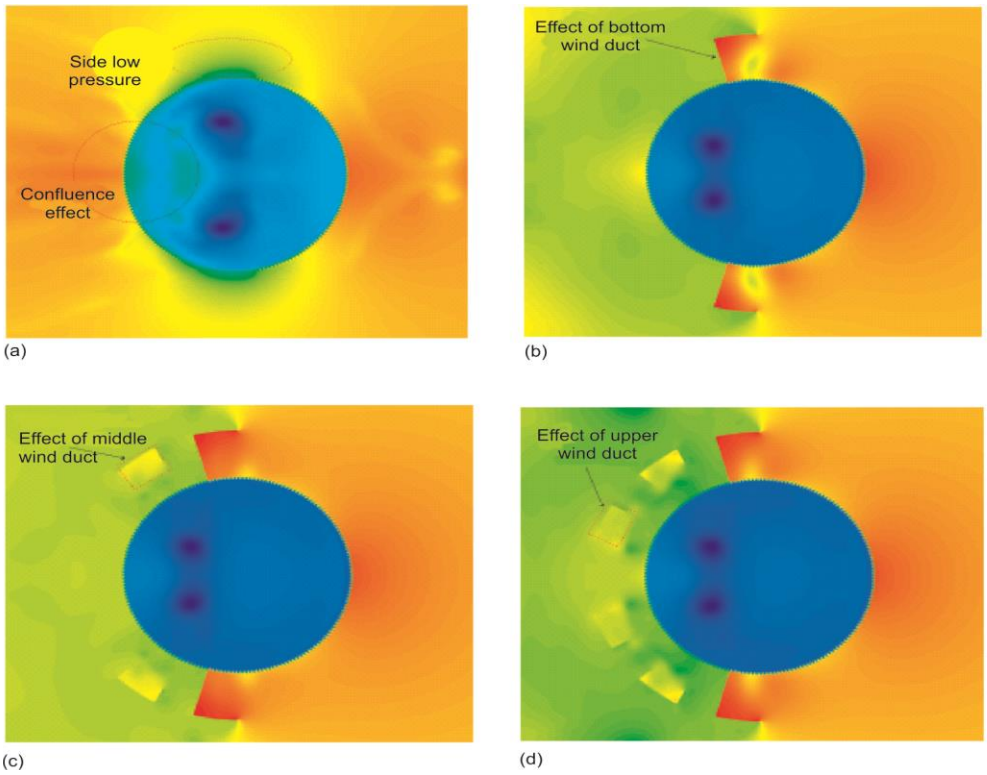

Figure 3. Pressure contour of the inlet middle section at 10 m/s; (a) baseline case, (b) one-duct case, (c) two-duct case, (d) three-duct case (*for colour image see journal web site*)

NDDCT, resulting in lateral low pressure areas. As the side accelerated flow moves to the rear side, flow separation arises around the radiator inlet. The flow separation produces many complicated vortices, and forms a confluence around the center of the rear side radiator inlet, leading to a high pressure area as shown in fig. 3(a). The high pressure area at the rear side promotes the local air intake, while the low pressure areas at the lateral sections hinder the local air intake.

By adoption of a bottom wind collecting duct (one-duct case), the lateral accelerated flow around the radiator inlet is directed as shown in fig. 1(a). As a result, the lateral low pressure areas are transformed into corresponding high pressure areas, while the rear side high pressure area disappears as the result of the breaking down of the side flow acceleration as fig. 3(b) shows. By further adoption of the middle and the upper wind collecting ducts (referred as two-duct and three-duct cases, respectively), the lateral middle and upper accelerated flow are supposed to be directed to the rear side accordingly as shown in figs. 1(b) and 1(c). As shown in figs. 3 (c) and 3(d), the local pressure around the lateral and rear side is found to be further increased, although the enhancement is not as obvious as expected.

The wind collecting effects on flow fields

The velocity at the middle section of the NDDCT inlet at 10 m/s under different cases is exhibited in fig. 4. As mentioned previously, the lateral flow acceleration and rear side

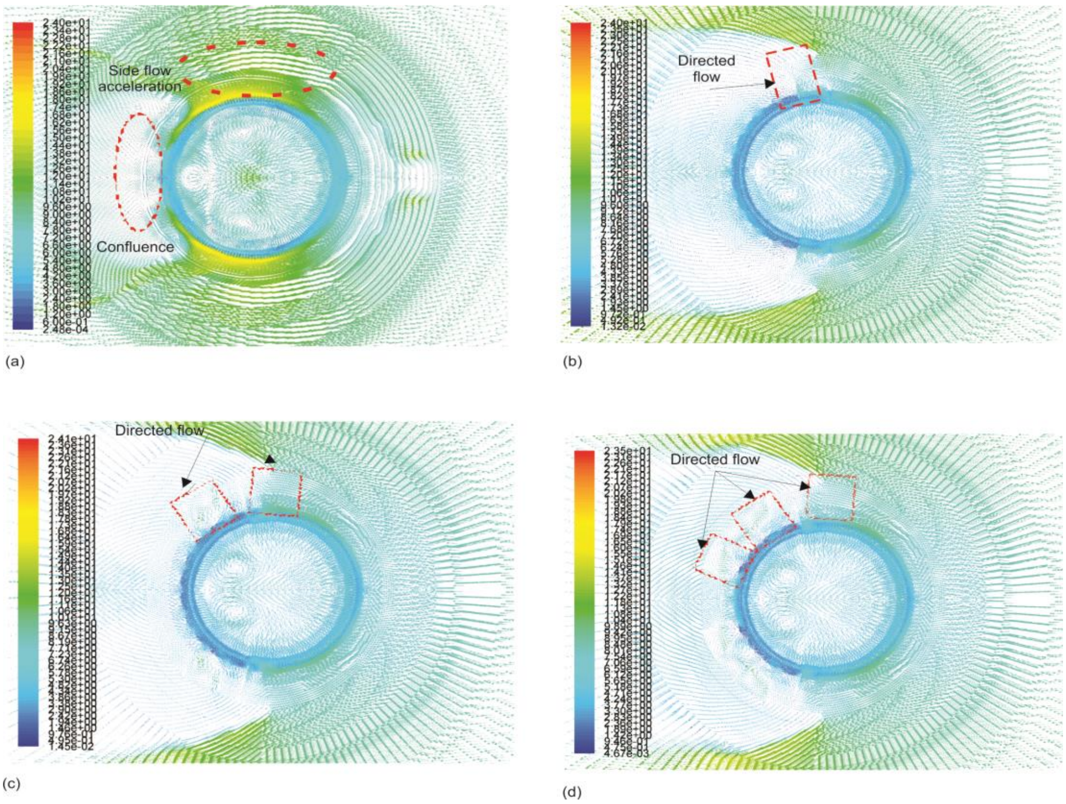

Figure 4. Velocity field of the inlet middle section at 10 m/s; (a) baseline case, (b) one-duct case, (c) two-duct case, (d) three-duct case (*for colour image see journal web site*)

confluence on baseline case are shown in fig. 4(a) as circled out by the dashed ellipses. On one-duct case, the lateral accelerated flow is found to be directed into the radiator inlet around lateral sections, leading to an enhancement of air intake at corresponding radiators as shown in fig. 4(b). On two-duct and three-duct cases, the lateral accelerated air-flow at the middle and upper sections is also found to be directed to the radiator inlet around the rear side sections, leading to an enhancement of air intake at corresponding radiators as shown in figs. 4(c) and 4(d), nevertheless, the air intake enhancement at rear side is relatively weak.

The streamline released from the inlet surface of the NDDCT is investigated under cross-wind condition on different cases, as shown in fig. 5. Consistent to previous studies [20, 26], two strong symmetric upward mainstream vortices arise from the inlet as the result of uneven air intake on baseline case (only one of them is exhibited in this paper). By adoption

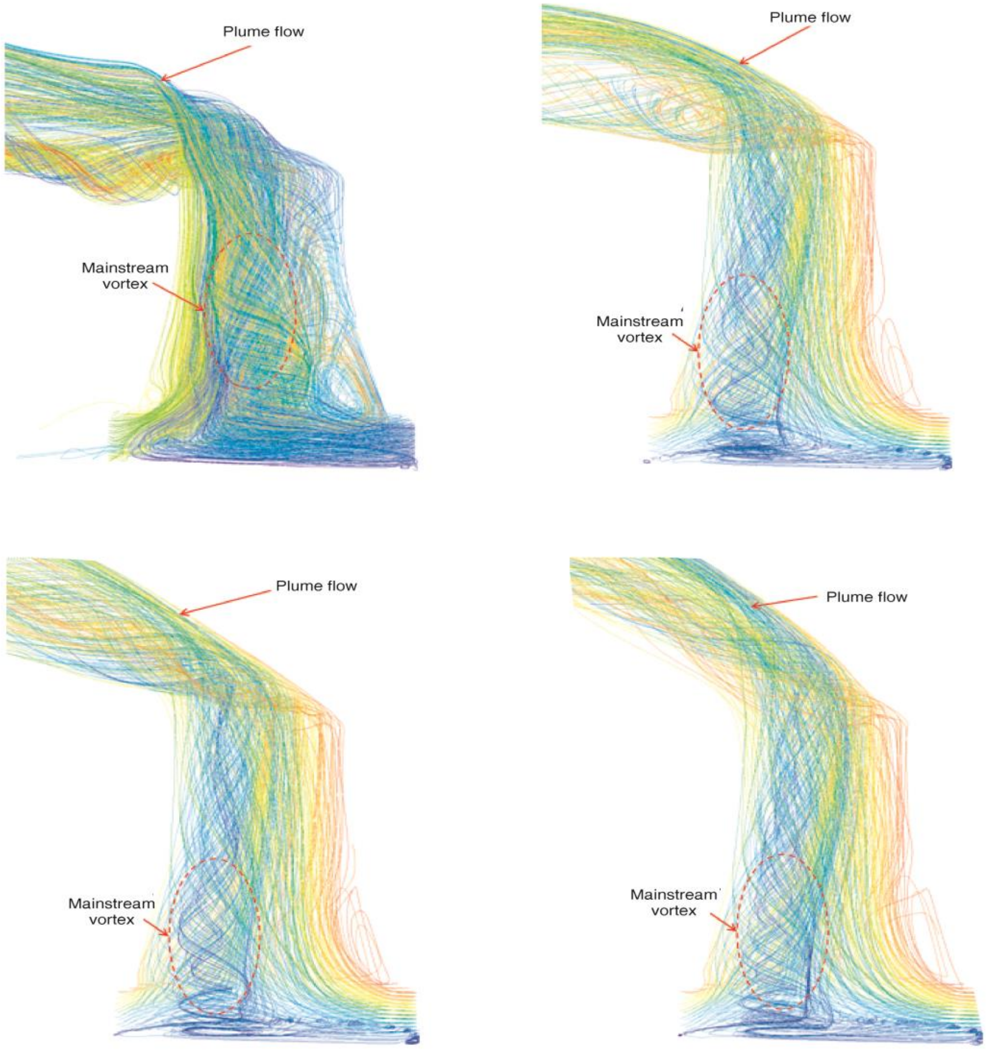

Figure 5. Streamline of the NDDCT at 10 m/s; (a) baseline case, (b) one-duct case, (c) two-duct case, (d) three-duct case (*for colour image see journal web site*)

of wind collecting ducts, the intensity of upward mainstream vortex is greatly reduced, the center of vortex is moved to the rear side, and the deflection of the plume flow is reduced, as shown in figs. 5(b) and 5(c). As the wind collecting duct increases from one to three, the deflection of the plume flow decreases gradually.

Given the same cross-wind, the deflection of plume flow is mainly influenced by the swirling intensity of the upward mainstream. The higher the swirling intensity of the mainstream vortex is, the less the stiffness of the upward flow is. Since the stiffness is inversely proportional to the ease of being deflected, the decrement of plume deflection means a reduction of upward mainstream swirling intensity.

The quantification of flow field variations

As investigated previously [12], a FLF is introduced to quantify the cross-wind effect on local flow field variation as eq. (1) shows, where P^* denotes a total pressure including the dynamic pressure and altitude pressure, Ω_f and U_f represent the flow resistance and potential flow as defined by eqs. (2) and (3), respectively. An inverse proportional relationship between the flow resistance and mass-flow rate is obtained as illustrated in eq. (4). The subscripts –r and –t denote the reference and the total conditions respectively:

$$\mathrm{FLF} = \frac{\Delta\Omega_\mathrm{f}}{\Omega_{\mathrm{f-r-t}}} = \mathrm{FLF}_0 + \frac{q_{\mathrm{m-r-t}}}{q_\mathrm{m}}\sqrt{\frac{\Delta P^*}{\Delta P^*_{r-t}}}\left[\frac{\mathrm{d}\left(\Delta P^*\right)}{2\Delta P^*} - \frac{\mathrm{d}\left(q_\mathrm{m}\right)}{q_\mathrm{m}}\right] \tag{1}$$

$$\Omega_\mathrm{f} = \frac{\sqrt{\xi}}{S} \tag{2}$$

$$U_\mathrm{f} = \sqrt{2\rho\Delta P^*} \tag{3}$$

$$U_\mathrm{f} = q_\mathrm{m}\Omega_\mathrm{f} \tag{4}$$

The FLF of each flow section on different wind collecting cases are calculated as shown in fig. 6. Compared to the baseline case, as shown in figs. 6(a) and 6(b), the adoption of bottom wind collecting duct reduces most of the FLF greatly in almost all investigated cross-wind range. However, the positive effective of FLF after NDDCT outlet is also reduced (minus value increased). When the middle wind collecting duct is added, as shown in fig. 6(c), all FLF including FLF-outlet are further reduced at cross-wind above 10 m/s. The FLF-total is even reduced to a minus value, indicating an overall ventilation enhancement compared to cross-wind free condition. However, as the further adoption of upper wind collecting duct, most of the FLF are increased as shown in fig. 6(d), resulting in overall performance degradation as the increased FLF-total indicates. The outlet of the upper wind collecting duct may play a barricade role to the rear side confluence, hence affecting the related FLF.

The ventilation enhancement and experimental verification

The ventilation tests of the experimental model introduced in fig. 2 are conducted in wind tunnel test rig. According to the momentum similarity, the cross-wind at a range of 0~20 m/s is modeled to a tunnel wind at a range of 0~2.4 m/s. The ventilation rates of the dif-

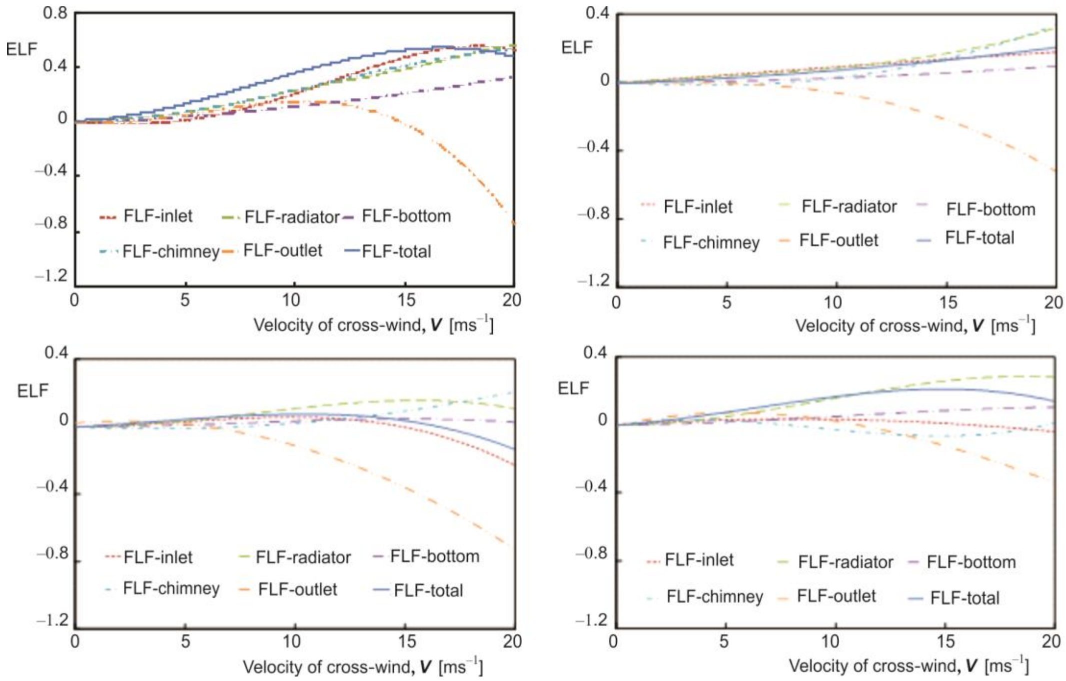

Figure 6. The FLF on different wind collecting cases; (a) baseline case, (b) one-duct case, (c) two-duct case, (d) three-duct case

ferent experimental models are measured. And the model ventilation rate of ~0.09 kg/s is correspondent to ~37500 kg/s. For the sake of easy comparison, the experimental and numerical results are transferred in a dimensionless way. As shown in fig. 7, the trends of numerical results are similar to those of the experimental results. The numerical results on baseline case are well confirmed by the experimental results. The trends of numerical results on wind collecting cases are consistent to those of the experimental results, although the calculated values are lower than those of the measured ones, with an average error of ~12%. Considering the experimental system error of ~10% on measuring such low speed velocity (~0.8 m/s), the error is well accepted.

Along with the effects of adopting wind collecting ducts discussed previously, the ventilation rate of each case changes accordingly. It can be seen that by adoption of wind collecting ducts, the overall ventilation rate increases greatly in all cross-wind range, resulting an approximately wind free performance. On comparison of the different wind collecting schemes, their overall performances differ not too much. The two-duct scheme surpasses the other two in high cross-wind, achieving a ~63% ventilation rate enhancement compared to the baseline case on high cross-wind condition (~20 m/s). On consideration of the cost of construction in industrial implementation, the one-duct scheme is also regarded as a good choice, which could achieve a ventilation enhancement of 43% compared to the baseline case in high cross-wind.

As introduced in previous publication, initial temperature difference (ITD) can be calculated from ventilation variation [3]. Based on previous the ventilation enhancement, the ITD could be reduced to 28.9 ºC at two duct model case in 20 m/s, compared to the baseline case of 39 ºC, the temperature of circulating water could be reduced by10.1 ºC. According to the International Formulation 1997 of the International Association for the Properties of Water and Steam, this reduction of circulating water temperature would reduce the back pressure of the units by 4~5 kPa, which will further lead to a reduction of the unit net coal consumption rate of 7~10 g/kWh by referring to the steam turbine thermal property of the investigated unit. By assuming the annual operation time as 5000 hours in the studied 660 MW unit, the annual coal consumption could be saved by 23500~33500 tons on condition of adopting the suggested proposal.

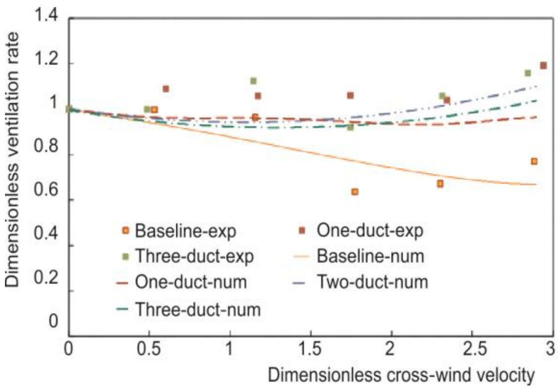

Figure 7. The ventilation rates on different wind collecting cases

Conclusions

The ventilation rate of a NDDCT is affected greatly by the cross-wind. According to the basic affecting mechanism, a wind collecting approach is designed to break up the lateral flow acceleration, and to transform the flow kinetic energy as an enhancement to the overall ventilation rate of the NDDCT. By adoption of CFD model, a quantitatively analyzing factor, FLF, and hot state experimental system, the wind collecting schemes are thoroughly investigated.

The wind collecting approach introduced in this paper is found to be effective in improving the pressure distribution around the radiator bundle, reinforcing the lateral air intake, reducing the intensity of mainstream vortices, and reducing the flow resistance of each flow section (FLF's), so as to enhance the ventilation rate of a NDDCT. Two-duct wind collecting scheme outstands the other ones considering the performance enhancement of a NDDCT. It may assure a NDDCT works in an approximately wind free manner in all investigated cross-wind range. Meanwhile, a ~63% ventilation rate enhancement is achieved on high cross-wind condition, *i. e.* the overall coal consumption of a 660 MW coal-fired unit could be reduced by 23500~33500 tons annually. The numerical results are well confirmed by modelling experimental results.

Acknowledgement

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Nomenclature

d – difference, [–]
P – pressure, [kPa]
q – mass-flow rate, [kgs^{-1}]
S – cross-section, [m^2]
U – potential flow, [kgs^{-1}m^{-2}]
V – average velocity, [ms^{-1}]

Greek letters

Δ – differential error, [–]
ρ – air density, [kgm^{-1}]
ξ – local resistance coefficient, [–]
Ω – flow resistance, [m^{-2}]

Superscripts

* – total value

Subscripts

0 – baseline value
bottom – area inside the radiator
chimney – area right inside the tower chamber
f – flow
inlet – area prior to the inlet of the NDDCT
m – mass
outlet – area above the outlet of the NDDCT
r – reference value
radiator– area between the radiator fins
t – total value
total – overall streamline field

Acronym

FLF – flow loss factor
ITD – initial temperature difference
NDDCT – Natural draft dry cooling tower

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