Wind-Induced Interference Effect Between Newly-Built Cooling Tower and Existing Cooling Tower

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Abstract: Disturbance effect is one of the important factors for wind damage to large cooling towers. Existing studies on the wind-induced interference of cooling tower groups are aimed at the same size and the lack of wind-induced interference effects between cooling towers of different sizes. With the background of the additional cooling tower project at Shandong Luxi Power Plant in China, the rigid body pressure wind tunnel test is carried out to obtain 194 conditions for the three combinations of the existing four-tower combination (small size), the new two-tower combination (large size) and the six-tower combination surface wind pressure distribution. Numerical simulation of the surrounding flow field of the cooling tower group with the most unfavorable interference condition of the six-tower combination is conducted using the computational fluid dynamics (CFD) method. Based on this, the characteristics of the average and pulsating wind pressure distribution of the cooling tower surface under the six-tower combination are mainly studied, and the load interference coefficients of the large-sized cooling tower and the small-sized cooling tower under the three tower group combinations are compared. The velocity flow field and vorticity changes around the cooling tower group at unfavorable wind angles are analyzed, and the wind-induced interference mechanism between cooling tower groups of different sizes is mainly refined. Research shows that the interference effect between such cooling tower groups of different sizes is much larger than that of cooling tower groups of the same size, which is specifically manifested as the enhancement effect of small-sized cooling towers and the shielding effect of large-sized cooling towers. The interference coefficient of large-sized cooling tower groups increases by 28%, and the interference coefficient of small-sized cooling tower groups decreases by 6.4%. The airflow acceleration caused by the pinch effect between small-sized cooling tower groups has an adverse effect on large-sized cooling towers and can significantly increase the magnitude of local wind load. The shielding effect of large-sized cooling towers can reduce the overall wind load of small-sized cooling towers. The research conclusions can provide the basis of wind load value design for wind resistance design of such large cooling tower addition projects.

Key words: cooling tower; wind tunnel test; wind-induced interference effect; mechanism of action; numerical simulation

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0 Introduction

With the implementation of China's policy of "developing large units and suppressing small ones" in the power industry, more and more large cooling towers with high energy supplies are constructed surrounding the original cooling towers in power plants. However, the space between newly built cooling towers and the existing towers is very small due to the limited land. Therefore, the interference effect among different cooling tower combinations cannot be ignored. Many wind damage events of cooling tower in history[1-2] have demonstrated that interference effect is one of important causes. Many scholars[3-8] have carried out systematic studies on in-

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terference effects of large cooling towers under different combination modes. The design codes of cooling towers[9-12] in various countries also stipulate corresponding tower group interference coefficient models. However, the existing studies focus on cooling tower of the same size, but lack the studies on interference effect of cooling tower groups of different sizes, available engineering experiences and design data for reference.

With respect to studies on wind-induced interference effect of cooling tower group of the same size, Ref.[13] studied the interference effect of surrounding buildings on a combination of two cooling towers through a series of pressure test. Ref.[3] tested wind-induced displacement under interferences of two cooling towers based on a complete aeroelasticity vibration test and studied the wind-induced interference effect. Ref.[4] studied the interference effect of three towers by calculating interference factors of shearing force factor at downwind and acrosswind bottom positions. Based on a large cooling tower under construction, Ref.[5] analyzed the interference effect of a typical combination of four cooling towers and the mechanism of action based on a rigid body pressure wind tunnel test. Based on wind tunnel test and finite element numerical calculation, Ref.[6] explored the interference effect of a 6-cooling tower combination from the structural reinforcement layer and proposed a principle for comparing interference effects with references to reinforcement ratio enveloping. Ref.[7] carried out a rigid body model pressure test to a 8-cooling tower group in a power plant and proposed the most unfavorable angle of wind direction and the values of interference factor based on the overall resistance coefficient. Ref.[8] studied the interference effect of cooling tower groups to the overall loads and wind-induced responses through a rigid body pressure wind tunnel test and the calculation of structural dynamics. Ref.[14] studied the wind-induced interference characteristics and the mechanism of cooling tower group with considerations to terrain effect (mountainous environment) through a wind tunnel test method. The existing research results hardly consider the wind-induced interference effect among cooling towers of different sizes.

On this basis, a comparative study on surface average and pulsation wind pressure distribution characteristics of the existing four-cooling tower combination (small size), new two-cooling tower combination (large size) and six-cooling tower combination in a power plant was carried out based on the rigid body pressure wind tunnel test. In addition, resistance coefficient and maximum negative pressure were used as the quantitative indexes of interference factors of small-sized cooling towers and large-sized cooling towers to analyze interference effect of large and small towers. Subsequently, a numerical simulation on surrounding flow field of the 6-cooling tower combination under the most unfavorable interference conditions was implemented through computational fluid dynamics (CFD). Meanwhile, surrounding speed and vorticity changes under the most unfavorable conditions were analyzed, and the wind-induced interference mechanism among cooling towers of different sizes was extracted.

1 Wind Tunnel Test

1.1 Introduction to engineering

This project builts new large-sized cooling towers surround the existing small-sized cooling towers. Four small-sized cooling towers distribute from the south to north in series on the east of the engineering site. Two new cooling towers (large size) are on the west side in parallel. The central distance between large and small towers is 158 m. Structural sizes of large-sized and small-sized cooling towers are shown in Tables 1,2.

Table 1 Main geometry scale of large-sized cooling tower

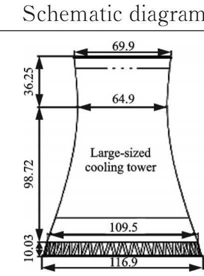
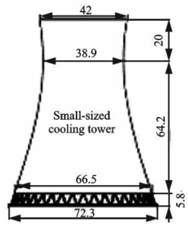
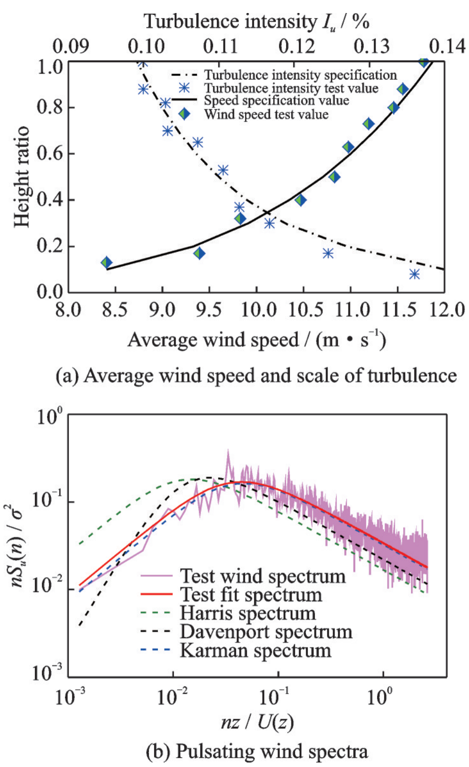
Structural parameter	Value/m	Schematic diagram
Tower elevation	145	
Tower diameter	69.9	
Throat elevation	108.75	
Throat diameter	64.9	
Inlet elevation	10.03	
Inlet diameter	109.5	
Bottom diameter	116.9	

Table 2 Main geometry scale of small-sized cooling tower

Structural parameter	Value/m	Schematic diagram
Tower elevation	90	
Tower diameter	42	
Throat elevation	70	
Throat diameter	36.9	
Inlet elevation	5.8	
Inlet diameter	66.5	
Bottom diameter	185	

1.2 Wind field simulation

The wind tunnel in the test is a closed reverse-flow rectangular sectional wind tunnel. The main test section was 4.4 m in width and 3 m in height. Wind speed can be adjusted continuously and the highest stable wind speed can reach 30 m/s. The testing wind field is simulated according to B type landform in the Load Norms for Architectural Structures. The triangle wedge and surface roughness elements are put in front end of the incoming flow to simulate the corresponding wind field. Simulation results are shown in Fig.1. It can be seen from Fig.1 that there is good simulation effect of wind field and it meets the test requirements. Fig.2 shows the pulsating wind pressure



(a) Average wind speed and scale of turbulence

(b) Pulsating wind spectra

Fig.1 Simulation of wind characteristics in atmospheric boundary layer wind tunnel

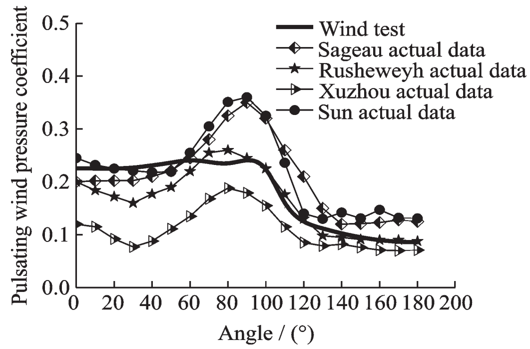


Fig. 2 Comparison of wind tunnel test results and actual measurements of pulsating wind pressure coefficient

curve of a single tower and the related measured curves obtained in a wind tunnel test. By comparison, the distribution law of pulsating wind pressure along the annulus in this paper is consistent with the measured curve at home and abroad, which verifies the credibility of pulsating wind load on the cooling tower surface of the wind tunnel test in this paper.

1.3 Simulation of Reynolds number effect

The scale of wind tunnel test model is 1∶250. Acrylic materials can assure enough rigidity and strength of the model. Twelve layers of external pressure testing points are set along meridian of the tower body and each layer has 36 testing points uniformly along the clockwise direction. Therefore, a total of 432 testing points are set on the tower body. Refs.[15-16] demonstrated that Reynolds number effect of the model test was compensated by increasing the surface roughness. In the wind tunnel test, the Reynolds number effect was corrected by adjusting wind speed (8—12 m/s) and setting 36 thick rough paper tapes (5 mm (in width) * 0.15 mm (in thickness)) at equal distances along the meridian on the external surface of cooling tower.

With respect to Reynolds effect simulation of large-sized and small-sized cooling towers, six classes of roughness working conditions are tested: surface smoothness; 1 layer of roughness paper tapes are pasted uniformly; 1/2 layers of roughness paper tapes are pasted at an interval; 2 layers of roughness paper tapes are pasted uniformly; 2/3 layers of roughness paper tapes are pasted uniformly; 3 layers of roughness paper tapes are pasted uniformly. Distribution curves of pressure coefficients at the throat height of large-sized and small-sized cooling towers under different roughness values are shown in Fig. 3, in which wind speed is fixed at 10 m/s. The distribution curves are compared with the wind pressure curves suggested by norms[9-10]. It can be seen from Fig. 3 that 3 layers of rough paper tapes are pasted uniformly on model surface at 10 m/s and it can simulate Reynolds number effects of large-sized and small-sized cooling towers. Simulation results are shown in Fig.4.

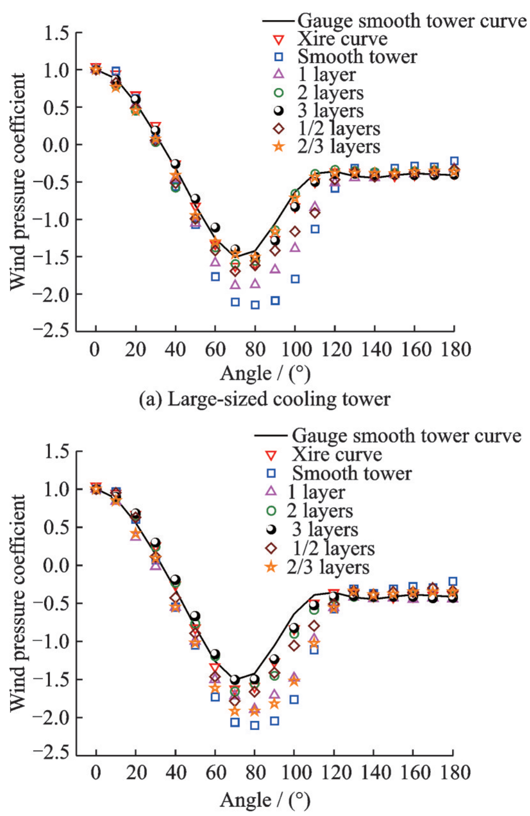


Fig.3 Wind pressure coefficients under different surface roughness

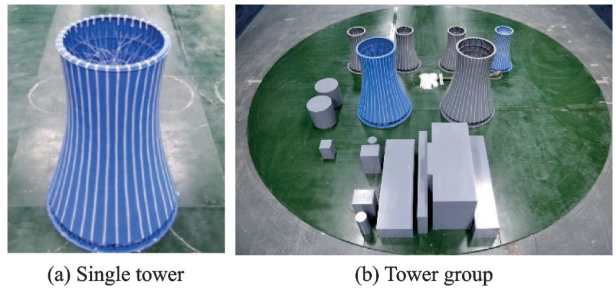


Fig.4 Reynolds number simulation measures

1.4 Working conditions in the test

The midperpendicular direction of Tower A and Tower B is defined 0° of wind angle and one working condition is set counterclockwise every 22.5°, thus forming a total of 16 working conditions. With references to practical engineering, surrounding interference buildings taller than 30 m are set to reflect interference effect of cooling tower accurately. For better studying the mutual wind-induced interference effect among cooling towers of different sizes, the direction of unfavorable incoming flow is determined. Three combinations are set as shown in Table 3 and Fig.5.

Table 3 Tower group combination form

Combination number	Four small cooling towers	Two large cooling towers	Disturbing building
Combination 1	Yes	Yes	Yes
Combination 2	Yes	No	Yes
Combination 3	No	Yes	Yes

2 CFD Numerical Simulation

2.1 Computational domain and meshing

To assure full development of wake flow on

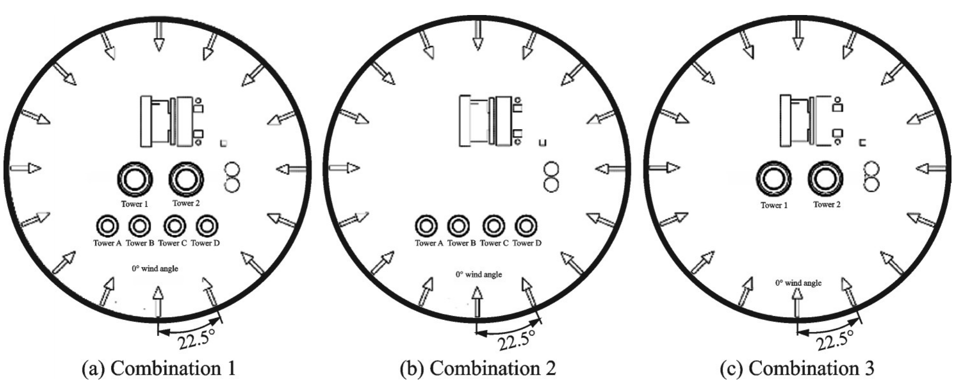


Fig.5 Schematic diagrams of tower group combination

large-sized cooling towers, the computational domain is set as 6 000 m (in clockwise) ×2 500 m (cross-wind) ×600 m (vertical direction). The center of model is 2 500 m away from the entrance of computational domain. With considerations to calculation efficiency and accuracy, the hybrid grid discrete form is adopted as the meshing program. The whole computational domain is divided into local encrypted region and peripheral region. The local encrypted region includes the cooling tower combination and surrounding interference buildings, and it adopts the non-structured meshing scheme. Peripheral region has regular shape and it adopts the high-quality structured meshing scheme. The minimum grid size of core region is 0.2 m and the total number of grids is about 26.80 million. The meshing schemes of computational domain and model are shown in Fig. 6 (limited by article space, only the working condition under 292.5° of wind angle is shown in Fig.6).

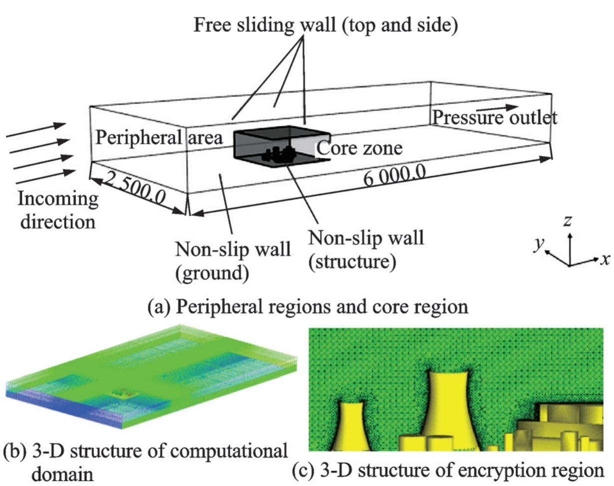


Fig.6 Sketch maps of computational field and model meshing

2.2 Boundary conditions and setting of parameters

The velocity inlet and pressure boundary outlet are used in the calculation domain. According to B type landform, the index wind profile and turbulence intensity profile of atmospheric boundary layer are set. The surface roughness index is 0.15 and the basic wind speed at the reference height of 10 m is 25.3 m/s. The nominal turbulence at 10 m height is determined as 0.14. The abovementioned pulsation wind field is defined by UDF document. The ground and cooling tower surface adopts non-slippage walls, while top and sides adopt symmetric boundary conditions which are equivalent to free slippage walls.

The numerical calculation uses a 3-D dual-accuracy separated solver and the air wind field chooses the incompressible flow field. The turbulence model uses the shear stress transfer(SST) model in Reynolds average method. Pressure speed coupling equation group is solved by SIMPLEC format and the convective term is solved in second-order format. During the calculation, grid tilt correction is set to increase calculation accuracy of hybrid grids. The calculation residual error of governance equation is set as 1×10^{-6}.

2.3 Numerical simulation of single tower and validity verification

Considering the symmetry of single cooling tower, only the working condition with 0° wind angle is tested. The average wind pressure coefficient curve on the throat section of single tower and standards[9-10] as well as the measurement curves are shown in Fig. 7. According to analysis, the average wind pressure distribution curve at throat section of single tower is consistent with the Sigercurve[17] in view of angles and standards of negative pressure extreme points and separation point. The numerical values of the wind pressure coefficients on the windward and leeward regions agree well. The numerical value of negative pressure on the lateral wind area is

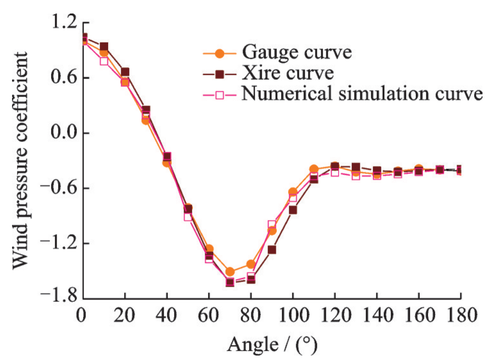


Fig.7 Contrast diagram among numerical simulation standard and actual measurement on throat section of single tower

between the standard curve and Siger curve.

3 Interference Analysis of Six-Cooling Tower Combination

The interference factor (F) is selected as the quantitative index of interference effect to evaluate the interference effect of surrounding buildings on disturbed buildings. It can be expressed as

$$F = \frac{P_g}{P_s} \tag{1}$$

where P_g is the interference parameter of cooling tower combination and P_s the parameter of single tower.

Currently, many domestic researches[18-20] would list the mean interference coefficient, root variance interference coefficient and extreme interference coefficient when calculating the interference coefficient, that is, the mean value, root variance or extreme value of the parameters in Eq.(1). With considerations to height of small-sized cooling towers, the large-sized cooling tower is divided into the direct interference section and indirect interference section along the height. Small-sized cooling towers are all in the interference range of large-sized cooling towers. Therefore, large-sized cooling towers focus on interference effects of local wind pressure, while small-sized cooling towers mainly involve interference effect of the overall wind pressure.

3.1 Interference effect of large-sized cooling towers on small-sized cooling towers

Variations of mean F of four small-sized cooling towers in the Combination 1 and Combination 2 based on the resistance coefficient with wind angle are shown in Fig.8. Obviously, the mean F of small-sized cooling towers changes significantly, indicating that large-sized cooling towers influence incoming flow and wind pressure distribution model of small-sized cooling towers significantly. In the Combination 1, the maximum mean F of Towers A, B, C and D are 1.73, 1.53, 151 and 1.72, respectively. The corresponding most unfavorable wind angles are 225°, 45°, 247.5° and 112.5°, respectively. In the Combination 2, the maximum mean F of Towers A, B, C and D are 1.85, 1.46, 1.63 and 1.76, respectively. The corresponding most unfavorable wind angles are 225°, 270°, 270° and 270°, respec-

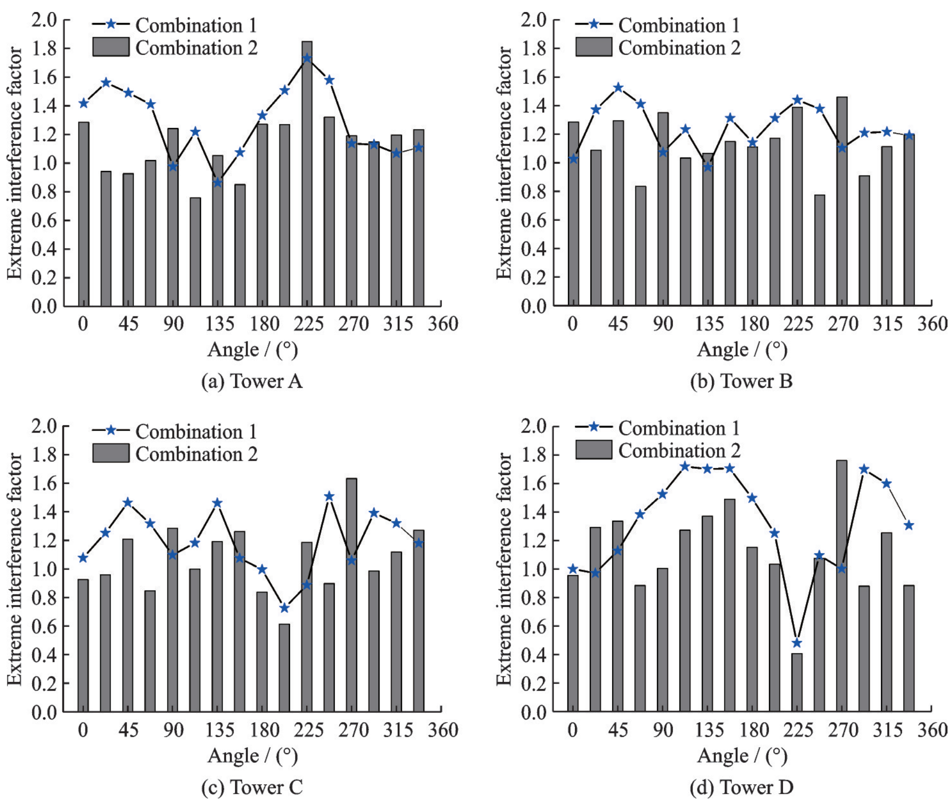
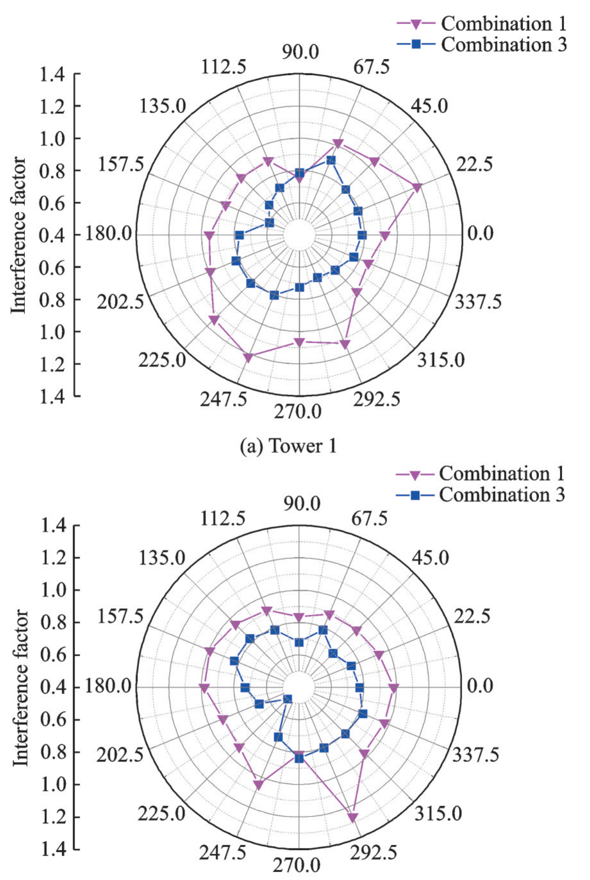


Fig.8 Interference factor distributions of small-sized cooling towers

tively. In Combination 1, the maximum mean F is 1.73, which is caused by Tower A when the wind angle of incoming flow is 225°. It is 6.4% lower than the maximum mean F in the Combination 2 under the most unfavorable working condition.

3.2 Interference effect of small-sized tower on large-sized tower

Numerical values of interference factor of two large-sized cooling towers based on the maximum negative pressure in the Combination 1 and Combination 3 as well as the corresponding wind angle are shown in Fig.9. It can be seen clearly that: due to the existence of small-sized cooling towers, the numerical value of interference factor of large-sized cooling tower is generally increased. In Combination 3, the corresponding height of maximum negative pressures of Tower 1 and Tower 2 under the most unfavorable wind angle is at the throat position of the tower. In Combination 1, the corresponding height of maximum negative pressures of two large-sized towers under the most unfavorable wind angle is relatively close to the height of small-sized towers. In Combination 1, the maximum interference factors of Tower 1 and Tower 2 are 1.22 and 1.26, and the corresponding wind angles are 247.5° and 292.5°, respectively. In Combination 3, the maximum interference factors of Tower 1 and Tower 2 are 0.9 and 0.84, and the corresponding wind angles are 67.5° and 270°, respectively. In Combination 3, the maximum interference factor under the most unfavorable wind angle of 67.5° is 0.9. In Combination 1, the maximum interference factor under the most unfavorable wind angle of 292.5° is 1.26, which is 28% higher than that in Combination 3.



(a) Tower 1

(b) Tower 2

Fig.9 Interference factor distributions of large-sized cooling towers

3.3 Mean and pulse wind pressure distribution features

The interference effect of tower combination is manifested as changes of wind pressure distribution on tower surface. According to distribution law of numerical values of interference factor in Figs.8, 9, wind-induced interference effect in the cooling tower combination with different sizes is very significant. To analyze relevant causes and interpret corresponding mechanism, the mean pressure coefficient and root variance distribution curve of pressure coefficient of throat sections of different cooling towers in the six-cooling tower combination under the most unfavorable wind angle are shown in Fig. 10. The pressure contours at typical height sections of different cooling towers are shown in Fig. 11. According to analysis, it concludes that: given a specific wind angle, the shielding effect of large-sized cooling towers to small-sized ones intensifies the mutual interference effect between the front and rear towers. Small-sized cooling tower in the rear position is not influenced by free incoming flow directly and the tower body is almost flooded in the wake flow of the front large-sized cooling towers. Wind pressure distribution is also influenced directly. Airflow will be accelerated in the narrow channel which is formed by cooling tower combination, resulting in the higher absolute value of negative pressure on the acceleration side of airflow than that on the other side. Therefore, the mean wind pressure distribution

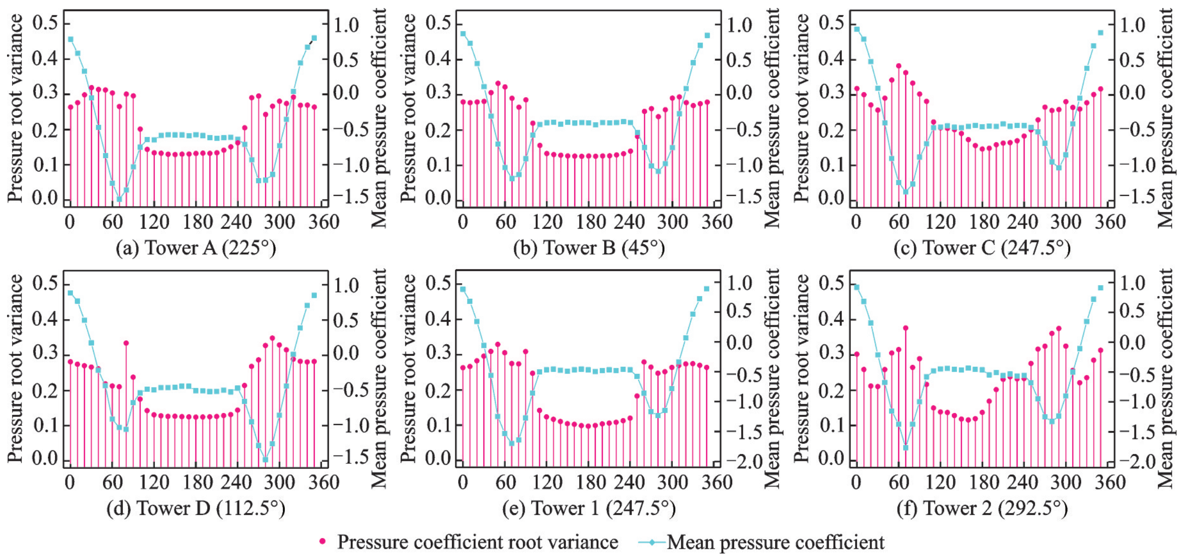


Fig.10 3-D contours of stress coefficients of different cooling towers under the most unfavorable wind angles

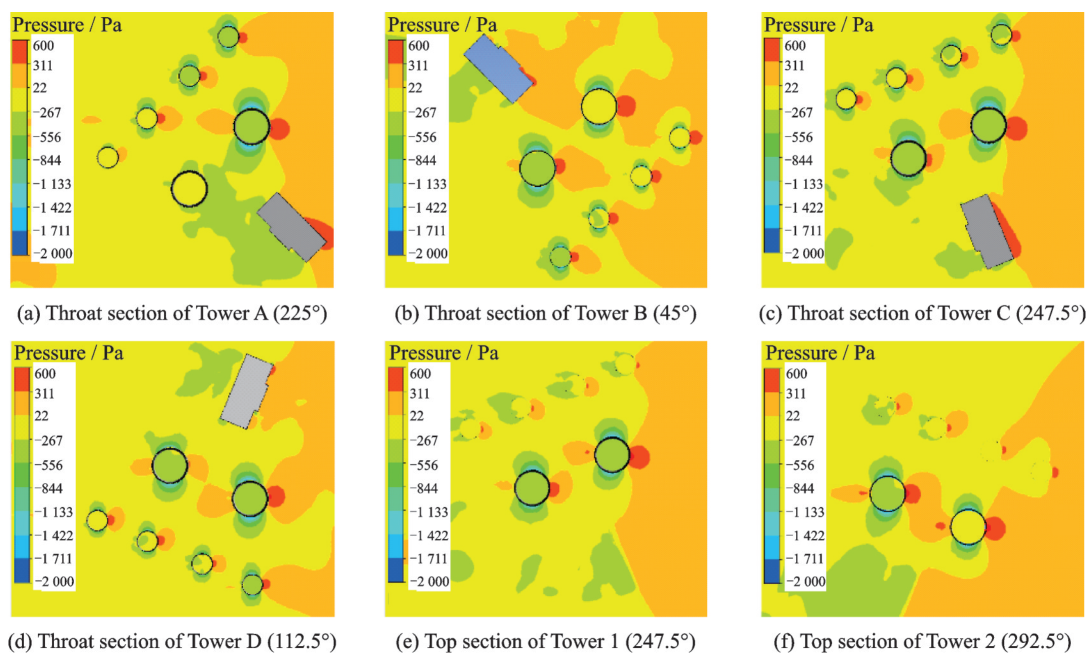


Fig.11 Typical sectional pressure contours of different cooling towers under the most unfavorable wind angles

curve is not symmetric. The vortex in the narrow channel between small-sized cooling towers in the front will act on the rear large-sized cooling towers after it falls, thus increasing the pulse wind pressure on the side of large-sized cooling towers dramatically. Therefore, the pulse wind pressure curve is not symmetric.

3.4 Interference mechanism

The typical sectional velocity flow field and typical section vortexes of different cooling towers under the most unfavorable wind angles are shown in Fig.12 and Fig.13. Obviously, we have:

(1) Under the most unfavorable working conditions, interference factor of small-sized cooling towers based on resistance coefficient can reach 1.73 up to the most, which is caused by Tower A when the wind angle is 225°. This can be analyzed as follows. Since the shielding effect of downwind and leeward surfaces of Tower A by upstream interference objects is weaker than other three small-sized cooling towers, the incoming flow is separated on the windward surface of cooling towers and flows around the external wall of tower body to two sides at an accelerating speed, further separating on leeward surface

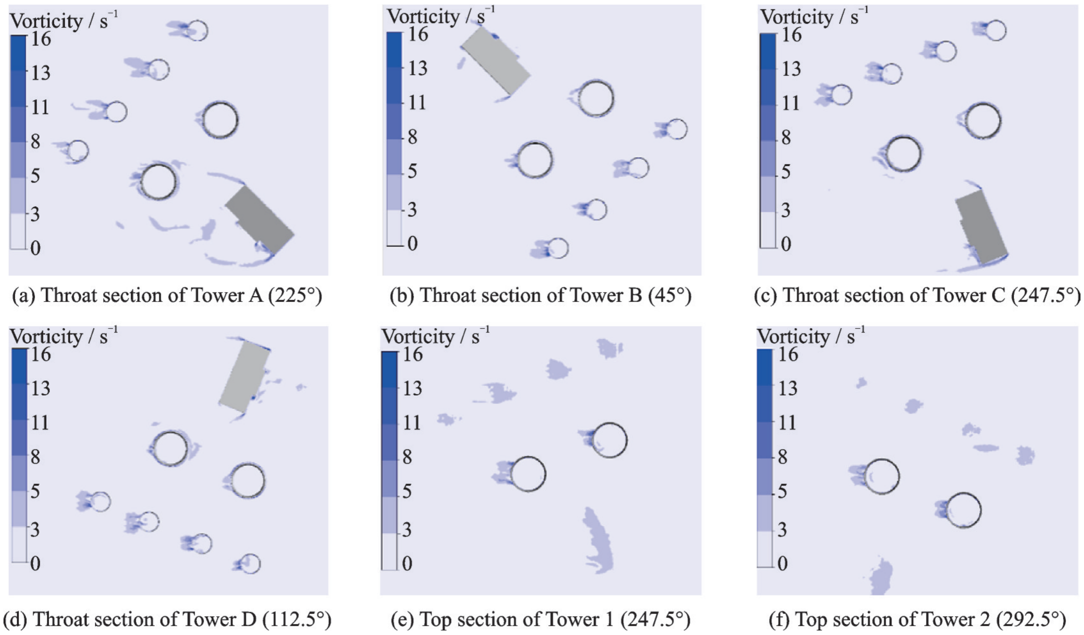


Fig.12 Typical vertex maps of different cooling towers under the most unfavorable wind directions

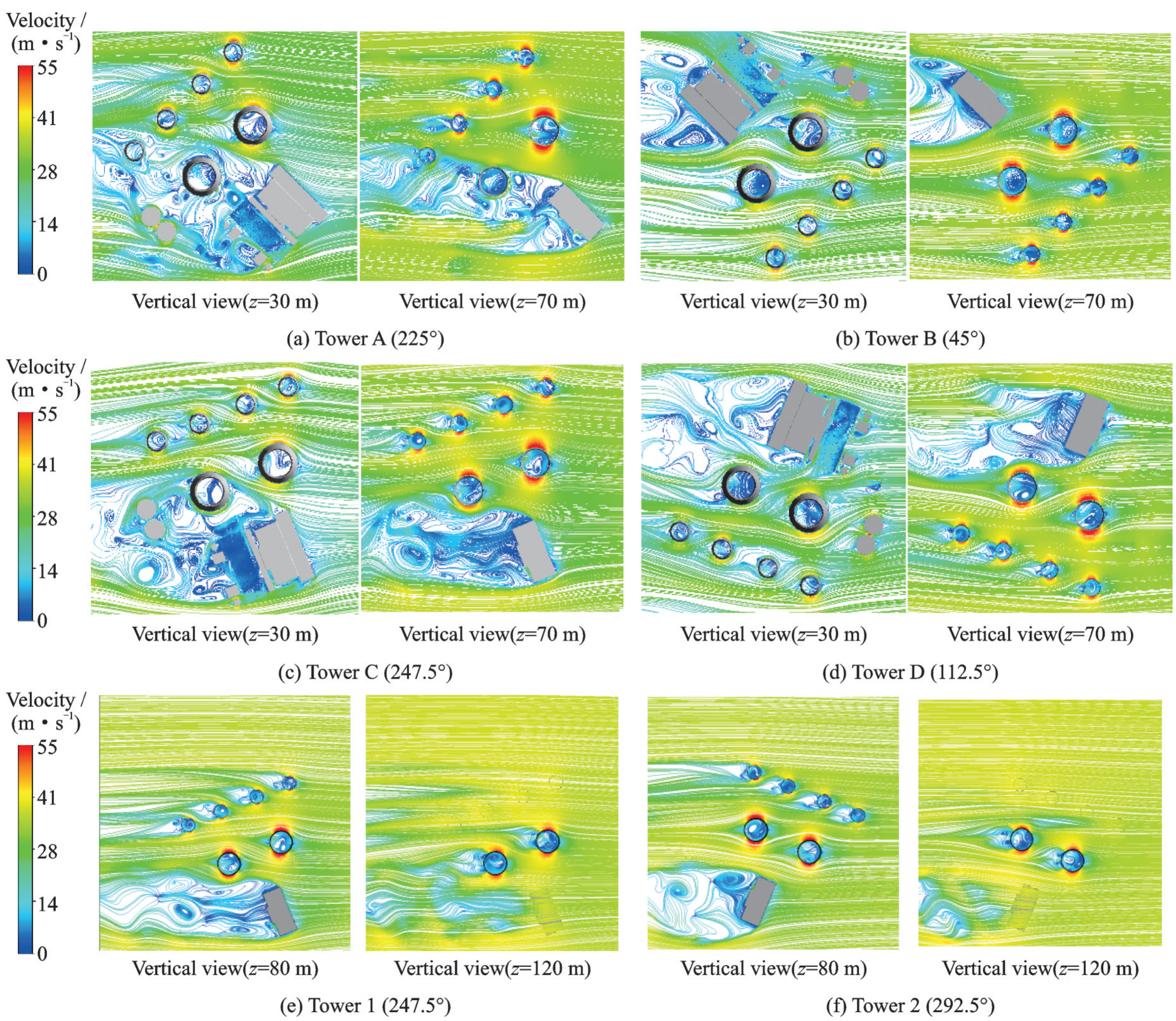


Fig.13 Velocity flow fields of the most unfavorable working conditions

and forming into large vortexes to fall. The high positive pressure on windward region and the high negative pressure on windward region act on the resistance coefficient together. On this basis, the shielding effect of large-sized cooling towers on small-sized ones can decrease resistance coefficient of small-sized cooling towers appropriately, thus weakening the interference effect of small-sized cooling tower combination.

(2) Under the most unfavorable working condition, the maximum interference factor of large-sized cooling tower based on maximum negative pressure is 1.26, which is caused by Tower 2 when the wind angle is 292.5°. This is because the narrow entrance formed by top regions of Towers A and B under this wind angle changes the incoming turbulence of cooling tower. Due to the "narrow channel effect" between Tower A and Tower B, the incoming wind is accelerated in the channel, thus increasing vortex strength in flow field surrounding Tower 2. The high-strength vortexes sweep the cross-wind region along the windward surface of Tower 2 and fall continuously. Finally, the maximum negative pressure of tower body on the side close to the front cooling tower is increased significantly.

4 Conclusions

Newly built cooling towers in a power plant are used as the engineering background in this study. Distribution laws of interference factors of cooling tower groups of different sizes are analyzed based on a wind tunnel test and CFD method. Wind pressure distribution on cooling tower surface is analyzed. Finally, the wind-induced interference mechanism among cooling towers of different sizes in the same combination is disclosed. Some major conclusions could be drawn as follows.

Compared with cooling tower combination of the same size, cooling tower combination of different sizes has stronger interference effect. The channel effect between small-sized cooling towers increases the interference factor of large-sized ones based on the maximum negative pressure by 28%. The wind-induced interference effect is enhanced significantly and cannot be ignored. Due to shielding effect of large-sized cooling towers, the interference factor of downstream small-sized ones based on resistance coefficient is decreased by 6.4%. Therefore, designers shall pay attentions to influences of the existing cooling towers on wind loads of surrounding newly built cooling towers in addition to influences of large-sized cooling towers on the wind loads of the existing small-sized ones in practical engineering projects.

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Author contributions Mr. **KE Shitang**, Ms. **ZHU Rongkuan** and Ms. **DU Lin** conducted wind tunnel tests on three tower group combinations at Shijiazhuang Railway University. Ms. **ZHU Rongkuan** and Mr. **YANG Jie** organized the wind tunnel test data through post-processing and mathematical statistics. Ms. **DU Lin** and Mr. **YANG Jie** numerically simulated the surrounding wind field. Mr. **KE Shitang**, Mr. **GE Yaojun** and Ms. **DU Lin** used the data to analyze the interference effect between the new cooling tower and the existing cooling tower. Finally, Ms. **DU Lin** wrote the manuscript, and all authors commented on the manuscript draft and approved the submission.

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新建冷却塔与既有冷却塔间风致干扰响应

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摘要：干扰效应是大型冷却塔风毁的重要因素之一，现有冷却塔群风致干扰研究均针对同一尺寸，缺乏不同尺寸冷却塔之间风致干扰效应研究。以中国山东鲁西电厂增建冷却塔工程为背景，针对既有四塔组合(小尺寸)、新建二塔组合(大尺寸)和六塔组合3种组合，采用刚体测压风洞试验获得194个工况下的表面风压分布；再基于计算流体动力学方法对六塔组合最不利干扰工况冷却塔群的周边流场进行数值模拟。在此基础上，重点研究了六塔组合下冷却塔表面平均和脉动风压分布特性，对比研究了3种塔群组合下大尺寸冷却塔与小尺寸冷却塔的荷载干扰系数；同步分析了最不利风向角下冷却塔群周边速度流场和涡量变化，着重提炼出不同尺寸冷却塔群之间的风致干扰机理。研究表明，此类不同尺寸冷却塔群之间的干扰效应要远远大于同一尺寸的冷却塔群，具体表现为小尺寸冷却塔的增强效应和大尺寸冷却塔的遮挡效应；大尺寸冷却塔群干扰系数相比增加28%，小尺寸冷却塔群干扰系数相比降低6.4%；小尺寸冷却塔群之间的夹道效应引起的气流加速对于大尺寸冷却塔存在不利影响，能够显著增加大尺寸冷却塔的局部风荷载；而大尺寸冷却塔的遮挡效应能降低小尺寸冷却塔的整体风荷载。研究结论可为此类大型冷却塔增建工程抗风设计提供风荷载取值依据。

关键词：冷却塔；风洞试验；风致干扰效应；作用机理；数值仿真