

Influence of thermal flow field of cooling tower on recirculation ratio of a direct air-cooled system for a power plant

Zhao Wanli, Liu Peiqing

(Key Laboratory for Fluid Mechanics of Ministry Education, Beijing University of Aeronautics and Astronauts, Beijing 100083, China)

Abstract: In order to get thermal flow field of direct air-cooled system, the hot water was supplied to the model of direct air-cooled condenser (ACC). The particle image velocimetry (PIV) experiments were carried out to get thermal flow field of a ACC under different conditions in low velocity wind tunnel, at the same time, the recirculation ratio at cooling tower was measured, so the relationship between flow field characteristics and recirculation ratio of cooling tower can be discussed. From the results we can see that the flow field configuration around cooling tower has great effects on average recirculation ratio under cooling tower. The eddy formed around cooling tower is a key reason that recirculation produces. The eddy intensity relates to velocity magnitude and direction angle, and the configuration of eddy lies on the geometry size of cooling tower. So changing the flow field configuration around cooling tower reasonably can decrease recirculation ratio under cooling tower, and heat dispel effect of ACC can also be improved.

Key words: direct air-cooled condenser; thermal flow field characteristics; recirculation ratio; PIV experiment

1 Introduction

Direct air-cooled condenser (Fig. 1) is commonly used to cool steam discharged from turbine in the construction of petroleum, chemical engineer and coal-fired power plant. Direct air-cooled system has many advantages, such as water-economization, frost-proofing, etc., but many problems still need settling, such as thermal flow field around cooling tower, recirculation, wind effects, etc.; the problems are interactive, they would influence the function of units, even caused great economic loss if they can't be resolved in time. It is reported that^[1], the cooling ability of ACC of No. 1 and No. 6 unit of Matimba power station in South African is dropped gradually and even forced to shut down for the sake of protection in summer hot days when the speed of cross wind blew from turbine house to cooling tower was over 6 m/s. In 22 May, 2005, air temperature was 30 °C, when cross wind blew to turbine house, high back pressure of turbine made the direct air-cooled units of Datong No. 2 power station in China brake off out of protection for many times. Zhao Wanli investigated the problem mentioned above, and found that in hot summer days when wind blew from boiler to cooling tower^[2], a complex flow field would be formed in fore-and-aft cooling tower which would

cause the hot air discharged from air-cooled condenser return to the bottom of cooling tower. That is how "recirculation" is formed. The recirculation causes temperature of the intake of ACC to increase. If heat rejected keeps constant, temperature in outlet of ACC will increase at the same time, which causes back pressure of turbine to augment acutely, and even causes turbine to shut off. So we can get the conclusion that the change of back pressure of the units is influenced mainly by recirculation resulted from ambient wind.

Gu Zhifu carried out the wind-tunnel simulation on the direct air-cooled system for a power plant in China, using the traced gas which density was different from the surrounding air to simulate hot air flow exhausted from ACC^[3,4]. Recirculation was weighed by measuring the concentration of traced gas. Although the traced gas could act as hot exhausted air from finned tubes with the thermal buoyancy effect, the heat exchange between the hot finned tube and the cold air could not be simulated realistically; yet backpressure of the steam turbine was extremely sensitive to ambient temperature. Therefore this model of the traced gas is unreasonable on the ACC system. At the same time, they also use smoke line method to get flow field of direct air-cooled system, but using this method is uncon-

Received 1 April 2008

summed. On one side, the flow field is complex, smoke line method can't well reflect the flow field around cooling tower; on the other side, the flow field they got was a cool flow field which couldn't reflect the real flow field.

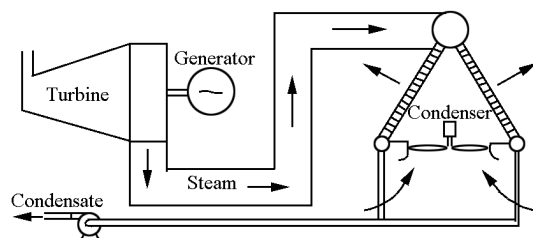


Fig. 1 Direct air-cooled condenser

In order to clearly get thermal flow field around cooling tower, and discuss the relationship among flow field around cooling tower, recirculation ratio under tower and wind effects, the hot buoyancy effects are introduced to experimental investigation in wind tunnel simulation on direct air-cooled system for a power plant. The experiment supplies the ducts with invariable temperature hot water in model of Datong No. 2 direct air-cooled system. When some certain similarity criteria meet, model tests of wind effects on direct air-cooled system are carried out to measure the temperature of measuring points, and calculate the recirculation ratio, and thermal flow field configuration around cooling tower is measured by PIV experiments, so relationship between flow field configuration around cooling tower and recirculation ratio can be discussed. The results can provide theoretical references to decrease recirculation ratio under cooling tower and improve the efficiency of heat dispersal for air cooled condenser.

2 The thermal circulation system and experimental equipment

2.1 The thermal circulation system

As shown in Fig. 2, the thermal circulative system includes five parts. They are heating system, temperature control system, model system, recycle system and drive system. Outside the model, heating the tank with

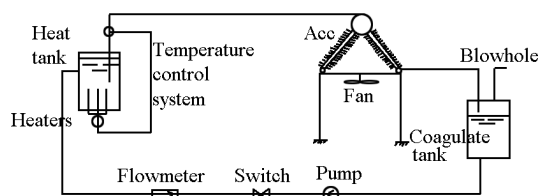


Fig. 2 Circulative sketch map of hot water in the model

three electric heaters of 9 kW, heating tank connected to steam ducts by plastic tubes, and plastic tubes were enwinding by gauze which can prevent heat in tubes from spreading to the air. In outlet of heating tank, a temperature control device is placed to keep temperature of hot water constant. (When temperature of hot water arrives at the needed temperature, the heater device may turn off automatically, and cease to heat; once temperature of hot water is below the needed temperature, the heater device begins to heat automatically. In this way, temperature in tank keeps constant.) Under the drive of pump backward position, hot water in heating tank is carried to model system, and accommodates the flux in steam ducts by switch, and then, hot water flows to the finned tube, and then, flows to coagulate tank through coagulate tubes, at last, dumps to the heating tank, so a circle is formed. On the top of coagulation tank, a blowhole connected to the air is placed, and keeps the height of blowhole higher than that of steam ducts. In this case, overflow can be avoided when the pump stops the hot water in steam ducts flows to coagulation tank. The main house and ACC are placed on the dial of wind tunnel, and heating system, recycle system and pump system are all fixed under the dial of the wind tunnel which insures devices rotate with model synchronously.

2.2 Wind tunnel and measuring temperature equipment

The experiment is carried out in FL-8 wind tunnel of Chinese Aviation Industry and Air Dynamic Research Institute. The wind tunnel is a single road, shut type tunnel, the test segment is a section of 3.5 m × 2.5 m flat eight-square, area of section is 7.685 m². The length of section is 5.5 m, and maximum velocity is 70 m/s. Scaling model is consistent with Datong No. 2 power plant direct air-cooled system, and the model scaling is 1:120, which is made up of organic glass. The boundary layer of type B is simulated in wind tunnel, and section plane exponent of time-average velocity $\alpha = 0.16$, the turbulence rate close to the ground is larger than 5%. The device of measuring temperature is a multi-channel (100 channels) temperature patrol system produced by Keithley Corporation of USA. And the sensor is thermocouple of type T. There are 92 measuring points altogether placed at inlets of fans and outlet of finned tubes. In model test, the electricity which 112 fans needed is supplied by 2 power supplies of direct current and steady voltage produced by Longwei electronic Co. Ltd. Hong Kong, the type is TPR-3030D, and voltage can change continuously.

3 Main parameters and similarity criteria in wind-tunnel simulation

3.1 Main parameters and evaluate criteria

In the practice, recirculation may be formed under the action of environment wind. In order to explain the recirculation in quantification, Zhao Wanli gives evaluation criteria of recirculation ratio^[2]:

$$R = \frac{T_{in} - T_a}{T_{out} - T_a} \quad (1)$$

The average recirculation rate is

$$\bar{R} = \frac{\sum_{i=1}^N R_i}{N} \quad (2)$$

Where, T_a is temperature of ambient air; T_{in} is average temperature of air at inlet of fans, and T_{out} is average temperature of finned tubes. So we can calculate the recirculation ratio of each measuring point by Eq.(1) through measuring the temperature of the inlet of fans and outlet of finned tubes; in different conditions, we can also get average recirculation rate by Eq.(2).

3.2 Similarity criteria and similarity condition

The problem of forcing convection and exchanging heat of ACC is a complex separated flow under the condition of environmental wind. The flow involves the interaction and interference of hot air flow and vortex separated flow, and deals with a special flow phenomenon under the action of fans' pumping, which is recirculation. The key problem is to simulate such a complex phenomenon correctly. So during the wind tunnel simulation, similarity criteria must be considered including aerodynamics, forcing convection resulted from fans, and hot buoyancy effects^[5,6].

4 Results and analyze of experiments

4.1 The influence of wind velocity on recirculation ration and flow field configuration

The environment wind has great influence on the recirculation ratio of ACC. Theoretically speaking, under windless condition, the recirculation is little. The velocity increases to a certain value, the recirculation ratio of different degrees may occur. Measuring the temperatures of the measuring points, we can find the points close to the turbine house are higher than the other points under the windless condition. That is because the stream distributed tubes used in model test locate between the turbine house and cooling tower, and the heat spreading from the stream distributed tubes is absorbed by the fans close to turbine house which makes the temperature closed to turbine house higher than others. When the environment wind blow

from the boiler house to the cooling tower (west wind), the velocity in the wind tunnel is 6, 8, 10, 12, 14 m/s, it can be found that as the velocity increasing, the average recirculation ratio under the tower is increasing as well, as shown in Fig. 3. The main reason of recirculation ratio increasing is the improved velocity makes the inertial force enhanced, and the buoyancy decreases, so the chances of the hot air coiled to bottom are increscent.

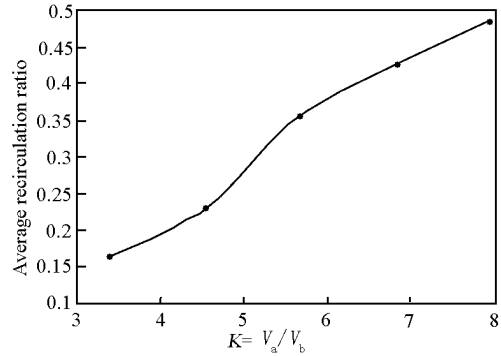


Fig. 3 The relationship between wind velocity and average recirculation ratio

In the absence of wind, cold air forced by fans passes through finned tubes, exchanges heat with finned tubes, and then, the cold air absorbs heat of the wings slice, becomes hot air to ascend. Here, the hot air raises only by hot buoyancy, and its appearance looks like plumes. However when crosswinds are present, especially when wind blows from the turbine house to cooling tower at the speed of 3 m/s or larger than 3 m/s, the plumes will be deflected, their trajectories will be "bent down", closer to intake faces, so the configuration of plumes flow will be changed. At the same time, air separated from the top of boiler house and boundary of platform far away from the turbine house forms two large eddies at the back of boiler house and backward position of the platform. On the boundary of eddy, strong entrainment and mix-up which causes more and more plumes rolled into vortex, and then, under the pump of fans, more and more plumes are drawn into the bottom of platform. The configuration and intensity of vortex is determined by magnitude and directions of wind velocity, so the quality of recirculation under cooling tower is greatly influenced by wind velocity. As the wind velocity increases, vortex intensity becomes strong, then, the action of entrainment and mix-up becomes strong, and the recirculation under cooling tower is excessive.

When the cross wind is present, the hot air (plumes) ascends under the function of buoyancy and inertial force, configuration of plumes will be influ-

enced by incoming wind velocity and directions. Analyzing the force acting on hot air during the plumes ascending process, as showed in Fig. 4, the hot air was functioned by buoyancy V_b upward and inertial force V_a horizontal or downward, assumed the synthetical velocity is V_i , then we can get the relationship:

$$V_i = (V_b + V_a)^{1/2} \quad (3)$$

And angle between V_a and V_b can be written as:

$$\tan \alpha = V_b/V_a \quad (4)$$

That is

$$\alpha = \arctan(V_b/V_a) \quad (5)$$

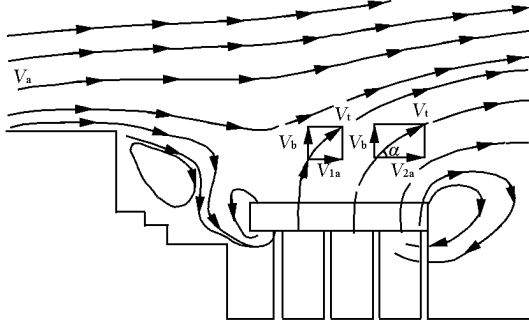


Fig. 4 Sketch map of recirculation produces under different velocities

Assumed incoming velocity is V_{1a} and V_{2a} (if $V_{1a} < V_{2a}$), then synthetical velocity V_i corresponding to V_{2a} is larger than V_i' corresponding to V_{1a} , so the angle between synthetical velocity and horizon is smaller. When buoyancy force keeps constant, the bigger the velocity is, the easier it can press the plumes into the platform, and then, with the coaction of turbulent entrainment and mix up, more and more plumes are drawn into vortex, while, boundary fans under platform can pump the plumes, so recirculation comes into being, which makes temperature at the inlet of ACC augment and leads to buoyancy decrease. When incoming velocity keep constant, from Eq. (5) we can see that the angle between buoyancy and inertial force becomes smaller, the climbing hot air will close to the platform, under the function of eddy, more and more hot air is rolled into the bottom of cooling tower, a vicious circle will be formed until the brake of system works for the sake of protection.

So we can find that the main reason which recirculation ratio increases along with wind velocity is incoming wind velocity increases, the inertial force enhances. Meanwhile, as wind velocity increases, eddy intensity around cooling tower also enhances, so more and more plumes are drawn into bottom of cooling tower, which decreases the effect of heat dispel of ACC.

4.2 Relationship between flow field and recirculation ratio

In order to investigate the relationship between flow field around cooling tower and recirculation ratio, the measures of increasing the height of wind wall and widen the platform are used to change the flow field. PIV experiments are carried out under different heights of wind walls and different widths of horizontal boards, and recirculation ratios of corresponding situations are also measured.

4.2.1 Increase the height of wind wall

In order to decrease recirculation ratio under cooling tower, wind velocity in wind tunnel is 6 m/s, wind direction angle $\beta = 0^\circ$ (west wind), the height of wind wall in model test is adopted by 108.3, 116.7, 125, 133.3, 141.7, 150 mm (corresponding height of prototype is 13 (design value), 14, 15, 16, 17, 18 m), so temperature of each measuring point is measured, and recirculation ratio of each point is also calculated, the influence of height of wind wall on recirculation ratio is analyzed. Fig. 5 gives the relationship between height of wind wall and average recirculation ratio under cooling tower.

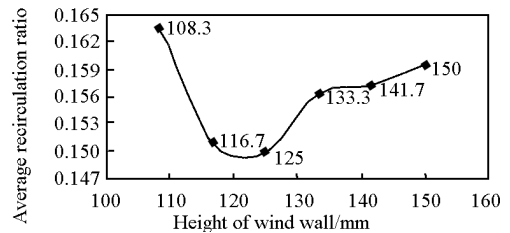


Fig. 5 Relationship between height of wind wall and average recirculation ratio

From Fig. 5, we can see as height of wind wall increasing, the average recirculation ratio decreases at first, and then increases. But the values of average recirculation ratio are all below that of design height of wind wall. At height of $H_w = 122$ mm (corresponding height of prototype is 14.64 m), average recirculation ratio is minimum, average recirculation ratio decreases by 1.5%, comparing with the design height of wind wall. So under the base of design height, increasing height of wind wall can benefit to decrease average recirculation ratio under cooling tower.

From the results of measuring temperature, increasing the height of wind wall can decrease the recirculation ratio under cooling tower. In order to get the relationship between recirculation ratio and flow field when height of wind wall is heighten, PIV experiments are carried out in the condition of same velocity and direction but different height of wind wall. Fig. 6 and Fig. 7 give the streamline picture at different heights of

wind walls under velocity of 6 m/s, and direction angle $\beta = 0^\circ$ (west wind).

From Fig. 6 we can see when the ambient wind blows from boiler to cooling tower, because of air separated from top of boiler and cooling platform, two large captive eddies that form on the lee side of the tower and downstream position of platform. That is one is on the top of turbine house, the other is at backward position of

wind wall away from turbine house. On the boundary of eddy, turbulent entrainment and mixing up which causes more and more plumes discharged from ACC are brought back into inlet of cooling tower, under action of fans' pumping; hot air is sent to ACC again. That is, the increase in the cold-air temperature raised the turbine back pressure and thereby reduced efficiency of ACC.

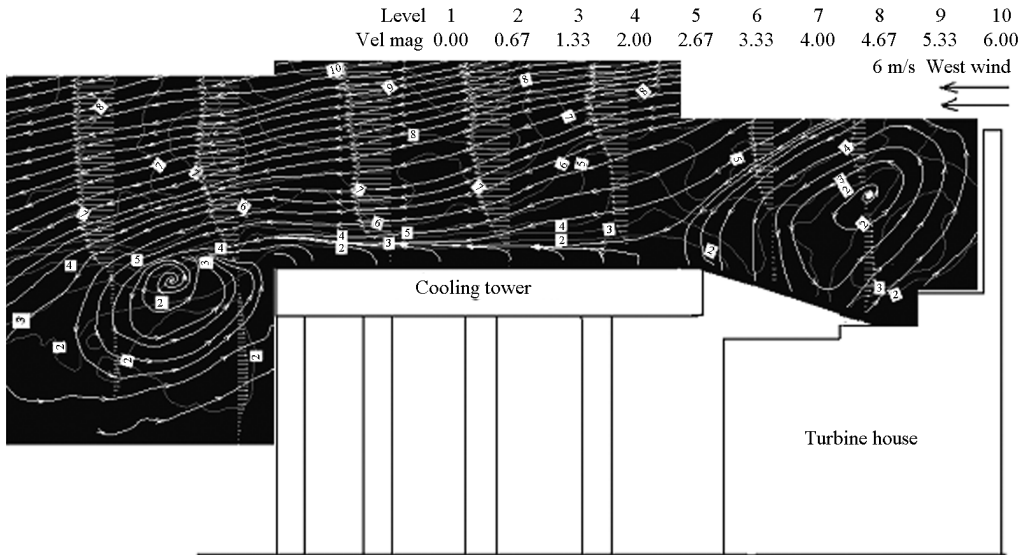


Fig. 6 The streamline picture of height of wind wall $H_w = 108.33$ mm

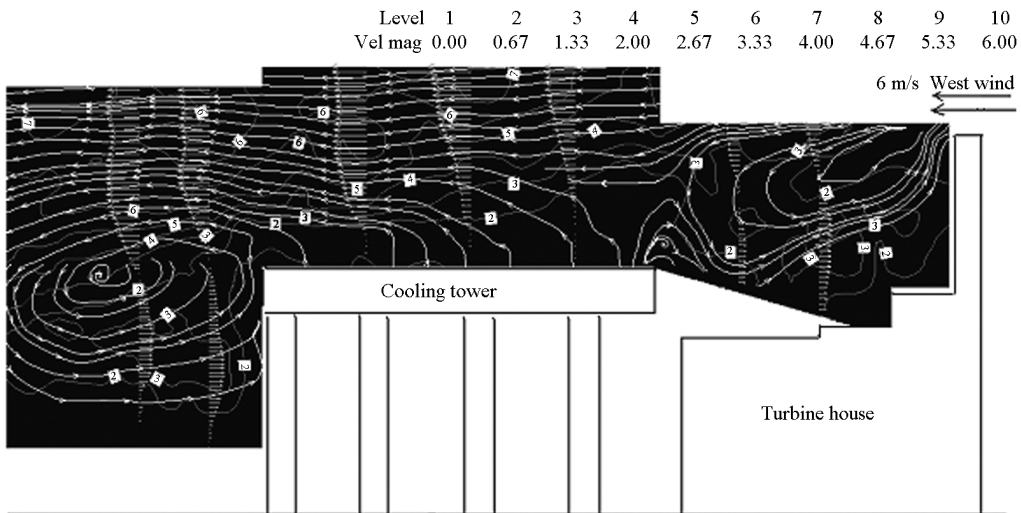


Fig. 7 The streamline picture of height of wind wall $H_w = 150$ mm

From Fig. 6 we could also see that, because of height of wind wall is lower, under the action of eddy on the lee side of boiler, a little “adverse flow” may appear in the boundary of wind wall closed to turbine house. From Fig. 7, comparing to design condition, we can find when height of wind wall $H_w = 150$ mm, the

large eddies at the lee back of the boiler are uplifted, and has the trend of throwing off backward position, so little plumes discharged from wind wall closed to turbine house are brought into eddy. We could also see that from velocity profile of mid-section of a unit in wind direction angle $\beta = 0$, comparing to design

height of wind wall, as height of wind wall is increased, velocity profile above the platform became slim, and magnitude of velocity is reducing close to the ACC. That means the horizontal inertial force became reduced, when buoyancy kept constant, which is helpful for hot air to discharge.

So we come to the conclusion that increasing the height of wind wall can change the flow field configuration around cooling tower, and can decrease the recirculation ratio under cooling tower, the result is in accord with measuring results of recirculation ratio^[7].

4.2.2 Widen the platform

The experiment widen the platform to change the flow field of cooling tower, the width B are 20 mm, 50 mm; and also lengthen the platform, the length L are 20 mm, 40 mm; temperature of each measuring points is measured when wind velocity is 6 m/s, and direction angle is $\beta = 0^\circ$. Table 1 gives the relationship between different conditions and percent of recirculation decrease.

crease.

Table 1 The relationship between different conditions and percent of recirculation decrease

Different conditions	Percent of recirculation ratio decrease /%
Design condition / mm	0.00
$B = 50$	2.69
$B = 20$	4.09
$L = 20$	1.65
$L = 40$	1.93
$B = 50, L = 40$	2.16

From Table 1, we can see that widen the platform and lengthen the platform can both decrease the recirculation ratio under cooling tower, and value of decrease changes with the width of board. Fig. 8 gives the streamline picture of height of wind wall is 108.3 mm, and width of front board is 50 mm.

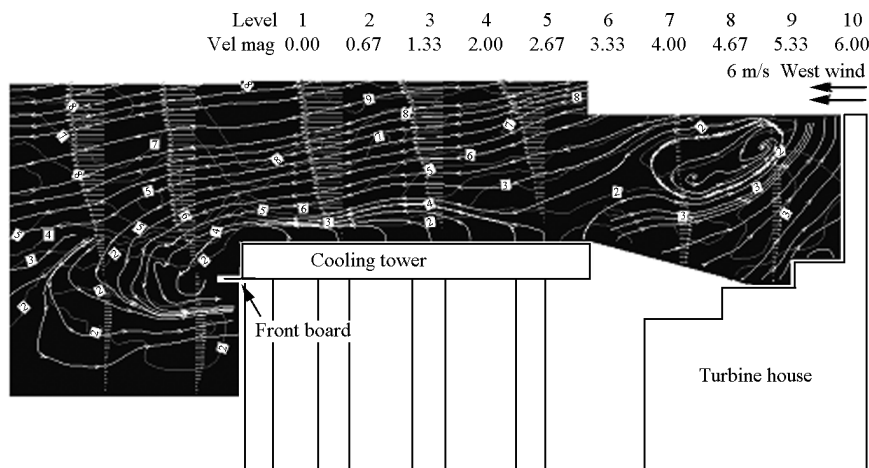


Fig. 8 The streamline picture of height of wind wall $H_w = 108.3$ mm, front board is 50 mm

Comparing Fig. 6 with Fig. 8, we can see, lay front board to the platform backward position, vortex configuration at the lee of boiler uplifts remarkably, and “adverse flow” close to turbine house weaken obviously; the eddy configuration downward position of cooling tower is destroyed, so when incoming flow condition keeps constant, turbulent entrainment and mix up intensity of eddy downward position weaken evidently, and then, the hot air discharged from ACC returned to the bottom of cooling tower becomes less. At the same time, from the velocity profile, we can get, because of front board supporting function, velocity profile above the platform become very slim and velocity close to the bottom of platform become less, and this can help the hot air to discharge. So lay front board to

platform can change the flow field configuration around cooling tower, and decreases recirculation ratio under cooling tower.

5 Conclusions

In order to investigate the influence of thermal flow field characteristics around cooling tower on average recirculation ratio under cooling tower, the PIV experiments were carried out in different conditions in low velocity wind tunnel for the first time. And found that, the flow field configuration around cooling tower has great effects on average recirculation ratio under cooling tower, two large eddies will form when wind blows from boiler to cooling tower, and eddy intensity increases with wind velocity increases, the size and configu-

ration of eddy changes around around cooling tower. Increase the height of wind wall, widen the platform can both ameliorate the flow field around cooling tower, which can decrease the average recirculation ratio under cooling tower, and then, improve the efficiency of heat dispersal for air cooled condenser.

References

- [1] Wang Peizhang. Draw on experience to develop direct air-cooling technology of large fossil-fuel power unit in China[J]. North China Electric Power, 2007, 5:31-38.
- [2] Zhao Wanli, Liu Peiqing. Recirculation produces under cooling tower and evaluate criteria for a power plant[A]. CCTAM2007-0001783[C]. Beijing, CCTAM, 143.
- [3] Gu Zhifu. Wind tunnel simulation on re-circulation of air-cooled condensers of a power plant[J]. Journal of Wind Engineering and Industrial Aerodynamics, 2005, 6: 509-520.
- [4] Gu Zhifu. Wind tunnel simulation on wind effects on air-cooled condensers of a large power plant[J]. Chinese Journal of Theoretical and Applied Mechanics, 2007, 37(5): 558-563.
- [5] Zhao Wanli, Liu Peiqing. Experimental researches on influence of environmental wind on recirculation under cooling tower of a direct air-cooled condenser for a power plant[J]. Power Engineering, 2008, 28(3):390-394.
- [6] Liu Peiqing, Zhao Wanli, Duan Huishen, et al. Simulative platform and test methods applied to thermal flow field configuration of direct air cooling tower for a power plant [P]. China: 200710118542.9, 2007-6-9.
- [7] Liu Peiqing, Zhao Wanli. Experimental investigation of the thermal effects simulation in wind tunnel on a direct air-cooled system for a power plant[J]. Journal of Engineering for Therm, Energy and Power, 2008,23(3):240-243.

Author

Zhao Wanli, male, born in 1980, graduated from North China University of Water Conservancy and Electric Power and now is a doctor student in School of Aeronautic Science and Engineering at Beihang University, Beijing, China. Mr. Zhao has published over 6 papers. His current research is thermal flow field, heat dispel, direct air-cooled condenser, etc. He can be reached by E-mail: bhvip@sohu.com