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Wind tunnel simulation on re-circulation of air-cooled condensers of a power plant ☆

Zhifu Gu[a,*], Hui Li[a], Wenhong Zhang[a], Yan Li[a], Jiye Peng[b]

[a] *Peking University, Beijing 100871, People's Republic of China*
[b] *Shanxi Electric Power Exploration & Design Institute, Shanxi 030001, People's Republic of China*

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Abstract

The criteria as well as the methods and measurements of wind tunnel simulation on wind effects on air-cooled condensers in a power plant were discussed. The parameter of re-circulation was suggested to describe the wind effects on the efficiency of the condenser. The result of practical project models shows that great wind effects of both wind speed and the angle of the incident flow on the efficiency of the condenser. It is recommended that in the initial stage of a new or an extension power plant, which is equipped with an air-cooled system, the wind tunnel simulation is necessary and helpful. Combined with the local wind climate data, a more reasonable, economic and safety schematic design of a power plant could be achieved.

Keywords: Re-circulation; Air-cooled condenser; Wind tunnel simulation; Power plant

1. Introduction

Although in many areas in the world, particularly in northern China, where coal reserves are abundant, an obstacle in the construction of mine-mouth power station

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*Corresponding author. Tel./fax: +86 10 62756079.
E-mail address: guzf@pku.edu.cn (Z. Gu).

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can be the lack of an assured supply of water. To minimize water use and avoid coal transport to a site where water is abundant, which is extremely costly, it is obvious that air-cooled condensers technology is a great solution and has become increasingly important in these areas.

A project of an extension power station, located in northern China, planned to use GEA air-cooled condensers for a 2×200 MW power plant. The GEA air-cooled condenser uses a space-saving A-frame design installed at grade level. The condensers are constructed with rugged galvanized steel elliptical fin tubes, which transfer heat consistently in the long-term. In an air-cooled condenser cell, exhaust turbine-steam flows inside the steel elliptical tubes; cooling air is drawn through the fins by a large fan, which is mounted underneath. The air takes the heat from the exhaust turbine-steam, which converts to condensate. In this project, 4×12 condenser cells arranged on a rectangular platform is supported by 2×6 concrete circular cylindrical props 31 m high. To avoid the unfavorable effect of wind and increase the efficiency of condensers, windbreak is constructed around the platform with an equivalent height of the condensers 10 m.

Due to the requirements of technological process of a power plant, air-cooled condensers platform usually sites behind the steam turbine room. The configurations of the proposed power plant, including the air-cooled condensers platform and buildings which comprises two 64 m high boiler rooms joint and a 31 m high steam turbine room, together with the definition of the angles of incident flow β are shown in Fig. 1.

According to the knowledge of bluff body aerodynamics, when flow passes through an object on the ground, a wide region of wake flow is formed. In the wake

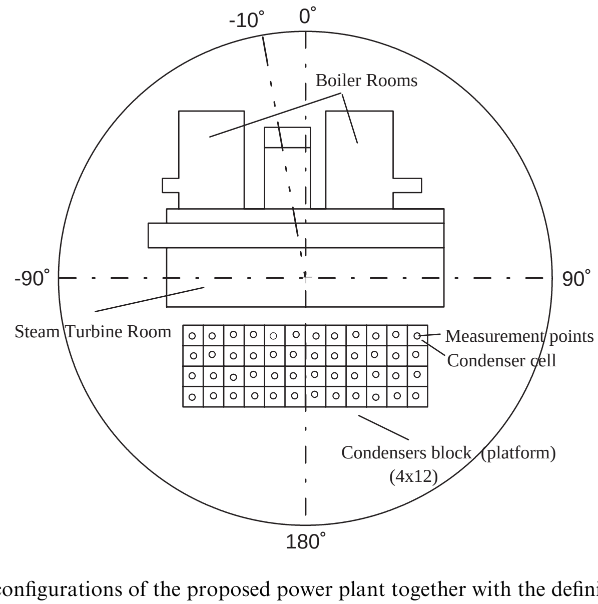

Fig. 1. Schematic configurations of the proposed power plant together with the definition of the angles of incident flow, β.

region, part of the air deflects downward forming a vortex and thus sweeps the ground in a reverse flow. In this project model, when wind blows from the right side of the boiler and steam turbine rooms, a large wake structure is formed. However, air-cooled condensers platform, just locates within this region; thus, it makes part of the hot exhaust air return back to the inlet region of condensers. If large amount re-circulation of exhaust hot air takes place, it forces a significant increase in the inlet air temperatures and leads to reduce the efficiency of the air-cooled condensers greatly. According to some reports, in practice, it might be forced to shut down the turbine in the most serious case during summer time. Therefore, it is very important to know the characteristics of the re-circulation combined with the information on local wind climate at the initial configuration design stage for a new or an extension power plant, which is equipped with an air-cooled system. On the other hand, in practice, because of some special limitations, especially an extension power station, the unfavorable wind condition may not be avoided. Thus, the second question of how to minimize the unfavorable effect of wind on air-cooled condensers is also raised.

Ziller et al. [1] studied the influence of wind speed and direction on the efficiency of mechanically driven cooling devices, which include multi-cell cooling towers and air-cooled condensers, by means of wind tunnel simulation. Their results show that the negative influence is not only affecting the cooling devices, but also surrounding plant structures like gas turbines which can suck hot exhaust air as fresh air can lead to a dramatical decrease of its efficiency.

In order to better understand the characteristics as well as the mechanism of wind effects on the performance of air-cooled condensers of the project and to minimize the unfavorable wind effects, the phenomenon of re-circulation of air-cooled condensers as investigated by means of wind tunnel simulation. Concentration measurements of a special tracer gas, which simulate the exhaust hot air from condensers, were conducted for different model conditions during the experiments. Total and distributions of re-circulation of hot air in the inlets of condensers platform were obtained and described. Some typical interesting results were given and analyzed. More attention was paid on the mechanism of occurrence of re-circulation in various models.

Flow visualization plays an important role in bluff body aerodynamic investigations from an overall description of the flow structure. In order to explain the mechanism of occurrence of re-circulation, flow visualization experiments of some typical model conditions were also conducted in another wind tunnel by the method of smoke-wire technology.

2. Experimental apparatus and data reduction

2.1. Experimental apparatus and data reduction

The measurements of concentration for the re-circulation were conducted in a boundary layer wind tunnel at Peking university, Beijing, China. The tunnel has a rectangular test section 3 m wide, 2 m high and 32 m long. The wind speed may change from 0.3 to 10 m/s. To simulate the atmospheric boundary layer with proper mean wind speed profiles and distributions of turbulence intensity, suitable roughness elements were placed and distributed on the floor of the test section.

The model of the power plant, including the air-cooled condensers platform, the boiler rooms and the steam turbine room, were positioned on a turntable, which locates at the downstream of the test section.

The flow visualization experiments were conducted in another low speed wind tunnel at the same university. It has an open circular test section of 2.25 m in diameter and 3.65 m long. The test section of the tunnel was modified by using a wood plate, which is lengthened through the throat of the tunnel into still chamber, to be a boundary layer tunnel. The vortex generation device (spires were used here) and roughness elements were provided on the plate. Atmospheric boundary layer with a suitable depth could be generated at the end of test section. The same models were used and the smoke-wire technology of flow visualization was adopted.

2.2. Similarity parameters and the models

To simulate flow field with gas dispersion in an ABLWT the most important similarity criteria must be met. Additionally, it is necessary to model the characteristics of naturally occurring wind, and the dynamic and thermal properties of the exhaust plume [2]. Although this statement is for the physical modeling of stack dispersion process of plume rise and diffusion into the atmosphere, however, it is believed that the mechanism is the same for the exhaust hot air from the air-cooled condensers.

To meet the boundary conditions, Jensen's Criterion was considered [3]. In order to obtain the proper roughness height for the model test, $_{\mathrm{om}}$, the parameters of roughness elements, such as the elements height and the spacing between elements, were carefully adjusted, to match that of the project site terrain of suburban (prototype) $_{\mathrm{op}} = 20 - 40\,\mathrm{cm}$. In other words, the following relationship is satisfied:

$$\frac{Z_{\mathrm{om}}}{L_{\mathrm{m}}} = \frac{Z_{\mathrm{op}}}{L_{\mathrm{p}}},$$

where L_{m} and L_{p} are the characteristic length of the model and the prototype, respectively. The longitudinal turbulence intensity is 18% at the height of the condensers platform.

For the prototype air-cooled condensers, the following thermodynamic data were assumed. Volume flow from each cell is $460\,\mathrm{m}^3/\mathrm{s}$ (48 cells), and temperature difference between the exhaust air and the ambient air is 30–33 °C. To maintain a correct ratio of hot air exhaust velocity from air-cooled condensers u_{c} to that of the ambient flow U, the following requirement,

$$\frac{u_{\mathrm{c}}}{U} = \mathrm{const},$$

was met both in the prototype and the model test.

Considering the blockage effects, the geometrical model scale of 1:120 was selected. The blockage ratio of model and the wind tunnel test section was about 6.5%. According to Isyumov [4], correcting for the effects of the distortion of the flow is more difficult. For a blockage ratio of 5% and less, distortion effects are negligible and a correction for the speed-up of flow at the model is sufficient. The wind tunnel ceiling was adjustable and locally raising the height of the ceiling above the model itself with gentle slopes upwind and downwind of the model was adopted in the experiments. No other corrections on blockage effect were performed on the experimental data.

The model of ACC platform was carefully made with 48 real micro-fans to form the two adjoining units. To simulate the resistant of fan tube heat exchangers, suitable stainless-steel screen were used. The speed of exhaust air can be adjusted through the current and the voltage, which were fed by a power supply.

In addition, to obtain the correct hot-air dispersion from the air-cooled condensers, a special gas with different density of the air, methane (CH_4), was used to simulate the buoyancy-effect as well the tracer gas. The methane gas was released through 48 brass tubes, which were mounted beneath the fan of each condenser cell. The tracer gas released with constant flow rate were mixed with air in the inlets by the fan and passes through the several layers of stainless-steel screens, which simulate the resistance of elliptical tubes, then finally exhausted from the top of condensers.

Based on satisfying the densimetric Froude number $(F_r)_d$, the different full-scale wind speeds may be simulated in wind tunnel by adjusting the incoming flow velocity. Then the similarity parameter between model and prototype can be written as

$$(F_r)_d = \left(\frac{U}{\sqrt{gL(\Delta T/T_a)}}\right)_p = \left(\frac{U}{\sqrt{gL(\Delta\rho/\rho_e)}}\right)_m,$$

where ΔT is the temperature difference between the exhaust hot air from ACC and ambient air, $\Delta\rho$ is the density difference between ambient air and a special gas, which will be described later, T_a is ambient air temperature of prototype, and ρ_e is density of the special gas.

By using the measurement of the tracer gas concentration in the inlet of each air-cooled condenser cell, degrees of re-circulation $R_c(\beta, I)$ is determined, which is defined as follows

$$R_c(\beta, I) = \frac{C_R(\beta, I)}{\bar{C}_R} \quad (I = 1, 2, 3, \ldots, 48),$$

where $C_R(\beta, I)$ is the concentration of exhaust tracer gas sampled in the inlet of each cell at the angle of incident flow β, $\bar{C}_R$, the averaged concentration of tracer gas exhaust from all condensers. In order to express the whole wind effects on the condensers at various wind directions related to the power plant buildings, the total re-circulation $R_T(\beta)$ is defined as

$$R_T(\beta) = \frac{1}{48}\sum_{I=1}^{48} R_c(\beta, I).$$

By means of measuring each cell re-circulation, $R_c(\beta, I)$ and/or the total re-circulation $R_T(\beta)$, the qualitative description of re-circulation of hot air may be obtained. It is understood that the quantitative relationship between the degrees of re-circulation and the efficiency of the air-cooled condensers is a complicated question. However, it is believed that at the same conditions, such as the same ambient temperature and output power of the fans, the efficiency of the air-cooled condensers should be inversely proportion to that of re-circulation. The best way to solve the problem is to perform a full-scale measurement after a power plant has been built and combine with the results of wind tunnel simulation.

3. Results and discussion

It is expected that the arrangement and geometric configurations of boiler rooms and steam turbine room, wind directions and wind speed of oncoming flow have great effects on the results of re-circulation. Four model conditions with different heights of condensers platform, i.e. concrete circular cylindrical props and windbreak configuration were tested. The four model conditions are as listed in Table 1.

3.1. Effect of wind direction

It is obvious that the wind directions have great effects on the re-circulation. Fig. 2 presents that the total re-circulation $R_T(\beta)$ varies with the angle of incident flow β. Since the configuration of the power plant is roughly symmetry, only half the number of wind direction were performed. The first three model conditions were employed in the wind direction effect experiments. The wind speed of 4 m/s corresponding to the full-scale at 10 m above the ground was selected for the tests.

Table 1
Three models of model condition

Model	Conditions
1	Condensers platform height $H = 31$ m
2	Condensers platform height $H = 34$ m
3	Condensers platform height $H = 31$ m, windbreak which facing to the steam turbine room raise 3 m
4	Condensers platform height $H = 31$ m, mount an additional platform between the top of steam turbine room and the platform of condensers platform

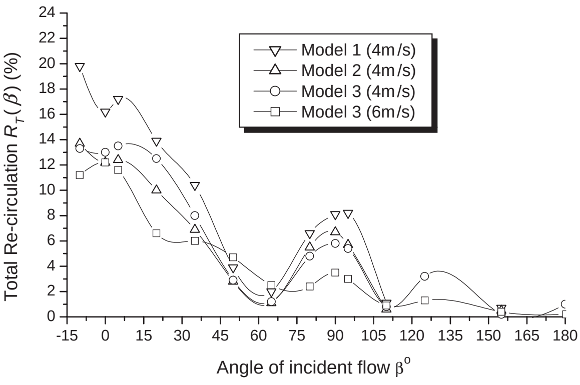

Fig. 2. Total re-circulation $R_T(\beta)$ varies with the angles of incident flow, β.

It is shown that as the wind blows normal to the boiler rooms or within $\pm 10^\circ$, the most unfavorable effects of wind on condensers result. As the wind directions deviate from this region, the total re-circulations reduce quickly and reach the minimum value less than 3% at $\beta = 65^\circ$. However, as the wind blows normal to the gap between the steam turbine room and the block of condensers ($\beta = 90^\circ$), the values of total re-circulation increase again, which form the second peaks of re-circulation for the three individual model. The mechanism of occurrence of this phenomenon will be explained later together with the results of their re-circulation distributions. Finally, as the wind blows normal to the condensers platform or within $\pm 70^\circ$, the value of total re-circulation is quite low; therefore the wind effects could be ignored.

Contrasting the results of Model 1 with Model 2, it is seen that the height of platform has a significant influence on the re-circulation, especially in unfavorable wind directions, as the wind comes from boiler room. In this case, however, overall decrease of re-circulation 30% is expected as the height of platform raise from 31 to 34 m.

In order to verify the effect of wind speed on the re-circulations at various wind directions, on the other hand, the experiments with wind speed of 6m/s were also conducted for Model 3. In contrast with the results of 4 m/s, the trend of reduction in re-circulation coincides well in the most angles of incident flow β, but increases at $\beta = 50^\circ$ and 60°. This reflects the complexity of flow around an unregulated bluff body due to the interference of shear layers, vortex shedding and wake structure (Fig. 3).

According to the local weather data of the project, the prevailing wind direction of incident flow is $\beta = -10^\circ$. In order to know the mechanism of occurrence of re-circulation, detailed information of re-circulation distributions on the inlets of the whole condensers block at various conditions and wind directions are necessary. Fig. 3 shows the re-circulation of hot air distributions of Model 1 in the inlets of the whole condensers block at four wind directions $\beta = -10^\circ$, 65°, 90° and 180°, respectively, in the form of a contour map. At $\beta = -10^\circ$, in general, the values of

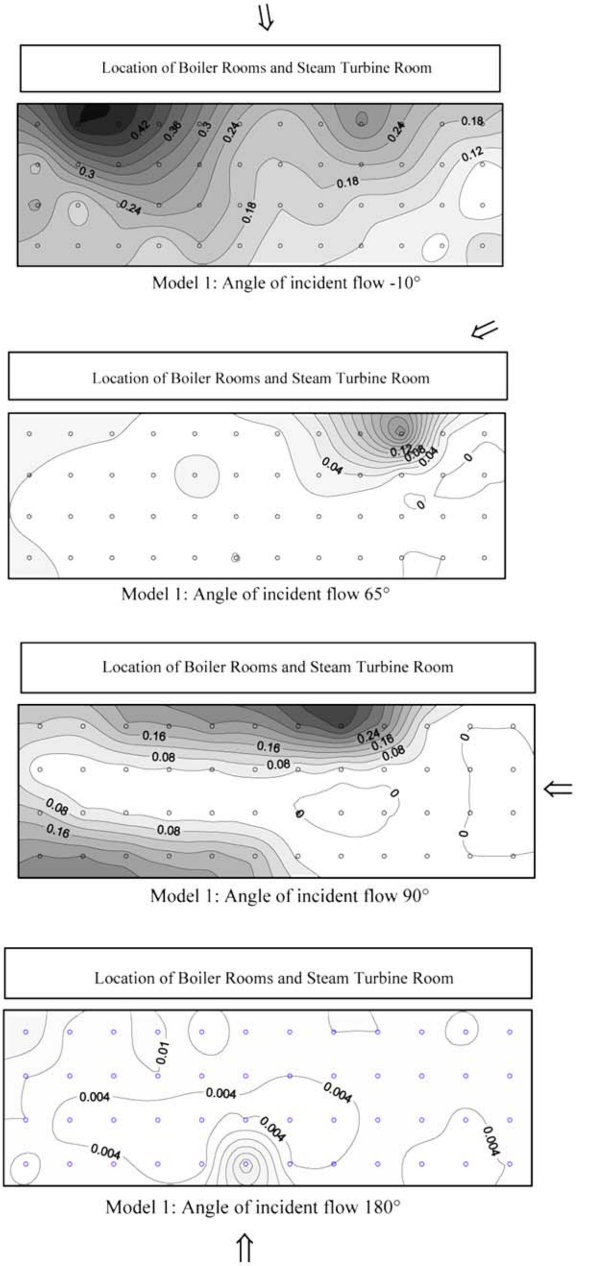

Fig. 3. Contours of re-circulation distributions of model 1 in the inlets of the whole condensers block at $\beta = -10^{\circ}$, 65°, 90° and 180°, respectively.

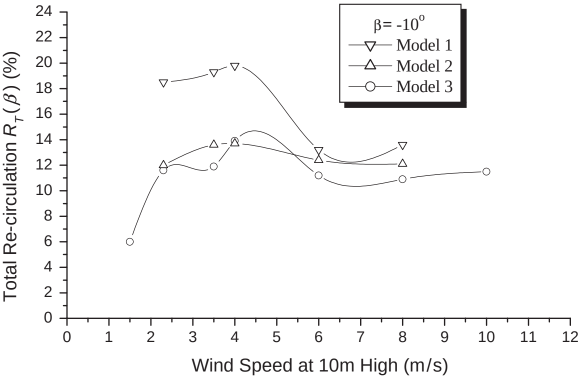

Fig. 4. Total re-circulation $R_T(\beta)$ ($\beta = -10^\circ$) varies with the wind speed for the three models of model condition.

Fig. 5. Flow visualization for Models 1 and 4 (with additional platform between the top of steam turbine room and the platform of condensers platform) at $\beta = 0^\circ$.

re-circulation in the inlets of the whole condensers block are high, especially two peak value regions formed located just downstream of the boiler rooms (Fig. 4). It means that the contribution of the re-circular exhaust air not only comes from the downstream of condensers block, but also comes from the upstream of the condensers block, especially the regions behind the boiler rooms. It is the most serious case in all the wind directions. The phenomenon could be explained that parts of the exhaust air from the condensers aside the steam turbine room, sucked by the strong reverse flow which forms behind the boiler rooms, pass through the gap between the steam turbine room and the condensers block to the inlet of condensers, it causes the two peak values of re-circulation regions. Another contribution of re-circulation comes from the down steam condensers block due to the reverse flow of the wake. It is confirmed by the results of flow visualization as shown in Fig. 5.

At $\beta = 65^\circ$, the wake structures generated by the boiler rooms are no longer acting on the condensers block directly, thus, only small local parts re-circulation with rather low values can be detected. Therefore, the total re-circulations reduce tremendously in all three models. However, as the angle of incident flow increasing further to $\beta = 90^\circ$, i.e., the wind blows normal to the gap between the boiler house and the block of condensers, the flow separates from leading edges of both the condenser platform's windbreak and the rear wall of the steam turbine room. Separating bubble forms underneath the separated shear layers cause the strong suction in the gap. Therefore, the local heave re-circulations occur in the adjacent region of the condensers inlets. That is the reason of the total re-circulations raise again at $\beta = 180^\circ$ for the all three models. As wind blows normal to the condensers block, or within $\pm 25^\circ$, e.g. $\beta = 180^\circ$ as shown in Fig. 3, almost no re-circulation can be detected in the all inlets of condensers block.

3.2. Effect of wind speed

According to the previous results of effects of wind direction, the angle of incident wind flow $\beta = -10^\circ$ is the most serious case of unfavorable wind effects. In order to determine the effect of wind speed on the re-circulation, at the worst wind direction, wind speeds corresponding to the full-scale 1.5, 2.0, 4.0, 6.0, 8.0 and 10 m/s at 10 m high were tested.

The results of the total re-circulation $R_T(\beta)$ ($\beta = -10^\circ$) for Models 1, 2 and 3 are shown in Fig. 4. It is shown that in Model 1 the maximum value of R_T reached at wind speed 4 m/s and reduces quickly at wind speed 6 m/s, it keeps almost the same value at 8 m/s. In Model 2, however, due to 3 m raise in platform height, the values of re-circulation reduces by almost 30% compared with Model 1 at wind speed between 2 and 4 m/s. Considering the strong effect of the platform height on the re-circulation. A scheme of raising the front windbreak of the condensers block, Model 3, was supposed instead of raising the concrete circular cylinder supports. As expected, the results of Model 3 agree with that of Model 2 very well, which means instead of increasing the height of the platform, which may be costly in practical engineering, to raise the windbreak just behind the steam room only could achieve the same benefits for reducing the re-circulation. As the wind speed reduces to 1.5 m/s, the total re-circulation of both Models 2 and 3 reduces tremendously to only 6%. It is believed that if there is no wind, the re-circulation vanishes and it is confirmed at the beginning of the experiments. As the wind speed is between 6 and 10 m/s, the values of re-circulation change with the wind speed smoothly for all the three models.

It is concluded that at the most unfavorable wind direction, the most serious re-circulation happens at the wind speed between 2 and 4 m/s. The heights of condensers have a strong effect on the re-circulation. As the wind speed exceeds to 6 m/s, the re-circulations tends to a constant value.

3.3. Improvement and flow visualization

Unfortunately, according to the weather report in this project, the local prevailing wind direction just coincides with the most unfavorable wind direction, i.e. $\beta = -10^\circ$. In order to reduce the re-circulations at the most unfavorable wind

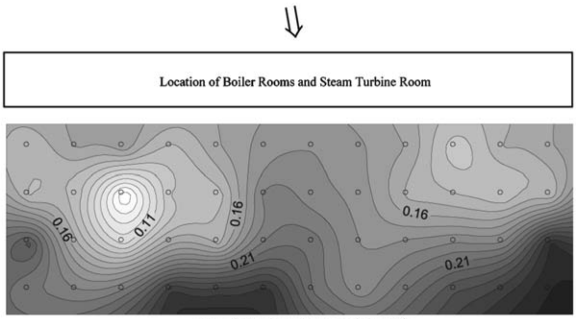

Fig. 6. Contours of re-circulation distributions of Model 4 (with additional platform between the top of steam turbine room and the platform of condensers platform) in the inlets of the whole condensers block at $\beta = 0^\circ$.

directions, which may not be avoided completely in practice, several steps, including Models 2 and 3, were supposed to improve the performance of condensers. Considering as the wind blows normal to the buildings, two peak values of re-circulation regions are formed located near the steam-house due to the direct reverse sink flow, it was suggested to construct an additional platform between the top of steam turbine room and the condensers platform, as Model 4, to obstruct the exhaust air pass through. However, the results show that, in this model condition, the value of total re-circulation only reduces slightly by 1.9%. Distributions of re-circulation in the inlets show that the two peak value regions are disappearing now (see Fig. 6), but large quantity re-circulations are created on the rear part of condensers platform inlet. The flow visualization (see Fig. 5) shows that there is no reverse flow found between the gap of steam-turbine room and the condensers platform, whereas the much strong reversed exhaust flow comes back to the inlets of downstream condensers block.

4. Conclusions

By means of concentration measurements, characteristics of the performance of air-cooled condensers in a power plant were simulated in wind tunnel tests. The most important criteria must be met, especially the dynamic and thermal properties of the exhaust hot air from the condensers.

Due to the interference of the neighboring buildings, such as the boiler rooms and the steam turbine room, the angles of incident flow have a great effect on the efficiency of air-cooled condensers. As the wind blows normal to or within $\pm 10^\circ$ the boiler rooms, the most unfavorable effects of wind on condensers result. On the other hand, at the most unfavorable wind directions the most serious re-circulation takes place at the wind speed between 2 and 4 m/s. Combined with the information of local wind climate, this model condition should be avoided as much as possible for a power plant equipped with air-cooled condensers. There is a great advantage in reducing the unfavorable wind effect on the performance of condensers by raise the height of platform or the windbreak. Therefore, it is possible to have some steps to reduce the unfavorable effect of wind on the condensers by means of wind tunnel simulation. Wind tunnel simulation could play an important role in the design stage of a new or extension power plant with air-cooled condensers.

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