Study on the performance of indirect air-cooled system influenced by environmental temperature

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Abstract. In order to explore the mechanism of the performance of Air-cooled system influenced by environmental temperature, indirect air-cooled towers with surface condensers in power plant were studied in this paper. Through a proper simplification, the geometric models of indirect air-cooled towers and other major buildings around which may affect the fluid flow were established. When it comes to the air-cooled towers, which were located in the central region of flow and heat transfer, the structure type of the towers and the radiators should be clearly presented. Flow resistance and heat transfer characteristics of radiators were correctly and objectively taken into account, the reliability of which was verified by field test. Numerical simulation study on the thermal performance of the indirect air-cooled system with surface condensers was conducted by creating corresponding mathematical and physical models on the condition of designed wind director and velocity. At the same time, the thermal performance of indirect air-cooled towers under different environmental temperature was studied. The results showed that, the volume flow rate of air into the indirect cooling tower under different environmental temperature is basically unchanged. With temperature rising up, the density of air reduces, which leaded to a decrease on the mass flow rate of air into tower. Besides, the trends and changing laws of performance parameters from the level of segments and the tower are achieved. What's more, the flow traces of air and flue gas in towers were basically similar which were clearly divided by a temperature line, but the two flows always melt into a whole one at the export of towers. The conclusions would be of guide significance to the optimal operation and design of indirect air-cooled system.

1. Introduction
As the modern electric industry develops rapidly, more and more thermal supercritical and ultrasound supercritical units with high capacities and high parameters are widely used. The electric industry requires not only large quantity of primary energy sources, but also large number of water[1]. Air-cooled technology is proposed for the purpose of saving water. By replacing water with air to be the cooling medium, the technology is applied effectively for cooling the exhaust jetting out of turbines directly or indirectly [2].

The system using air-cooled technology is called air-cooled system, which could be divided into two classes according to the cooling method, direct air-cooled system and indirect air-cooled system. In contrast, direct air-cooled system is more sensitive to the environmental wind. It is very likely to cause tripping operation if not adjusting the load in time[3]. During the summer time with high ambient temperature, there is a temperature limitation for the condensate finishing resin. But the
indirect air-cooled system can take a good advantage in every aspect mentioned above. For the time being, the indirect air-cooled system extensively used is called SCAL system, which is designed by North China Power Engineering (Beijing) Co., Ltd adopting the vertical layout of the surface condenser and radiators [4].

The natural driving force caused by the difference of air densities between inlets and outlets leads to the suction effect of indirect air-cooled system. The environmental temperature has a obvious effect on the air density, so as to the inlet flow rate and cooling performance. The air intake and heat dissipation performance of the air-cooled towers will be affected by the surrounding environment, and the impact mechanism is very complex.

A large amount of scholars have conducted a series of research work on air cooling tower structure, air flow field inside and outside the tower, and operational performance[5-7]. Frezze et al [8-11] analyzed the effect of radiator arrangement on the cooling performance and ambient flow field of the air cooling tower under lateral wind conditions, and proposed a reasonable layout of the radiator and the installation of a wind walls to reduce the lateral wind to the adverse effects of the air-cooled towers. Rafat Al-Wakeda [12], Zhao [13] and Lu et al[14] studied the effect of windshield installation and the location of openings on the air flow field and heat dissipation characteristics of an air cooling tower by the ways of simulation. Xi et al [15] calculated the effect of chimney height on the heat dissipation performance of the air-cooled towers at different wind speeds. The results showed that the height of the chimneys in the tower had a weak influence on the heat transfer performance of the tower, which could be negligible within the extent of engineering error.

With the development of computer technology, more and more engineering problems are investigated by the ways of computational fluid dynamics [16]. For the research of air-cooled systems, it will take less time and research funds to get overall, detailed results including velocity, temperature fields, helping in real engineering design[17].

This paper will study on a specific 2 600MW power plant with SCAL class indirect air-cooled system through numerical simulation method, calculating the performance in different environmental temperatures using commercial software FLUENT. By analyzing the change trend of main performance parameters, and the flow field counters, it is possible to get some patterns about how this system operates.

2. Basic principles

2.1. Mathematical models
Since the air around the power plant could be treated as incompressible, so the air flow field governing equations should be [18]:

2.1.1. Continuity equation
\[
\frac{\partial}{\partial t} (\rho) + \frac{\partial}{\partial x_i} (\rho u_i) = 0
\]  (1)

2.1.2. Momentum equation
\[
\frac{\partial}{\partial t} (\rho u) + \nabla \cdot (\rho u u) = \nabla \cdot (\mu \nabla u) - \nabla p + S_i
\]  (2)

2.1.3. Energy equation
\[
\frac{\partial}{\partial t} (\rho T) + \text{div}(\rho u T) = \text{div}\left(\frac{k}{c_p} \nabla T\right) + S_f
\]  (3)

In the formulas above, \(\rho\) represents the air density; and \(u\) is for the velocity; \(p\) for pressure; \(T\) for
temperature; \( S_t \) for the source term in momentum equation; \( S_f \) for the source term in energy equation; \( k \) for heat conductivity coefficient of the air; \( c_p \) for specific heat capacity; \( \mu \) for coefficient of kinetic viscosity; \( i = 1, 2, 3 \).

This paper adopts the RNG \( k-\varepsilon \) turbulence model, which is concluded by the renormalization theory, based on the experiences before, this model is suitable for separated flow. Because there are a lot of separation flow spaces around the power plant, so it fits to adopts this model.

As the flow field outside the indirectly air-cooled system is assumed to be incompressible. There is a need to solve the continuity equation and momentum equation in the same time for the purpose of solving the basic equations. The SIMPLE algorithm is adopted and pressure correction method is used for solving the steady outfield governing equations. SIMPLE algorithm [19] is an often-used pressure correction method. The basic idea of the algorithm is firstly assuming a velocity field and a pressure field. Then the momentum equation is solved successively. Pressure correction is gotten based on the continuity equation and the velocity is amended based on the pressure correction. At the same time, the \( k, \varepsilon \) equation is solved. After completing the above steps above, calculations of the velocity field and pressure field will be taken as assumed value, in the next loop of recalculation.

### 2.2. Geometric model

The power plant studied is of 2×600MW units, with supercritical indirect air-cooled system (ISC system). By adopting one-unit-one-tower pattern, the stack is built in the cooling tower. Through the natural cycling driving forces, the flue gas is taken away, which is called of NDCT with flue gas injection in short. Indirect air-cooled heat exchangers are made up with some exactly same triangle units around the tower vertically. In this paper the simulation geometric model is constructed as the real structure to get a more precise flow field. Figure 1 is the schematic drawing of the triangle heat exchanger.

![Figure 1. Heat exchangers.](image1)

![Figure 2. The whole calculation space geometric model.](image2)

The effects on air flow in the calculation scope are mainly caused by the buildings and equipment’ arrangement in the power plant. In addition, some unnecessary areas can be eliminated since the meteorological condition around this plant is known. The main buildings nearby the air-cooled towers, (like the boiler room, turbine room and stacks) are all included in the computational model. Finally, the whole calculation space adopted is determined to be 1000 meters long, 1000 meters wide, 500meters high. The geometric model is as below figure 2:

### 2.3. Mesh generation

In this paper, the real size of the structure is adopted, and the space is meshed before the calculation. Because the size of the heat exchangers and the size of the whole calculation space are in different level, it is necessary to build very fine meshes to capture the information of the flow field, and less
fine meshes for the external space. Mesh in different spaces should be treated respectively. Firstly, the whole space must be divided into different blocks. Secondly, different size of the meshes for each block is adopted. The rule is to make the meshes around the heat exchanger small and the space nearby the air-cooled towers slightly larger relatively larger for the other spaces. Finally, the number of the meshes is about 8.6 million. The meshing is illustrated below in figure 3.

![Meshing generation](image)

**Figure 3.** Meshing generation.

2.4. **Region naming**

The mathematical model is built according to the floor plan of power plant, and the relative positions are showed below. Each tower consists of 8 dependent fan sections, which is named based on specific rules: along the direction of dominant wind, there are 8 sections from Num8 to Num1 counterclockwise (showed in figure 4).

![Region naming](image)

**Figure 4.** Region naming.

2.5. **Boundary conditions**

2.5.1. **Finned tubular radiator boundary condition.** For the finned tubular radiator, the heat exchanger model (RADIATOR) provided by FLUENT is adopted during the simulation. And the incidence formula is provided by the experiment and the design materials.

2.5.2. **Inlet condition.** The velocity-inlet boundary condition is adopted for the inlet. Air flow near the
earth’s surface will be affected by buildings and other factors, and the velocity of air flow is lower when getting closer to the surface. In this paper, a boundary function is introduced:

\[
\frac{U_i}{U_\infty} = \left(\frac{Z_i}{Z_\infty}\right)^\alpha
\]  

(4)

In the formula (4), \(Z_\infty\) represent the height when velocity is equalized, based on design conditions, \(U_\infty\) is the velocity in the height of \(Z_\infty\), which is called environmental design wind speed, and it’s 4m/s in this situation, \(Z_i\) represents a random height, \(U_i\) is the velocity in the height of \(Z_i\). \(\alpha\) is the roughness coefficient of the surface, and will be larger when the surface getting rougher. The parameters should be calculated based on specific situations and with a UDF to calculate the final value. In this study we choose: \(Z = 10\, \text{m}, \alpha = 0.2\).

2.5.3. Outlet condition. We adopt a pressure-outlet condition, by a given static pressure on the outlet.

2.5.4. Other boundary condition. For the surfaces of buildings and ground in the simulation model, they are defined as wall conditions, without considering heat loss.

3. Field test verification

In order to verify the accuracy of the numerical calculation results, the numerical simulation results are compared with the results of the assessment test. Refer to the measured water temperature entering tower and the external environmental conditions (wind temperature, wind speed, etc.) under field test conditions, the conditions for setting the boundary conditions for the numerical simulation are the same as that measured in field test. The comparison results are as follows.

**Table 1.** Accuracy verification of numerical simulation.

| Item                                | Unit  | Contents |
|-------------------------------------|-------|----------|
| Test inlet Air Temperature          | °C    | 33.41    |
| Ambient Wind Speed at the Height of 10 Meters | m/s   | 1.34     |
| Water Temperature Entering Tower   | °C    | 64.02    |
| Circulating Water temperature drop | °C    | 9.91     |
| simulated temperature drop         | °C    | 10.10    |

The results in table 1 show that, under the same water temperature and external environment conditions, the temperature drop of the circulating cooling water measured by the entering and coming out of air-cooled towers and the numerical simulation temperature are different by 0.18°C. For the percentage difference between test and simulation was within 2%, the numerical simulation results are in good agreement with the on-site assessment tests. It shows that the measured results fully verified the accuracy and reliability of the digital-analog calculation.

4. Calculation result and analysis

Calculation conditions: Along the direction of dominant wind, the speed in the height of 10m is 4m/s. And simulations at the temperature of 5°C, 15.7°C, 25°C, 32.5°C, 38°C are conducted respectively. The other parameters will be set as same as design conditions during calculation. Results of volume and mass flow rate at different temperature are shown in the [Table 2](#).

Because of the surrounding buildings, the results of two towers perhaps will be different slightly. But the change trends are basically the same. In the following analysis, the north tower is taken as an example.
Table 2. Volume and mass flow rate at different temperature.

| Temperature/ ℃ | Northern tower | | | | | Southern tower | | | |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|                | Temperature/ ℃ | 5 | 15.7 | 25 | 32.5 | 38 | 5 | 15.7 | 25 | 32.5 | 38 |
| Volume flow rate/ m³.s⁻¹ | 35258.95 | 35660.90 | 35511.94 | 35803.76 | 35574.18 | 35660.90 | 35511.94 | 35803.76 | 35574.18 |
| Air density / kg.m⁻³ | 1.22 | 1.17 | 1.14 | 1.11 | 1.09 | 1.22 | 1.17 | 1.14 | 1.11 | 1.09 |
| Mass flow rate / kg.s⁻¹ | 42938.33 | 41799.98 | 40312.57 | 39642.10 | 38695.04 | 42474.17 | 41221.19 | 39809.50 | 39148.17 | 38254.58 |

4.1. Outlet temperatures, inlet flow rate change trends as to different environmental temperatures

Figure 5 shows the diagram that shows outlet temperatures in different fan sections at different environmental temperature. As is showed in the figure, the upwind side outlet temperature is lower than the two flanks. And the difference between each two neighbour fan sections remains a constant. Because of the environmental wind, the static pressures of every sector inlet are different. It leads to the flow rates being different, as well as the water temperature outlet.

4.2. The performance at different temperature

As showed in figure 6, the mass flow rate increases as the temperature decreases. Mainly because of the density decreasing, the air mass flow rate decreases. When the temperature is 5 ℃, mass flow rate is 42938.33 kg/s, when 38 ℃, it is 38695.04 kg/s, 4243.29 kg/s less than when it is 5 ℃, about 9.88%.

Corresponding to the air mass flow rate trend, the dissipating heat of air-cooled tower and outlet water temperature increase with the increasing of ambient temperature. When the temperature is 5 ℃, the dissipating heat of air-cooled tower is 769.99 MW and outlet temperature is 22.67 ℃. When the temperature is 38 ℃, the dissipating heat of air-cooled tower is 851.52 MW and outlet temperature is 58.72 ℃. The dissipating heat of air-cooled tower increase by 81.53 MW with temperature increasing by 36.05 ℃. The trends are showed as below figures 7 and 8.
The water temperature outlet is linear to the environmental temperature, which can be simply summarized as a law: $t_{\text{out}} = 1.092t_{\text{ambient}} + 17.20$ ($t_{\text{out}}$ means water temperature outlet, $t_{\text{ambient}}$ means the environmental temperature). The law acquired can be used when designing or operating an indirect air-cooled tower.

4.3. Typical flow fields
Figures 9 to 11 show parts of the flow field contours at different temperatures. As there are too many flow field graphics, several typical ones are listed when the temperature is $5^\circ\text{C}$, $25^\circ\text{C}$, $38^\circ\text{C}$. The formation of the temperature field and pressure field in the natural ventilation air-cooled tower is the result of the joint action of air pressure, viscous force and buoyancy force in the tower.
Figure 11. Temperature field contour at the temperature of 38°C.

By the influence of the external environmental wind, the air flow field at the cooling delta inlet on both sides of the air-cooled tower is distorted. And the static pressure distribution near the air inlet of the air-cooled radiator changes. In the windward region, the static pressure is the largest. The static pressure in the side wind region is the smallest. And the static pressure in the leeward region is between the windward surface region and the lateral wind surface region. As the temperature of the inlet air of the air-cooled tower changes, the lift of the flue gas in the tower receives different degrees of influence of the hot air in the tower.

From the temperature distribution counter, it shall be seen that the flue gas emitted from the exhaust device and the hot air in the empty tower have a clear distinction in the temperature distribution due to the flue gas temperature higher than the hot air inside the tower. As the ambient temperature changes, the distributions of flue gas in the tower and hot air temperature are similar. The flue gas is surrounded by a large amount of hot air and rises up to the outside of the tower, blocking the contact between the flue gas and the inner wall of the air cooling tower effectively. And it is more conducive to preventing the flue gas from corroding the inner wall surface of the upper air-cooled tower.

Comparing the field contour diagrams above, it can be concluded that, the flow traces of air are basically similar in a large range of temperature as well as the temperature distribution. Because of the temperature of flue gas taken away remaining constant, the air and flue gas is divided clearly by a temperature line. But the two flows always melt into a whole one at the exports of air-cooled towers.

5. Conclusions
This paper studies on a 2×600MW indirect air-cooled power plant and mathematical and geometric models are built. At the design environmental temperature and wind speed, the environmental temperature’s effect on the cooling system performance is simulated. The main conclusions we get are as below.

- When environmental temperature increases, the density of air decreases. But the volume flow rate basically remains constant, so the mass flow rate decreases.
- The upwind side outlet temperature is lower than the two flanks, and differences between each two neighbor fan sections remain a constant.
- The outlet temperature is linear to the environmental temperature, which can be simply summarized as: \( t_{\text{out}} = 1.092t_{\text{ambient}} + 17.20 \) (\( t_{\text{out}} \) means water temperature outlet, \( t_{\text{ambient}} \) means the environmental temperature).
- In a large range of temperature, the flow traces of air are basically similar, and so as the temperature distribution. Because of the temperature of flue gas taken away remains constant, the air and flue gas is divided clearly by a temperature line. But the two flows always melt into a whole one at the exports of air-cooled towers.
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