Study on energy-saving reconstruction plans for cold end system of direct air-cooling unit

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Abstract. Taking several recent successful technological transformation cases as technical reference, technical transformation plans are purposefully reviewed, pointing at questions at high temperature, for example, high back-pressure and high coal consumption for power generation. The peak cooling system distributes part of steam turbine exhaust and the air-cooling condenser thermal load reduces with the fixed cooling capacity of air cooling system. Or the capacity-increasing improves the cooling capacity with the fixed heat load of cold end system. The chosen of technical plan of direct air-cooling unit should be made on the base of its real situation.

1. Introduction

Air-cooling condenser is primary choice for power plant cooling in northern China for its excellent water-saving performance. The future of air-cooling technology is still promising, not only for water-scarce areas, but also for a significantly practical application in terms of reducing water consumption and promoting the sustainable use of water resources even in areas with abundant water resources. The installed capacity of power in China in 2017 reached 1.78 billion kilowatts, ranking first in the world. The related research shows that air-cooling system for power plant cooling can save water approximately 0.55 m³/s in a 1000 MW coal-fired generating unit compared to wet cooling system [1].

There are mainly three types of air-cooling system used in power plants: direct air-cooling condenser (ACC), surface condenser (SCALE system) and jet condenser (HELLER system). By reviewing the development of air-cooling technology in power plant, the conclusion can be drawn that the chosen of air-cooling system type is depended on material processing technology, manufacturing level, supporting auxiliary machine and technical economic analysis. Since the first domestic 300 MW subcritical direct air-cooling unit put into operation in Shanxi in September 2004, air-cooling technology develops rapidly in the direction of high parameters (subcritical, supercritical and ultra-supercritical), high capacity (300 MW, 350 MW, 600 MW, 1000 MW, 1100 MW) and localization.

The rich experience was gained by decades of on-site operating, and many obvious problems were exposed such as environmentally sensitive, hot air reflux, high back-pressure. The most serious problem is high back-pressure in summer, which leads to insufficient output and high coal consumption. Meanwhile, the air pollution is significantly serious in recent years, and this phenomenon is particularly serious in northern China in winter. So the energy-saving reconstruction shows imminent for coal-fired unit so as to decrease coal consumption.

Research institutes, test units, equipment manufacturers and power plants have been made a large
number of theoretical explorations and engineering practices, achieved satisfactory results and accumulated significant experience. The technical principles, effects, and applications of energy-saving reconstruction plans were summarized in this paper as a certain reference for improving the economic efficiency of air cooling units.

2. Technical principle

Taking the air-cooling condenser as heat exchanger, the correlation calculation equation as follows (DING 1992):

\[
    t_s = \frac{\Delta t_a}{1 - e^{-NTU}} + t_a + \delta t = \frac{D_0 \times (h_k - h_c)}{3600 \times A_w \times v_w \times \rho_a \times C_a} \times \frac{1}{1 - e^{-NTU}} + t_a + \delta t
\]

Where \( t_s \) is steam condensation temperature of ACC in °C, \( \Delta t_a \) is cooling air temperature rise of ACC in °C, \( 1 - e^{-NTU} \) show heat transfer efficiency of ACC, \( t_a \) is cooling air dry bulb temperature in °C, \( \delta t \) is temperature drop due to pipe line heat loss in °C, \( D_0 \) is the steam turbine exhaust volume in kg/s, \( h_k \) and \( h_c \) express turbine exhaust enthalpy and condensate enthalpy respectively in kJ/kg, \( A_w \) is the front wind area of ACC in m², \( v_w \) is the fin tube face velocity of cooling air in m/s, \( \rho_a \) is the average density of cooling air in kg/m³, \( C_a \) is the average specific heat capacity of cooling air in kJ/kg K.

Equation (1) indicates that the steam condensation temperature of ACC is the function of steam turbine exhaust volume \( D_0 \), front wind area of ACC \( A_w \), fin tube face velocity of cooling air \( v_w \), average heat transfer coefficient \( K \) and ambient air temperature \( t_a \). Therefore, changing influence parameters such as \( D_0 \), or \( A_w \), or \( v_w \), or \( t_a \) will impose change on steam condensation temperature (back-pressure).

\[
    p_C = f(D_0, G_a, t_a, K, A_w)
\]

Where \( p_C \) is back-pressure of air cooling unit in kPa, \( G_a \) is cooling air volume of ACC in m³/s, \( K \) is average heat transfer coefficient of ACC in W/m²·K.

The way to reduce the back pressure is to reduce the ambient temperature, reduce the thermal load of the air-cooling condenser, keep the air-cooled condenser clean, increase the overall heat transfer area of the air-cooling condenser, improve the overall heat transfer coefficient, and increase the air flow.

The air flow is influenced by the fan operating mode and ambient wind. The fan will turn into full-frequency mode in hot summer. Therefore, it is required to upgrade the fan, or to increase its rotational speed to get a higher flow rate. In most cases, these two methods are not practical: The introducing of a bigger fan is often impossible because of the space limitation in the current pipeline system; and the increasing of rotational speed always increases the noise and the strength risk of the fan together.

According to the principles of heat transfer, the thermal resistance of the air-cooling system consists of the condensation heat resistance in the tube bundle, the thermal resistance of the tube wall, the convection heat transfer resistance of air-side, and the thermal resistance of the fouling. The convective heat transfer resistance on the air side dominates the total thermal resistance, owning the greatest potential to change the total thermal resistance. The air-side convection heat transfer coefficient mainly depends on the air flow rate. As the fin tube face velocity of cooling air increases, the average heat transfer coefficient first increases and then tends to a fixed value, but the wind resistance increases linearly [2]. So the optimum value of face velocity is 2.1~2.3 m/s in engineering design. However, as described above, the fan in hot summer has also been operated at full frequency, and the air flow rate has reached a maximum and design condition. So there is no space for improving the average heat transfer coefficient.

Air-cooling condensers can be categorized into single-row, double-row and triple-row tubes, and the single-row pipe type gradually becomes dominate for its excellent flow heat transfer characteristics. In general, fin tube wall thickness is 1.5 mm and fin thickness is within 0.25~0.3 mm. With the decreasing wall thickness, the thermal resistance decreases, but the probability of wear and leakage of fin tube increases accordingly, leading to air leakage into cold end system and back pressure increase.
Therefore, thermal resistance in the tube bundle cannot be changed by physicochemical methods based on operating equipment operation and other reasons.

Therefore, the factors that can change the back pressure are thermal load, overall heat transfer area, and the degree of contamination on the outer surface of the tube bundle.

As the cold end of the coal-fired unit, the air-cooling system has two methods for improving performance and reducing energy consumption of the unit: 1) Building a peak cooling system for diverting the heat load of the original air-cooling system and reducing operating back pressure. 2) Expanding reconstruction of the original air-cooling system for improving cooling capacity.

3. Peak cooling technology
This technical solution can change the thermal load of the air-cooled system. Some steam turbine exhaust steam was import into the peak cooling condensation, therefore the heat load of the air-cooling system will decrease, as well as the back pressure of the steam turbine.

There are mainly two kinds of this peak cooler: wet condenser and evaporative cooler.

3.1. Wet condenser type
Direct air-cooling unit exhaust pipe was drilled and part of the exhaust steam bypassed to the wet condenser for condensation so as to reduce the heat-load of ACC. Then the operating back-pressure declines as well as the coal consumption under the fixed ambient air temperature, air cooler operation mode and unit load. The system schematic is shown in figure 1 [3-7].

![Figure 1. System schematic diagram for wet condenser [3-7].](image-url)

The wet condenser is a tube-bundle heat exchanger widely used in the wet-cooled unit, and the technology is extremely mature. Auxiliary systems mainly include vacuum system, condensate system, circulating water and circulating water cooling system, thermal control and electrical systems. The supporting equipment mainly includes circulating water pumps and cooling towers.

The table 1 shows the project performance of the wet condenser applied for energy saving retrofit of direct air cooling system.

| No. | Power Plant Name | Installed capacity | exhaust steam | Shunt ratio | location |
|-----|------------------|--------------------|--------------|------------|----------|

Table 1. Part of statistics of project performance of wet condenser.
3.2. **Evaporative cooler type**
Evaporative cooling technology combines traditional condensers and cooling towers into a simple system. According to the heat exchanger structure, it can be divided into tube bundle type and plate type.

| No. | Name     | Power | Efficiency | Location          |
|-----|----------|-------|------------|-------------------|
| 1   | TUO KE TUO | 2×600MW | 19%        | Inner Mongolia    |
| 2   | DA BA   | 2×600MW | 30%        | Ningxia Province  |
| 3   | HE JIN  | 2×300MW | 39%        | Shanxi Province   |
| 4   | YU SHE  | 2×300MW | 50%        | Shanxi Province   |
| 5   | PU ZHOU | 2×300MW | 39%        | Shanxi Province   |
| 6   | ZHANG SHAN | 2×300MW | 40%        | Shanxi Province   |
| 7   | WU XIANG | 2×600MW | 13%        | Shanxi Province   |
| 8   | YUN CHENG | 2×600MW | 13%        | Shanxi Province   |
| 9   | SHANG AN | 600MW   | 23%        | Hebei Province    |
| 10  | SHA HE  | 600MW   | 19%        | Hebei Province    |

**Figure 2.** Structure scheme of a plate evaporative condenser unit.
1 air deflector, 2 cold air inlet, 3 condensate outlet, 4 heat exchanger plate, 5 steam turbine exhaust inlet, 6 spray distribution device, 7 cold air inlet, 8 vacuum piping outlet, 9 hot air outlet, 10 water collector, 11 maintenance entrance, 12 spray water pipeline, 13 Electronic descaler, 14 PVC filler, 15 circulating pump

Taking plate evaporative cooler as an example, the principle of evaporative cooling technology is introduced as follows. As shown in figure 2, a typical plate evaporative condenser is composed of Axial fan, Plate condenser, Air convection cavity, Circulating basin, PVC filler, auxiliary pipes and
valves. The evaporative cooler combines wet condenser and cooling equipment of circulating water into a compact structure, which makes the total peak cooling system simpler and cheaper.

Spray water evenly distributed on the outer surface of the heat exchanger is the main heat carrier from the steam turbine exhaust to the external environment. The heat transfer effect mainly depends on spray density, film thickness, heat and mass transfer temperature difference, and surface cleanliness. According to influence parameters such as local environmental meteorological parameters, unit load rate, water quality, the optimization of the evaporative cooler is significantly important.

Compared to the conventional condenser (Coil evaporative condenser), plate evaporative condenser shows some obvious advantages are as follows: 1) Compacter structure and smaller size. This condenser combines plate heat exchanger, spray water circulating system and forced ventilation system together. The plate evaporative condenser dimensions are about 6 mx3 mx6 m (LxWxH) with cooling capacity of 7 t/h. 2) Higher heat transfer coefficient. Compared with the plane tube of coil evaporative condenser, uniform concave-convex spots distributed in plate surface disturb the flow film and strengthen heat transfer effect. 3) More convenient for online cleaning and maintenance. The significantly dense arrangement of the tube bundles in the coil evaporative condenser substantially reduces the overall effect of mechanical cleaning. Meanwhile, a relatively large space in plate evaporative condenser effectively guarantees the overall effect of mechanical cleaning, leading the long-term excellent performance. 4) Lower investment cost. The turbine exhaust inlet, inlet and outlet air are in the same direction, so the multiple devices can be arranged together side by side, and it can save the equipment area and costs. From the talk above, the plate evaporative condenser shows strong comprehensive comparative advantage with conventional condenser, as well as wide application prospect in the future.

The schematic diagram of the system of energy saving transformation of the plate evaporative cooler applied to the direct air cooling unit is shown in figure 3 [8-11].

![Figure 3. System schematic diagram for evaporative condenser [8,9].](image)

As shown in figure 3, part of turbine exhaust is distributed to plate evaporative condenser system and condensed to water, therefore heat load of ACC decreases and back pressure decreases accordingly. The condensate of plate evaporative condenser system flows into water tank firstly, and then to the hot well by self-gravity. Therefore, the auxiliary system contains steam distribution pipe, condensate system, vacuum pumping system, circulating and supplementary water system, instrument and control system, and electrical system.
The table 2 shows the project performance of the evaporative cooling technology applied for energy saving retrofit of direct air cooling system.

Table 2. Part of statistics of project performance of evaporative cooling technology.

| No. | Power Plant Name | Installed capacity | exhaust steam | Shunt ratio | location         |
|-----|------------------|--------------------|---------------|-------------|-----------------|
| 1   | YUAN YANG HU     | 2×600MW            | 24%/27%       | Ningxia Province |
| 2   | ZHANG SHAN       | 2×600MW            | 50%           | Shanxi Province |
| 3   | BAI CHENG        | 2×600MW            | 22%           | Jinlin Province |
| 4   | WAN JI           | 2×300MW            | 22%           | Henan Province  |
| 5   | DENG KOU         | 2×300MW            | 22%           | Inner Mongolia |
| 6   | HUO LIN HE       | 2×300MW            | 8%            | Inner Mongolia  |

3.3. Transformation effect
The figure 4 shows the characteristics of the change in the back pressure drop value with respect to the flow rate at the rated load and the design air temperature. The effect of the back-pressure drop is proportional to the ratio of the exhaust steam flow rate. The greater the diversion ratio, the more obvious the energy-saving effect, but the indicators such as investment, equipment occupation, and water consumption also increase simultaneously.

Figure 4. Characteristics of the change in the back pressure drop with ratio of exhaust.

4. Capacity increasing technology
This technical solution changes the total heat transfer area and cooling capacity of cold-end system.

In the process of domestic direct air-cooling technology development, the design margin of the overall heat transfer area of the air-cooled condenser was small based on factors such as design concepts and equipment investment at the time, which was insufficient to ensure the operating performance of the air-cooled system. As shown in figure 5, considering the site layout, ease of maintenance and overall appearance of the principle, the capacity increasing was carried out by extensive increasing air cooling units in the form of whole row or/and column based on the original air island. The type of new adding air-cooled condenser and air-cooling fan is the same as the original design. The height of new adding air-cooled condenser platform is the same as that of the original air-
cooling island. Therefore, the total heat transfer area and cooling capacity increase, the back-pressure reduces accordingly.

![Diagram](image)

**Figure 5.** System schematic diagram for capacity increasing technology.

The table 3 shows the project performance of the capacity increasing technology applied for energy saving retrofit of direct air cooling system.

The effect of the back-pressure drop is proportional to the ratio of increase rate of heat transfer area. At the rated load and the design air temperature of project performances listed in table 3, the back-pressure drop is 5 kPa, 5 kPa and 8.3 kPa respectively.

**Table 3.** Part of statistics of project performance of capacity increasing technology.

| No. | Power Plant Name | Installed capacity | Increase rate of heat transfer area | location |
|-----|------------------|--------------------|-------------------------------------|----------|
| 1   | ZHUN DA          | 300MW              | 17%(5/30)                           | Inner Mongolia |
| 2   | XIN FENG         | 300MW              | 17%(5/30)                           | Inner Mongolia |
| 3   | SHANG DU         | 600MW              | 24%(15/64)                          | Inner Mongolia |
| 4   | HUO LIN GUO LE(ing) | 300MW          | 26%(8/30)                           | Inner Mongolia |

**5. Comprehensive comparison**

Table 4 lists a comprehensive comparison of the three forms of technical solutions. Each of the three options has its own advantages and disadvantages, and its advantages and disadvantages may change with each other as technology advances. For example, water consumption is a significant disadvantage of peak cooling technology. But when heat exchangers use materials with high corrosion resistance such as titanium alloys, and municipal wastewater will be recycled as a supplement to the spike cooling system. From this perspective, water consumption has become an advantage of this technology.

**Table 4.** Comparison of the three forms of technical solutions.

| No. | Wet condenser | Evaporative cooler | Capacity increasing |
|-----|---------------|--------------------|---------------------|
|     | Water         | Water & air        | air                 |
|     | Need          | Not need           | Not need            |
|     | equipped with cooling |             |                     |
| Ancillary system composition | Steam distribution system, vacuum pumping system, condensate system, circulating water and make-up water system, circulating water cooling system, rubber ball cleaning system, thermal control and electrical system | Steam distribution system, vacuum pumping system, condensate system, water supply system, thermal control and electrical system | Steam distribution system, vacuum pumping system, air supply system, condensate system, spray system, thermal control and electrical system |
|-----------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| Ancillary system complexity  | Very complicated                                                                                | Simpler                                                                                         | Simpler                                                                                         |
| Equipment Area              | Smaller                                                                                          | Medium                                                                                         | Larger                                                                                         |
| Back-pressure drop target$^1$| 10kPa                                                                                           | 10kPa                                                                                          | 10kPa                                                                                          |
| Other energy consumption indicators | Circulating water flow 18000t/h, Water Consumption 530t/h, power consumption~1500kW | Water Consumption 280t/h, power consumption~1000kW, power consumption ~2300kW                  | Water Consumption 0t/h, power consumption ~0t/h, power consumption ~2300kW                     |
| Total investment             | Medium                                                                                          | Less Expensive                                                                                | More Expensive                                                                                |

Note: 1 Taking a certain 600MW subcritical direct air-cooled unit as a technical support, the back pressure drop of 10 kPa before and after the transformation of the TRL working condition is the objective function.

6. Conclusion

With the other fixed parameters, the peak cooling system bypasses part of exhaust steam entering into the air-cooling condenser and reduces the thermal load, as well as the operating back-pressure. The reduction of the operating back-pressure depends on the rate of the split-bypass flow.

With the other fixed parameters, the capacity increasing technology increases the total heat exchange area of the air-cooled condenser by increasing the number of air-cooled units, as well as the total cooling capacity. The reduction degree of back pressure before and after operation depends on the rate of the heat transfer area increase.

For the specific direct air-cooling system energy-saving transformation, it is recommended that the optimal reconstruction plan should be selected based on the unit load rate, the water resources situation, and the spatial location around the air cooling island.

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