Back pressure optimization of direct air-cooled condenser considering anti-freezing and low-load operation

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Abstract. Direct air-cooled condensers are widely applied in northwest China because of water-saving. In order to improve the economical operation of the direct air-cooled condenser, based on the mechanism model, this paper calculates the optimal back pressure considering anti-freezing and low-load operation with considering the switching state of the exhaust steam isolation valves, and ensuring the minimum exhaust steam. The influences of ambient temperature and load ratio on optimal back pressure and energy saving are studied, which provide guidance for cold-end optimization and economic operation of direct air cooled condensers.

1. Introduction

As China's renewable water resources account for only 6.5% of the world, direct air-cooled condenser have been widely applied in thermal power plants and concentrated solar power plants in northern China due to its excellent performance in water-saving[1].

The direct air condenser uses axial fans to drive the ambient air to heat exchange with the finned tube, at the cost of energy consumption accounting for 0.7-1.5% of the unit. The back pressure is a crucial parameter in the direct air-cooled unit, its setpoint value is directly related to power unit operation safety and economy. Increasing the fan frequency reduces the back pressure and increases the turbine output, at the cost of increasing the fans power consumption, which makes it an optimization problem. When the back pressure setpoint value is relatively high, the output power of the steam turbine is reduced, and the power generation efficiency of the unit is reduced. When the back pressure setpoint value is relatively low, the axial fan group consumes more power. In addition, the minimum temperature in winter in some area can be lower than -30℃, therefore, if the back pressure setpoint is unreasonable, it will cause the finned tube to freeze and damage the finned tube structure. Figure 1 shows the broken finned tube in Baicheng power plant, which is located in Jinlin Province. Therefore, it is important to set reasonable back pressure value under different ambient temperatures and unit loads.

Back pressure optimization has been studied by theoretical formula derivation[2], numerical simulation and artificial intelligence methods[3]. The common method for the optimal back pressure study of direct air-cooled condenser is to construct an objective function, which is the difference between the unit turbine power and air-cooled fans consumed power under a series of constraints[4]. When the difference is the maximum, the back pressure value is optimum. Zhang [5] proposed an optimal design method of direct air-cooled condenser based on minimizing the annual expenses and a 600 MW thermal power plant was used as an example to illustrate the application. Li [6] described a back pressure regulation problem based on grey difference incremental correlation method by
applying the computational fluid dynamics techniques, and gave examples of reductions in turbine back pressure by increasing the speed of fans with higher correlation degree. Li [7] established a data-driven model of direct air-cooled condenser with support vector regression based on reconciliation method and proposed a back pressure online optimization strategy. However, back pressure optimization articles seldom consider the anti-freezing requirements of air-cooled cells.

Figure 1. The broken finned tube

Most of the literatures proposed anti-freezing schemes from the perspective of the design of air-cooled condenser platform, tube type and fan frequency regulation[8]. From the application of direct air-cooled condensers, the feasibility of operating in severe cold and water-deficient areas has attracted attention. Hu introduced the application experience of direct air-cooled condenser of Wyodak power plant and explained the reliability of direct air-cooled condenser[9]. The freezing problem of finned tubes has an important relationship with the structure of finned tube, ambient temperature, exhaust steam flow rate, axial fan speed, number of finned tube bundles and other factors[10]. Guo [11] proposed an anti-freezing method that increase the setpoint of back pressure by 3 kPa when the ambient temperature is lower than a certain set value, which can effectively avoid the problem of freezing, but inevitably leads to the drop the output of turbine.

When the ambient temperature is low in winter, after stopping all the fans, the isolation valves valve on the steam distribution pipe can be closed to drop out part of the cooling cells and increase the heat load of other cells to prevent freezing. Thus, the anti-freezing constraint in this paper is to ensure the minimum exhaust flow into the air condenser, which is generally calculated in columns because there are isolation valves between the columns of the air condenser to separate the steam. As wind and solar power are fluctuant, intermittent, anti-peaking, coal-fired power plants play an important role to keep the power system stable. Therefore, in addition to the anti-freezing problem, the impact of low-load operation of the thermal power plant on the air-cooled condenser has also been concerned, especially the influence of low-load operation on the economics of unit under severe cold environments.

Back pressure optimization of direct air-cooled condenser considering anti-freezing and low-load operation is introduced in this paper. The innovation lies in taking the isolation valve switching states of exhaust steam into account, and adding anti-freezing constraint to achieve the safe and economic operation of the direct air condenser. This paper is organized as follows: In section 2, the mechanism model of air-cooled system is introduced. In section 3, the optimization considering anti-freezing is presented and solved by particle swarm optimization. In section 4, optimum back pressure calculation is carried out, and energy saving analysis is presented. Finally, the conclusions are drawn in Section 5.
2. Modelling

A 660MW direct air-cooled, thermal power plant located in northwest China is taken as the research object. The ACC is comprised of 64 air-cooled modules, containing 8 columns with 8 cells in each column. Note that the frequencies of all running fans are kept the same during operation.

2.1. Mechanism model of air-cooled system

The mechanism model of the air-cooled condenser is introduced in Ref.[4,12]:

\[
\frac{t_c}{t_{ex}} = (D a C_{pa} C_{trans})^{1/2} \frac{D a C_{pw}}{D a C_{trans}}
\]

\[
NTU = K A \times \left( D a C_{pa} N \right)^{1/2}
\]

\[
\varepsilon = 1 - e^{-NTU}
\]

\[
P_{back} = \left( \frac{t_c + 100}{57.66} \right)^{7.46} \times 0.0098
\]

Where \(t_c\) and \(h_c\) represent the temperature and enthalpy of condenser water; and \(h_{ex}\) are the mass flow rate and enthalpy of exhaust steam; \(t_{air,in}\) is the inlet air temperature; \(NTU\) is the number of transfer units; \(K\) and \(A\) indicate the total heat transfer coefficient and the total heat transfer area; \(D a\) is the fan cooling air mass flow rate; \(C_{pa}\) and \(C_{pw}\) are the specific heat capacity of air and condenser water; \(P_{back}\) is the condenser back pressure, commonly calculated by empirical equation; \(N\) is the number of columns of air-cooled cells in operation.

2.2. Fan mass flow rate

The fan mass flow rate is calculated from the fan operating point:

\[
D_a = n V_a \rho_a
\]

where \(n\) is the number of air-cooled cells, and \(n = 8N\); \(V_a\) is the single fan cooling air volume flow rate; \(\rho_a\) is the density of air.

The fan operating point at any rotational speed can be theoretically obtained through the intersection of fan characteristic curve and resistance curve:

\[
\Delta p_a = c_2 V_a^2 + c_1 \omega V_a + c_0 \omega^2
\]

where \(\Delta p\) is the fan pressure head; \(\omega\) is the fan frequency ratio; and \(c_0, c_1, c_2, c_3\) are constants, which are shown in table 1.

| Table 1. Coefficients of fan characteristic and resistance |
|-----------------|---------|---------|---------|
| c0              | 109     | 0.102   | -0.0005 | 0.00036 |

2.3. Mass flow rate and enthalpy of exhaust steam

Statistics show that the exhausted steam mass flow rate and enthalpy are in proportion to the turbine steam load ratio. Therefore, the exhausted steam flow and enthalpy can be obtained through polynomial fitting function with design parameters provided by turbine manufacturer, as shown in table 2.

| Table 2. Design parameters of heat balance diagram |
|----------------|---------|---------|---------|---------|
| Load ratio     | 40%     | 50%     | 60%     | 75%     |
| \(D_{ex}/(t/h)\) | 539.32  | 648     | 755.54  | 923.42  |
| \(h_{ex}/(kJ/kg)\) | 2503    | 2480    | 2462    | 2436.8  |
3. Optimization Considering Anti-freezing

3.1. Mass flow rate and enthalpy of exhaust steam

Increasing the fan frequency can reduce the back pressure and increase the turbine output, at the cost of increasing the fans power consumption, which makes it an optimization problem. When the difference between unit turbine power and air-cooled fans consumed power is maximum, the back pressure is optimum. The optimization objective function can be expressed:

$$\max \Delta N = N_t - N_f$$

where $\Delta N$ is the net power income; where $N_t$ is the turbine power; $N_f$ is the fan consumed power.

The objective function can be solved under four constraints. 1. The back pressure setting value needs to be between the blocking back pressure and the secure back pressure. 2. Exhaust flow must be greater than the minimum flow designed value. 3. When the axial fan works below 30% of rated power, with the decrease of the fan speed, the power will not change or even increase. Therefore, the axial fan needs to work above 30% of rated power. 4. The number of columns in operation of ACC should be between 1 and 8.

The constraints are as follows:

1) Back pressure constraint

$$P_{back,min} \leq P_{back} \leq P_{back,max}$$

2) Exhaust steam mass flow rate constraint

$$D_{ex} \geq D_{ex,min}$$

3) Fan frequency ratio constraint

$$0.3 \leq \omega \leq 1$$

4) Number of columns in operation

$$1 \leq N \leq 8$$

where $P_{back,min}$ and $P_{back,max}$ are block back pressure (7 kPa) and secure back pressure (30 kPa); $D_{ex,min}$ is the require minimum exhaust steam mass flow rate, which is also called anti-freezing exhaust steam flow rate.

Considering the anti-freezing and heat exchange efficiency, the air-cooled cells are put into operation in order from the middle to the two sides, so only the number of columns is optimized, rather than a specific column.

3.2. Influence of back pressure to turbine power

Back pressure has a significant influence on the power generation of steam turbines when the turbine is operating under variable conditions. The turbine power under the corresponding working conditions is calculated according to the relationship between turbine power relative deviation and condenser pressure, which is shown in figure 2. The turbine power is calculated as follows[12]:

$$\gamma = k \left( P_{back} - P_{back,0} \right)$$

$$k = f (\beta)$$

$$N_t = N_{t,0} \beta (1 + \gamma)$$

where $\gamma$ is the turbine power relative deviation, $k$ is the slope of back pressure-turbine power increment curve, $P_{back,0}$ is the rated back pressure, $N_{t,0}$ is the rated turbine power. And $\beta$ is the turbine steam load ratio. The relationship between $k$ and $\beta$ is obtain through polynomial fitting.

For the consumed power of fans, it depends on the fan frequency. Affinity laws are commonly used to solve it.

$$N_f = \omega^3 N_{f,0}$$

where $N_{f,0}$ is the rated fan consumed power.
3.3. Anti-freezing exhaust steam flow

The exhaust steam flow rate should be more than one certain value to prevent the condensate from freezing at a given ambient temperature and a fixed fan frequency ratio, which is defined as the anti-freezing exhaust steam flow rate\[13\].

\[
d_{\text{ex, min}} = d_{\text{ex}} \times N
\]  

where \( N \) is the number of columns in operation; \( d_{\text{ex}} \) is the required minimum exhaust steam mass flow rate of each column, which is obtained through polynomial fitting with design parameters, as shown in figure 3.

3.4. Optimization solution

With a combination of Eq. (7-11), the optimum back pressure can be calculated. The objective function described in Eq. (7) is a nonlinear equation. Intelligent algorithms particle swarm optimization (PSO) which was proposed by Eberhart and Kennedy[14], is adopt to solve this function. The algorithm flowchart is shown in figure 4.
4. Result and discussion

4.1. Optimum back pressure calculation

A 660MW direct air-cooled unit is considered in this paper. The heat transfer coefficient of air-cooled system is $39 \text{ W/} (\text{m}^2 \cdot \text{K})$. Total heat transfer area is $1266461 \text{ m}^2$. The rate back pressure is 10 kPa. The designed axial fan power is 132kW.

According to the objective function and constraints in Section 3.1, the optimum condenser pressure and corresponding optimum fan frequency ratio in certain operating conditions are obtained as demonstrated in Table 3. Also, the optimal numbers of column in operation are shown in Table 4.

| Optimum back pressure/kPa | Load ratio |
|---------------------------|------------|
|                           | 30%        | 40%        | 50%        | 60%        | 70%        | 80%        | 90%        | 100%       |
| Temperature/°C             |            |            |            |            |            |            |            |            |
| -30                        | 7.4(0.59)  | 7.0(0.56)  | 7.2(0.53)  | 7.0(0.62)  | 7.2(0.50)  | 7.0(0.49)  | 7.1(0.54)  | 7.1(0.59)  |
| -20                        | 7.1(0.49)  | 7.0(0.49)  | 7.4(0.48)  | 7.3(0.42)  | 7.1(0.48)  | 7.4(0.53)  | 7.2(0.59)  | 7.3(0.64)  |
| -10                        | 7.1(0.36)  | 7.0(0.45)  | 7.0(0.47)  | 7.2(0.54)  | 7.3(0.61)  | 7.1(0.69)  | 7.1(0.76)  | 7.1(0.83)  |
| 0                          | 7.3(0.39)  | 7.1(0.49)  | 7.0(0.59)  | 7.1(0.68)  | 7.2(0.77)  | 7.2(0.86)  | 7.1(0.95)  | 7.1(1)     |
| 10                         | 7.1(0.53)  | 7.1(0.66)  | 7.1(0.79)  | 7.0(0.92)  | 7.5(1)     | 8.9(1)     | 10.6(1)    | 12.4(1)    |
| 20                         | 7.3(0.78)  | 7.8(0.91)  | 8.6(1)     | 10.3(1)    | 12.2(1)    | 14.3(1)    | 16.7(1)    | 19.4(1)    |
| 30                         | 11.1(0.85) | 11.7(1)    | 13.9(1)    | 16.5(1)    | 19.3(1)    | 22.3(1)    | 25.8(1)    | 29.5(1)    |

It can be seen that the higher the ambient temperature, as well as the greater the load ratio, the more columns of fan are required, and the higher the fan frequency is needed. The optimal back pressure and optimal fan frequency ratio increase with the increase in ambient temperature and load ratio. When the ambient temperature is above 0°C, all of fans need to put into operation. Furthermore, when the load ratio is reached 70%, the fan frequency is reached 100%, and there is basically no room for optimization. When the load ratio is less than 70%, especially in lower load ratio such as 30%-40%,
optimum back pressure can be reached by adjusting fan frequency, which guaranteed efficient and economical operation of the unit under low load. The net power income curves with load ratios of 30% and 100% are separately shown in figure 5.

When the ambient temperature is below 0°C, optimum back pressure can be reached by adjusting fan frequency and columns of fan. The optimum number of columns reduce with the decrease of temperature and load ratio. However, in reality, only 1 or 2 columns can be close, so, when the ambient temperature is extremely low, the operators should pay attention to avoid the low load conditions, and the optimal back pressure is not significant.

| Number of column | Load ratio |
|------------------|------------|
| Temperature/°C   | 30% 40% 50% 60% 70% 80% 90% |
| -30              | 3  4  5  6  7  7  8 |
| -20              | 5  5  8  8  8  8  8 |
| -10              | 7  7  8  8  8  8  8 |
| 0                | 8  8  8  8  8  8  8 |

Table 4: Optimal number of column in operation

Figure 5. Relationship between minimum exhaust steam mass flow rate of each column and temperature

4.2. Energy saving analysis

It is obvious that when the fan frequency ratio is too low, there is not enough heat transfer capacity cooling exhaust steam, so the high back pressure can cause a decrease in net power income. On the contrary, when the fan frequency is too high, high power consumption of axial fan group can also cause a decrease in net power income. Otherwise, the reduction of ambient temperature can directly enhance the heat transfer capacity of ACC, thus reducing the energy consumption of axial fan group. The fan frequency and columns of fan are two significant parameters in back pressure optimization.

The increment of net power income represents the net power that is increased by back pressure optimization at the same coal consumption, which is illustrated in figure 6, where the temperature above zero is shown in figure 6 (a) and the temperature below zero is shown in figure 6 (b).

In figure 6 (a), the increment of net power income increases first and then decreases as the load ratio increases, and decreases as the ambient temperature increases. The maximum increment of net power income also means maximum coal consumption saving, which decreases as the ambient temperature increases, and corresponding load ratio decreases as well. A net power increment less than zero indicates an increase in coal consumption, which is not shown in the figure.
In figure 6 (b), the increment of net power income has the same trend when the load ratio is higher than 60%. When the load ratio is lower than 60%, the increment of net power income increases as the ambient temperature increases, because the number of air-cooled columns in operation is reduced in low ambient temperature.

Figure 6. The increment of net power income in different fan load ratio and ambient temperature

5. Conclusion
With the introduction of back pressure optimization of direct air-cooled condenser considering anti-freezing and low-load operation, following conclusions are drawn in this paper:

1) The optimal back pressure, the corresponding optimal speed and the switch state of isolation valve under various temperature and load conditions are given, and the energy saving is quantitatively analyzed.

2) It is reasonable to consider closing partial isolation valves when the ambient temperature is below 0°C, which is conducive to improving the safety and economy of air-cooled condenser.

3) It has energy-saving potential at low-load operation. In the case of severe cold and low-load operation, considering closing part of isolation valves can increase the net power increment of the unit.

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