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Thermal Power Plants Hybrid Heat Supply Technology for Low-Temperature Heat Source Enhancement Economic Analysis

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Abstract. To solve the defects of insufficient heating capacity and high energy cost in the traditional heating mode of the thermal power plant, two 300 MW pumped-condensing air-cooled heating units are retrofitted by adopting a high backpressure operation mode and utilizing the low-temperature heat source quality-improving hybrid heating technology. It is found that when the load is 210 MW and the operating back pressure is 45 kPa and 54 kPa after the retrofit, the consumption of standard coal for every 1 GJ of heat is 8.19 kg and 9.76 kg, which is 16.81 kg and 15.24 kg less than that of the traditional heat supply method. When the load is 250 MW and the operating back pressure is 45 kPa, the consumption of standard coal is 8.65 kg per GJ of heat supplied, which is 16.35 kg less than that of the traditional heating method. The ROI of the retrofit is 49.01%, with a payback period of about 2.04 years, after which it can bring an annual profit of 24.5504 million RMB per year to the power plant. It can reduce the emission of soot by 152.17 t, carbon dioxide by 82.17 t, sulfur dioxide by 258.68 t, and nitrogen oxides by 225.20 t per year. Therefore, this transformation is a green and efficient, energy-saving, and environmentally friendly technology with high economic returns and good prospects, providing a way of thinking about the new heating technology of the power plant.

Keywords: low-temperature heat source; hybrid heating; coal consumption rate; heat consumption rate; economic analysis

1. Introduction

The continuous development of efficient, clean, and flexible power generation technology is the key development direction of the power industry [1~2]. The problem of heat loss in thermal power plants has attracted widespread attention, and the search for a transformation program that can effectively reduce heat loss has become an urgent problem for thermal power plants.

At present, the common heat supply transformation of power plants mainly includes low-pressure cylinder resection technology, high and low-pressure bypass transformation, heat storage electric boiler heat supply technology, and low-temperature heat source to improve the quality of hybrid heat supply transformation. Low-pressure cylinder excision technology refers to the excision of part of the low-pressure cylinder before the final low-pressure cylinder of the high-temperature and high-pressure turbine, which only transmits the torque generated by the high-pressure cylinder, realizing the zero-output of the system, which has a strong peak-adjusting capability and is generally used for heating of a larger area. However, the rotor needs to be replaced in the heating season and non-heating season, which greatly increases the operation difficulty [3~6]; the high and low-pressure bypass steam external heat supply technology adopts the way of extracting steam for heat supply and steam bypass, and this technology can meet the requirements of stable combustion and denitrification of the unit at low loads, just as the back-pressure heat supply modification technology. However, the loss of this technology is relatively large, the overall efficiency is low, the peak depth is limited to have a throttling loss, coal consumption increases and is not suitable for large area heating [7~9], and thermal storage electric boiler heating in the actual peak load is consumed by its boiler, the power into the grid can be reduced to almost zero and is not subject to boiler and other equipment operation. However, the biggest problem is that the initial investment in the system is too high. In addition, the thermal storage system also produces a large footprint, and this technology converts high-grade to low-grade for heating, which is bound to have the problem of inefficient application of high-grade energy [10].

The unit described in this paper adopts the low-temperature heat source quality improvement hybrid heating technology. Increasing the operating back pressure of the unit increases the steam exhaust temperature of the turbine so that this part of the exhaust steam is directly used to heat the circulating water of the heat network, which is called the primary heating process. The heated water flows into the first heating station and will continue to absorb heat to get warm, which is called the second heating process. The high-temperature water after the two heating processes enters the heat exchange area for heat exchange and heating and finally cools down and enters the condenser for heating, repeating the above process to form a circulating heating loop. This method can effectively utilize the steam turbine exhaust waste heat, reduce the cold source loss of the unit's waste heat utilization to zero, and significantly improve the unit's circulating thermal efficiency. At the same time, it can increase the unit's heating capacity and heating area without increasing the unit size. Through thermodynamic analysis of the system, the operating parameters of the unit after modification are obtained, and conclusions are drawn by comparing them with the parameters of the unit before modification, and an economic evaluation is made.

2. System description

2.1. Project profile

The project is based on a power plant in the north. The plant is equipped with two 300 MW pumped condensing air-cooled units. Equipped with two 1164 t/h sub-critical parameters of pulverized coal boilers, a total heating area of 10.23 million square meters, heat load of 665 MW, the plant is responsible for providing a city centralized heating heat required. From the local heating company in the city, it is understood that the existing centralized heating area in the city is 20 million square meters. At present, there are still about 10 million square meters of users are still using decentralized self-heating. The scale of heating needs to be expanded, the new city plan gives the city's centralized heating area is expected to reach 40 million square meters.

2.2. Turbine design parameters

The No. 2 turbine of the power plant is a subcritical, intermediate reheat, single-shaft, two-cylinder, two-displacement, direct air-cooled (/back-pressure heating) type turbine. The design parameters of the turbine are provided by the design specification of the steam engine plant, as shown in Table 1:

The main steam, reheat steam, and main feedwater systems are unitary. The unit is equipped with two auxiliary-type steam header boxes, high and low, inside the unit. A secondary tandem electric bypass system of 30% capacity with a three-stage desuperheater is used. The system is based on a seven-stage extractor-return system with three low-pressure heaters, three high-pressure heaters, and a deaerator. The three high-pressure heaters are supplied with steam from the first to third stage extraction, while the fifth to seventh stage extraction feeds the three low-pressure heaters. Among them, the heat network heating steam source and the low-pressure auxiliary steam source are provided by the fifth stage of steam extraction.

Table 1. Turbine design parameters in detail

Project name	Parameter	
Turbine Model	NZK300/263-16.7/0.054/537/537 (combined cylinder)	
Turbine type	Subcritical, intermediate reheat, single-shaft, double-cylinder, double-discharge vapor, direct air-cooled (/back-pressure heating) type	
Rated main steam flow rate	944.56/t-h-1	
Main Steam Pressure	16.6/MPa	
Main Steam Temperature	537/° C	
Hot reheat steam temperature	537/° C	
reheat system	3 high-fill, 1 deaerator, 3 low-fill	
Rated working speed	3000/r-min-1	
	pre-conversion	after conversion
Generator power (heating)	300.00/MW	263.39/MW
Rated back pressure	15/kPa	54/kPa
Number of low-pressure cylinder stages (symmetrical)	2× 5	2× 3

2.3. Technical principles

The low-temperature heat source to improve the quality of hybrid heating technology is different from the low back pressure under the traditional heating method, as shown in Figure 1. The heat network circulating water is used as exhaust cooling water during the heating period, and the work mass is passed through the low-temperature heat source heater to recover the waste heat. The circulating water of the heat network is heated by the low-temperature heat source heater and then transported to the high-temperature heat source heater, and then heated by the high-temperature work mass steam of the medium-pressure cylinder, and finally, the circulating water of the heat network is heated to the appropriate temperature and then transported to the residents or enterprises. During the heating period, if the hot water supply temperature requirement is less than 69 °C, only the spent steam heating circulating water can meet the heating demand. If the water supply temperature is greater than 69 °C during the peak heating period, the five-stage steam extracted from the medium-pressure cylinder is used for peak heating, and the water supply temperature required for heating is reached after secondary heating.

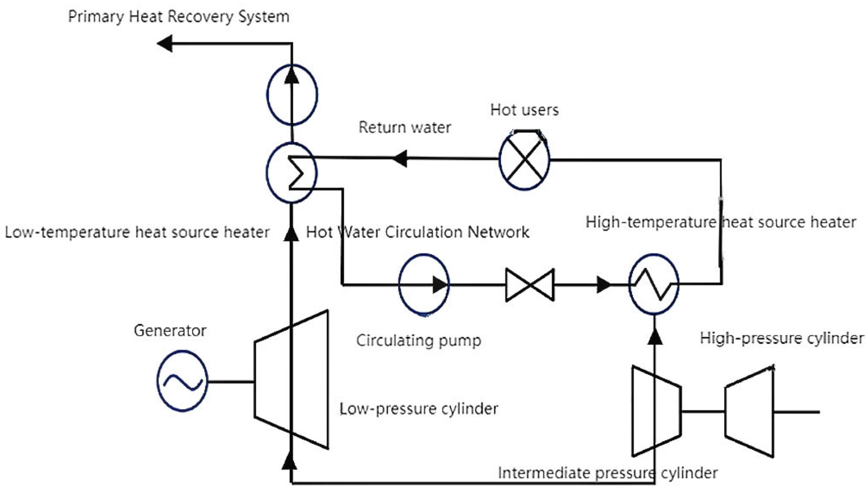

Figure 1. Low-temperature heat source to improve the quality of the hybrid heating system diagram

The low-temperature heat source quality-enhancing hybrid heating technology greatly reduces the energy waste caused by the traditional heating method, realizes the mixed use of low-level and high-level energy of the work-quality steam, reduces the steam parameter of the heating, reduces the emission, and improves the efficiency. In addition, low-temperature heat sources to improve the quality of hybrid heating technology after the transformation of the system can also be all the absorption of heat loss of cold sources, turning waste into treasure, the waste heat of the mass of work into heat energy can be utilized to improve the heating capacity of the system, a substantial reduction in the consumption of the unit to reduce energy consumption.

To realize the above low-temperature heat source quality-enhancing hybrid heating renovation, it is necessary to increase the operating back pressure of the thermal power unit to about 30 kPa during the heating period. The main objective of this retrofit is to convert the condenser into a low-temperature heat source heater with flexible switching operation to meet the demand for low-pressure industrial circulating water in summer and high-pressure heat network circulating water in winter. It was also necessary to modify the new low-pressure cylinder rotor to enable it to operate under summer and winter backpressure. In addition, the condenser circulating water piping switching system and the heat network circulating water system need to be modified, and additional equipment such as heat network circulating water pumps need to be installed.

2.4. Operating methods

When it is in the heating period, the circulating water from the heat network is used as the exhaust cooling water of the unit. Firstly, it enters the low-temperature heat source heater converted from the condenser of the big machine, and is heated by the spent steam of the big machine and the exhaust steam of the small machine as the basic heating, and then is heated by the peak heating of the middle exhaust steam, and then the temperature of the water is upgraded to that required by the external network heating and then is supplied to the outside world. At the beginning and end of the heating period, when the circulating water supply temperature of the heat network is below 65 ℃, the water can be heated only by the spent steam exhaust heat and directly supplied to the heat users through the bypass pipeline. In the cold period of heat supply, it needs to be heated by the spent steam first and then by the medium-pressure cylinder exhaust steam peak before it can be supplied to the heat users. When the unit is in a non-heating period, the unit is restored to pure condensing operation mode, the heat network circulating water system is shut down, and the condenser cooling water is switched back to the original circulating cooling water system [11].

2.5. Modification of core equipment

2.5.1. Turbine modification

Before the low-temperature heat source quality improvement and hybrid heating renovation, the large turbine and the small turbine shared a common condenser. During the heating period, the back pressure of the unit will increase after operation, and the exhaust pressure of the small turbine will increase accordingly. During the non-heating period, the unit operates with lower back pressure and exhaust pressure. To ensure the safe operation of the unit, it is necessary to modify the rotor and partition of the small turbine so that it can simultaneously meet the demand for back pressure operation in different heating periods.

2.5.2. Low-voltage rrotor modification

A low-pressure rotor was redesigned to produce a low-pressure rotor that would allow it to meet both summer and winter back pressure operating ranges [12]. The low-pressure cylinder rotor does not need to be replaced during the summer and winter months, converting the counter wheel connection to a hydraulic bolt.

2.5.3. Condenser modification

Since the turbine in the unit has been operating under high backpressure conditions, the exhaust gas temperature is relatively high, which can adversely affect the stability of the condenser, the shaft components, and the medium and low-pressure cylinders. Therefore, it is necessary to make certain modifications to the brackets and interfaces of the condenser itself, to adapt to problems such as changes in condenser expansion due to temperature changes [13]. During the heating period, the cooling water in the condenser of the unit will be replaced by the circulating water of the heat network, and the condenser pressure and heat transfer temperature will be increased, which has higher requirements for the temperature and pressure resistance of the condenser material. The condenser itself is reformed by reforming the tube sheet and tube bundle, thickening the shell, etc. However, the tube sheet and tube bundle are thickened. However, the total heat transfer coefficient of the condenser will be decreased after the tube plate and tube bundle are thickened, the heat exchange area will be increased, and the arrangement form of the tube plate and tube bundle will be changed accordingly.

3. Methodology

3.1. Exergy

Thermodynamic energy is the thermodynamic system interacting with the environment, the highest share of energy that can be converted into useful work is called the energy of that energy, also known as usable energy, as shown in equation (1).

$$e_x = (h - h_0) - T_0(s - s_0) \tag{1}$$

In the equation: e_x- exergy, kJ/kg; h - specific enthalpy, kJ/kg; h0 - specific enthalpy at ambient temperature, kJ/kg; T0 - ambient temperature, K; s - specific entropy of kJ/(kg • K); s0 - specific entropy at ambient temperature, kJ/(kg • K).

3.2. Main steam flow

The formula of the main steam flow is shown in Equation (2).

$$F_s = F_f - F_b - F_u' \tag{2}$$

In the equation: Fs - main steam flow rate, kg/h; Ff - total system flow rate, kg/h; Fb - boiler-side leakage, kg/h; F_u'- unknown boiler-side leakage flow rate, kg/h[14].

3.3. Coal consumption rate

To make rational use of energy, thermal power plants have been established, and the main economic indicators for thermal power plants should be the standard coal consumption for power supply and the standard coal consumption for heating[15].

The amount of coal consumed in power generation:

$$B_d = B(1 - \alpha) \tag{3}$$

Heating coal consumption:

$$B_r = \alpha B \tag{4}$$

In the equation: Bd - coal consumption for power generation, t; Br - coal consumption for heat supply, t; B - total coal consumption, t; α - heat supply ratio.

3.4. Heat consumption rate

The heat consumption rate is a metric used to measure energy utilization efficiency. It describes the relationship between the energy consumed during energy conversion or utilization processes and the generated effective heat. Heat consumption rate holds significant importance in energy management and industrial production. By evaluating and monitoring the heat consumption rate, one can identify energy wastage and improvement potential, thereby enhancing energy utilization efficiency and reducing energy consumption.

Heat Consumption Rate:

$$\eta_t = \frac{(F_s - F_{sh}) \times (H_s - H_f) + F_{cr}(H_r - H_{cr})}{P_w} + \frac{F_{rh}(H_r - H_{rh}) + F_{sh}(H_s - H_{sh}) - Q}{P_w} \quad (5)$$

The symbols are described in Table 2:

Tab. 2 Explanation of the symbols of the heat consumption rate formula

Notation	Instructions
Fsh	Superheated desuperheated water flow rate/kg • h-1
Fcr	Cold reheated steam flow rate/kg • h-1
Frh	Reheat desuperheating water flow rate/kg • h-1
Hf	Main feed water enthalpy/kJ • kg-1
Hrh	Enthalpy of reheated desuperheated water/kJ • kg-1
Hsh	Enthalpy of superheated desuperheated water/kJ • kg-1
Q	Total unit heat supply/kg • h-1
Pw	Total unit power consumption/kW

4. Results and discussion

4.1. Performance comparison analysis

4.1.1. Comparison of data

The heat balance diagram in the specification provided by the steam engine plant and the data calculated by the above formula are shown in Table 3.

Table 3 Parameters of the unit before and after modification

	pre-conversion		After the transformation of low-temperature heat source and mixed heating technology		
Load/MW	210	250	210	210	250
Back pressure/kPa	10	10	45	54	45
Main steam flow rate/t • h-1			708.76	720.60	828.17
Medium pressure cylinder efficiency/%			90.23	90.15	90.15
High-pressure cylinder efficiency/%			76.15	77.40	79.11
Coal consumption rate g/(kW • h)			204.69	211.69	237.26
Heat consumption rate kJ/(kW • h)	8384.35	8274.78	3702.68	3743.54	3731.25

4.1.2. Analysis of comparative results

(1) When the unit operates with a load of 210 MW and a back pressure of 45 kPa, the useful energy consumed is 13.17%. Among the heating heat, useful energy accounts for 9.24% of the total heat supply. Calculating 319 g/(kW·h) as the coal consumption of a pure condensing unit for power generation, it can be obtained that the standard coal consumption per 1 GJ of heat supplied is 8.19 kg.

(2) When the unit operates with a load of 210 MW and a back pressure of 54 kPa, the useful energy consumed is 16.02%. Among the heating heat, the useful energy accounts for 11.02% of the total heat supply. Calculating 319 g/(kW·h) as the coal consumption of a pure condensing unit for power generation, it can be found that the amount of standard coal consumed per 1 GJ of heat is 9.76 kg.

(3) When the unit operates with a load of 250 MW and a back pressure of 45 kPa, the useful energy consumed is 13.16%. Among the heating heat, useful energy accounts for 9.67% of the total heat supply. Calculating 315 g/(kW·h) as the coal consumption of a pure condensing unit for power generation, it can be found that the amount of standard coal consumed per 1 GJ of heat is 8.65 kg.

Traditional extraction steam heating mainly uses holes in the connection pipe of the medium-pressure cylinder exhaust steam to extract steam and then sends it to the heater to heat the circulating water of the heating network [16]. A certain unit is undergoing heating transformation based on steam extraction. The parameters of the pressure cylinder exhaust steam are as follows: pressure 0.80 MPa, temperature 333.40 ℃, and enthalpy 3127.20 kJ/kg. The enthalpy value of the exhaust steam of the pure condensing unit is 2488.90 kJ/kg, and the heat that can be supplied by 1kg of extraction steam is 2625 kJ/kg. During this process, the useful energy lost due to heat supply is 638.30 kJ/kg, and the useful energy in heat supply accounts for 24.30% of the total heat supply. The calculation is based on the coal consumption of pure condensing unit power generation being 320 g/(kW·h), which is equivalent to consuming 21.61 kg of standard coal for every 1 GJ of heat supplied. Taking into account the throttling loss and the reduction in the efficiency of the low-pressure cylinder caused by extracting the exhaust steam from the medium-pressure cylinder for heat supply, approximately 25 kg of standard coal is consumed for every 1 GJ of heat supplied by using the middle-pressure exhaust steam for co-heating.

Compared with the traditional heating method, if the heat input of the modified steam turbine is the same, the power generation capacity and heating capacity of the modified unit will be improved to a certain extent. After the low-temperature heat source upgrading mixed heating transformation, although the coal consumption rate will increase as the back pressure increases, the unit's exhaust steam is used to replace the medium-pressure cylinder exhaust outlet extraction steam for heat supply, and the unit's cold source heat loss can be fully recovered, reducing the heat loss of the cold source to zero. With low-temperature heat sources and mixed heating, the power generation and heating capabilities of the unit are significantly enhanced, and coal consumption is significantly reduced. The power plant may transform into a cogeneration enterprise.

4.2. Economic analysis

4.2.1. Heating coal savings

It is calculated based on the coal consumption rate of the 250 MW~0.045 MPa unit reduced from 25 kg/GJ to 8.65 kg/GJ after the transformation. According to the data of the steam turbine plant, the annual heat supply of the unit is calculated as 1,191,626 GJ, so the transformation will save the power plant a total of approximately 19,483 tons of coal per year due to heat supply.

4.2.2. Coal savings in power generation

After the unit transformation, the coal consumption rate of the unit for power generation dropped from 320 g/(kW·h) to 315 g/(kW·h). Then based on the 250 MW working condition for a year, the total amount of coal saved due to power generation in a year is about 10,950 tons.

4.2.3. Economic cost of annual coal savings

The total amount of coal saved in one year is the sum of 3,043 tons of coal saved for heating and power generation. To calculate the specific economic cost of 30,433 tons of coal, the Bohai Rim thermal coal prices published by CCTD (China Coal Price Index) are collected as shown in Figure 2. It can be seen from the figure that as of the first half of 2023, the average price of thermal coal in the Bohai Rim is around 806.70 yuan/ton, so the cost savings of purchasing coal after unit modification is approximately 24.5504 million yuan.

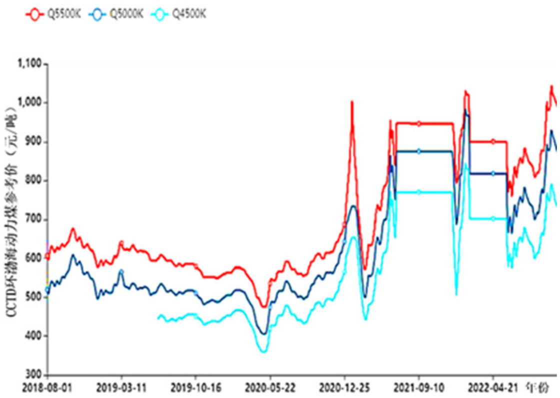

Figure 2. CCTD Bohai Rim Power Coal Reference Price Trend

4.2.4. Return on investment (ROI)

Return on investment refers to the value that should be returned through investment. It is an indicator of the profitability and effectiveness of an investment [17]. The formula is shown in Equation (6).

$$\mathrm{ROI} = \frac{\text{annual profit}}{\text{total investment}} \times 100\% \tag{6}$$

It has been calculated that the annual profit that the unit modification can bring is 24.5504 million yuan. The estimated cost of unit modification is 50 million yuan, and the return on investment for this modification is 49.10%.

Capital recovery cycle

The capital recovery cycle is the time required for the profit to reach the investment cost. The capital recovery cycle of this transformation can be calculated as 2.04 years. That is to say, it is expected that the cost can be recovered in 2.04 years after the transformation is completed, and thereafter it will bring a profit of 24.5504 million yuan to the power plant every year, with a return on investment of 49.10%. The current general return on capital is around 20%, so the return is relatively high [18].

4.2.5. Pollutant reductions

This transformation has saved the power plant 30,433 tons of coal every year. According to surveys, every 1 ton of coal burned in a power plant will produce 5 kg of soot, 2.70 kg of carbon dioxide, 8.50 kg of sulfur dioxide, and 7.40 kg of nitrogen oxides. Calculated according to this standard, this technological transformation can reduce annual pollutant emissions. The calculation results are shown in Table 4.

It can reduce 152.17t of smoke, 82.17t of carbon dioxide, 258.68t of sulfur dioxide, and 225.20t of nitrogen oxide every year, reducing a large amount of greenhouse gas emissions and improving air quality. Therefore, this low-temperature heat source high-quality mixed heating transformation plays a very positive role in reducing pollution and emissions and responding to the national green, environmentally friendly, and efficient development strategy.

Table 4 Emission reductions by pollutant

Name of pollutant	Emission reduction/t
soot	152.17
carbon dioxide CO2	82.17
sulfur dioxide SO2	258.68
nitrogen oxide	225.20

5. Conclusions

The power generation and heating capabilities of the unit are significantly enhanced and the coal consumption is significantly reduced under the low-temperature heat source-enhanced mixed heating, which is of great significance in improving energy utilization.

(1) After the transformation, when the load is 210 MW and the operating back pressure is 45 kPa and 54 kPa, the useful energy consumed is 13.17% and 16.02% respectively, and the useful energy in heating heat accounts for 9.24% and 11.02% of the total heat supply. Calculated based on the coal consumption of pure condensing unit power generation being 319 g/(kW·h), it is equivalent to consuming 8.19 kg and 9.76 kg of standard coal per 1 GJ of heat supply, which is a reduction of 16.81 kg and 15.24 kg of standard coal compared with traditional heating methods. consumption. When the load is 250 MW and the operating back pressure is 45 kPa, the effective energy consumed is 13.16%, and the effective energy in heating heat accounts for 9.67% of the total heat supply. Calculated based on the coal consumption of pure condensing unit power generation being 315 g/(kW·h), which is equivalent to 8.65 kg of standard coal consumed for every 1 GJ of heat supplied. Compared with the traditional heating method, the consumption of standard coal is reduced by 16.35 kg.

(2) The return on investment of the transformation is 49.01%, and the capital recovery cycle is about 2.04 years. After that, it can bring an annual profit of 24.5504 million yuan to the power plant, and the return on investment is relatively high.

(3) Low-temperature heat source mixed heating technology can bring certain environmental benefits. It can reduce approximately 152.17 t of soot emissions, 82.17 t of carbon dioxide, 258.68 t of sulfur dioxide, and 225.20 t of nitrogen oxides every year, responding to the green development strategy under the national carbon neutrality goal.

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