Research on Improving Flexibility of Thermal Power Units by Flue Gas-water Heat Exchanger

Fuxing Cui *, Xuhui Zhang
Shandong Electric Power Research Institute, Jinan 250002, China

*Corresponding author e-mail: 666cfx@sina.com

Abstract. The proportion of renewable energy in the power supply structure of Shandong power grid is increasing day by day. Thermal power units inevitably face deep-peak shaving and frequent-peak shaving. The problem of thermal power contradiction is prominent when thermal power units are heating in winter, which has a negative impact on the security and stability of power grid and the consumption of renewable energy. Traditional thermoelectric decoupling technology has some problems such as narrow load adjustment range and poor overall energy utilization efficiency. A scheme of adding flue gas-water heat exchanger is proposed to supplement the traditional IP cylinder extraction technology for heating. According to the calculation, the minimum electric power of flue gas heating mode is significantly lower than that of traditional heating mode under small heating demand, and the maximum and minimum electric power of hybrid heating mode are better than that of traditional heating mode under the same heating demand, and the maximum heating capacity under the mixed heating mode is significantly increased, which can improve the operation flexibility of the unit and enhance the thermoelectric decoupling ability of the unit.

1. Introduction
By the end of 2020, the total installed capacity of Shandong power grid is 130 million kilowatts, including 68.75 million kilowatts of coal-fired thermal power, 17.94 million kilowatts of wind power, 8.15 million kilowatts of centralized photovoltaic, 14.58 million kilowatts of distributed photovoltaic, and new energy installed capacity increased by 37% year on year. Moreover, with several UHV lines officially put into operation, the proportion of external power to Shandong is increasing. The planning goal of Shandong power grid is that the proportion of traditional thermal power, new energy and UHV external power to Shandong will reach 1:1:1, so that the traditional thermal power units will face the situation that the available hours of units will continue to decline for a long time With the development of Shandong power auxiliary service market and the improvement of spot market [1], the existing direct regulation thermal power units actively carry out technical transformation to cope with the more complex situation in the future [2].

Thermal power units account for more than 76% of the direct dispatching thermal power units in Shandong Province. At present, thermal power units implement the operation mode of "determining electricity by heat", which gives priority to the people's livelihood heating, followed by power generation. Due to the strong thermoelectric coupling of heating units, the load space of power grid dispatching adjustment units is seriously limited in winter, especially in heating peak period [3]. Some
units, such as high back pressure units, basically have no peak shaving capacity, which not only brings
great hidden danger to power grid security, but also reduces the load of new energy grid due to the
excessive thermal power load. As a result, the new energy consumption capacity of power grid is
reduced, so the flexible transformation of thermal power units is particularly important.

The flexibility transformation of thermal power unit is mainly to reduce the degree of thermal power
coupling, so that the heating and power supply of the unit can be carried out separately as far as possible.
At present, the main methods include heat storage technology, low-pressure cylinder removal
technology, low-pressure cylinder optical axis technology, etc. [4]. The heat storage technology can be
divided into electric boiler heat storage, heat storage tank, etc. Although the electric boiler can reduce
the power transmission outside the grid (on the premise of using the auxiliary power of the plant), it can
make the unit carry greater heat load under smaller electric load, but the heat storage source comes from
high-grade electric energy, and the overall energy utilization efficiency of the unit is poor [5]. Low
pressure cylinder cutting technology and low pressure cylinder optical axis technology may replace or
remove the blades of low pressure cylinder, resulting in the decrease of unit power capacity [6]. The
heat source of the heat storage tank generally comes from the exhaust steam of the intermediate pressure
cylinder. The temperature of the cold water in the tank is increased by the heat storage tank heat
exchanger. After the heat is stored, part or all of the heating load will be replaced during the severe
thermoelectric conflict period. After the heat load of the unit is reduced, the electric load adjustment
space will be expanded to achieve the purpose of thermal electrolytic coupling. Due to the limitation of
boiler stable combustion, the extraction steam flow and other parameters are not up to standard, which
affects the heat storage efficiency and quality.

In this paper, a design scheme is adopted to add a flue gas-water heat exchanger in the circulating
water circuit of the heat supply network to improve the overall flexibility of heating and power supply
of the unit, alleviate the thermoelectric contradiction of the thermal power unit in winter, and effectively
use the heat of low-grade flue gas.

2. Design scheme and operation mode

2.1. Design scheme
The heating design scheme of adding flue gas heat storage device is shown in Figure 1. In the figure: 1-
the furnace; 2- flue gas-water heat exchanger; 3- the heating station; 4- high temperature flue gas outlet
baffle; 5-s the outlet baffle of low temperature flue gas; 6- the outlet valve of circulating water of heat
supply network after heat absorption by flue gas-water heat exchanger, and the downstream is the heat
station; 7- the outlet valve of circulating water in heat supply network after heat absorption by flue gas-
water heat exchanger, and the downstream is the user of heat supply network; 8- the valve to control the
circulating water of heat supply network to enter the flue gas-water heat exchanger; 9- the valve to
to control the circulating water of heat supply network to enter the heating station.

Figure 1. Design scheme
2.2. Operation mode
There are four operation modes for heating and power supply of thermal power unit after adding flue gas-water heat exchanger.

2.2.1. Short circuit mode of flue gas-water heat exchanger. No.9 valve is fully open and other valves are closed. After heating up, the circulating water of heat supply network flows through the heat supply network users from the heat supply station 3 to release heat, and the low-temperature water enters the heat supply station through the heat supply pipeline and valve 9 to absorb heat. This is the current conventional heating operation mode of thermal power plant, which is suitable for the situation that the demand of heat load and power grid dispatching are not tight, such as the initial stage and final stage of heating, when the heating demand is large, it generally can not meet the requirements of dispatching power load.

2.2.2. Short circuit mode of thermal power station. The No.4 and No.5 baffles on the flue gas side are opened, and the high-temperature flue gas and low-temperature flue gas are mixed to form medium temperature flue gas, which enters into the flue gas-water heat exchanger for heat release and then discharged into the tail flue of the original boiler. The flow ratio of high-temperature and low-temperature flue gas is adjusted according to the opening of No.4 and No.5 baffle plates, and the flue gas temperature entering the flue gas-water heat exchanger can be adjusted according to the heating demand; No. 6 and No. 9 valves on the water side are fully closed, No. 7 and No. 8 valves are fully opened, and the low-temperature circulating water from the heat supply network enters the flue gas-water heat exchanger through No. 8 valve to absorb heat and rise to the qualified parameters, and then flows to the heat supply network users through No. 7 valve. Due to the short circuit of the heating station, there is no need to extract steam from the intermediate pressure cylinder. This part of steam can participate in the work, which is suitable for the situation of high power generation demand and general heat load demand of the power grid, such as high load at the initial stage of heating.

2.2.3. Series mode of heat exchanger and heating station. The low temperature circulating water of heat supply network first flows through the flue gas-water heat exchanger, then flows through the heating station, and then is sent to the users of heat supply network. The No.4 and No.5 flue gas baffles on the flue gas side are opened, and the mixed flue gas enters the flue gas-water heat exchanger for heat release; No. 6 and No. 8 valves are fully open, No. 7 and No. 9 valves are fully closed, which is suitable for the situation of high demand of heating load and electric load, such as high load in the middle heating period.

2.2.4. Parallel mode of heat exchanger and heating station. One part of the low-temperature circulating water in the heat network is absorbed by the flue gas-water heat exchanger, the other part of the low-temperature circulating water of the heat network absorbs heat through the thermal station, and the two parts join together to enter the heating network for heating. At this time, No. 4 and No. 5 flue gas baffle on the flue gas side are opened; the valve 7, 8 and 9 are fully open and valve 6 is fully closed, which is suitable for the high demand of heat load and electric load, such as high load in the middle of heating.

3. Analysis of thermoelectric characteristics after installation
The "thermoelectric characteristics" of thermal power unit refers to the correlation and coupling relationship between the generating power P and the extraction steam quantity G for external heating. When the extraction capacity of external heating is Gx, the generating power Px should meet the constraint of equation (1), where P\text{\textsubscript{x,max}}, P\text{\textsubscript{x,min}} respectively represent the maximum and minimum power of the unit under the current extraction capacity, that is, the unit output range that can be dispatched by the provincial control center. With the change of external heating demand, Gx will change, and the maximum power P\text{\textsubscript{x,max}} and minimum power P\text{\textsubscript{x,min}} of the unit will also change. By connecting the corresponding
\( P_{x,\text{max}}, P_{x,\text{min}} \) under different G\(_x\) into a line, the thermoelectric characteristic curve of the unit can be obtained, and the safe operation points of the thermoelectric unit are distributed in the closed area surrounded by the characteristic curve.

\[
P_{x,\text{min}} \leq P_x \leq P_{x,\text{max}}
\]  

(1)

### 3.1. Short circuit mode of flue gas-water heat exchanger

This condition belongs to the operation condition of conventional thermal power unit, as shown in Figure 2. In a 330MW thermal power unit, the minimum steam intake of LP cylinder is 140t/h, the maximum steam extraction is 400t/h, the load range is [233MW, 263MW], and the load range without heating is [165MW, 346MW]. The AB line is the constraint line of extraction steam quantity and electric power under the maximum main steam flow, as shown in equation (2); BC line is the electric power constraint line under the maximum extraction capacity; CD line is the constraint line of extraction steam volume and electric power under the minimum steam intake of LP cylinder, as shown in equation (3); The de line is the constraint line of extraction steam quantity and electric power under the minimum main steam flow, and the slope is consistent with ab line, see equation (4); EA line is the constraint line of electric power when the extraction steam quantity is 0, D point is the working point of the unit when the minimum inlet steam quantity of the low pressure cylinder is guaranteed under the minimum main steam flow, and the operation state of the thermal power unit is in the closed section ABCDE.

AB Line:  
\[
y = -0.2075x + 346
\]  

(2)

CD Line:  
\[
y = 0.18x - 14.2
\]  

(3)

DE Line:  
\[
y = -0.2075x + 165
\]  

(4)

![Figure 2. Thermoelectric characteristic curve of typical thermal power unit (330MW)](image)

### 3.2. Short circuit mode of thermal power station

The external heating is provided by adding a flue gas-water heat exchanger. At this time, the thermal station is short circuited, and the exhaust steam of the medium pressure cylinder enters the low pressure cylinder for work. The horizontal coordinate in Figure 2 changes to the extraction flue gas flow. For comparison, it is assumed that the heat exchange efficiency of the flue gas-water heat exchanger and the heat exchanger in the thermal station is consistent, and the exhaust gas flow is converted into the steam extraction quantity according to the principle of equivalent heat, as shown in formula 5.

\[
M_g (h_{g1} - h_{g2}) = M_w (h_{w1} - h_{w2}) = M_{cw} (h_{cw2} - h_{cw1})
\]  

(5)

Where: \( M_g, M_w \) and \( M_{cw} \) are the mass flow rates of flue gas, intermediate exhaust steam and circulating water of heat supply network, kg/h respectively; \( h_{g1}, h_{w1} \) and \( h_{cw1} \) are the inlet enthalpies of
flue gas, intermediate exhaust steam and circulating water of heat exchanger, respectively, kJ/kg; \( H_{g2} \), \( H_{s2} \) and \( h_{cw2} \) are the outlet enthalpies of flue gas, intermediate exhaust steam and circulating water of heat exchanger, respectively, kJ/kg.

The relevant calculation is shown in Table 1. The general heat supply network adopts quality regulation, and the overall heat supply is adjusted by changing the inlet water temperature to keep the water flow unchanged. Assuming that the extraction parameters remain unchanged, the inlet parameters are 0.5MPa and 330°C; the exhaust parameters are 55°C saturated water; the high temperature flue gas comes from the bottom of the furnace at 1000°C. In order to avoid excessive extraction of high-temperature flue gas leading to the deterioration of furnace heat transfer, some low-temperature flue gas is extracted at 350°C from SCR inlet of tail flue. In order to avoid corrosion caused by too low exhaust gas temperature, the exhaust gas temperature is 110°C. When the steam extraction capacity is 400t/h, the high-temperature flue gas flow is 1170t/h, which is close to the design maximum flow of 1524t/h. Considering the safety factor, the working state can not be achieved in practice. The calculation is only for the need of comparison. Considering that the adiabatic combustion temperature of coal is close to 2000°C, about 1/3 of full load is converted, and the load is about 232MW.

In Table 1, the flue gas heat under equivalent 100t/h steam extraction capacity accounts for about 10% of the total input heat of the boiler under full load. The pulverizing system of the unit is designed according to "five operation and one standby". When six coal mills are fully opened, the input heat is increased by 10%. It can be considered that the load under equivalent 100t/h steam extraction capacity can be maintained at full load under short circuit mode of thermal station. Excessive extraction of flue gas will lead to the imbalance of radiation heat transfer and convection heat transfer. Considering that different boilers can bear different amount of flue gas extraction, the actual operating point can be determined by field test. It is agreed that 50% of the flue gas amount under equal load is the maximum extractable flue gas amount, which is the actual maximum extraction operating point. The steam extraction capacity corresponding to 50% of full load flue gas volume is 286t/h, and the load is about 285MW, that is, point B (286t/h, 285MW). Therefore, the load is fixed as a point B, that is, B and C coincide.

Since the steam turbine is no longer involved in steam extraction, the original limited factors such as the minimum steam intake of low pressure cylinder and the intermediate exhaust pressure are easy to meet, and the boiler stable combustion \([7]\) and hydrodynamic circulation \([8]\) become the limited factors. Generally, the 35% BMCR minimum stable combustion test can be completed when the new coal-fired boiler is put into operation, and the conservative value of 40% rated load is taken as the minimum load, that is, point e becomes (0,132MW), and the flue gas volume is about 620t/h. When the equivalent steam extraction capacity is 100t/h, the high temperature flue gas extraction capacity is 290t/h. at this time, the electric load is about 101MW, accounting for 30.6% of the rated capacity. For once through boiler, it is close to the upper limit of dry wet state conversion (26% ~ 28%), that is, point D becomes (100t/h, 101MW). Connect the CD line as the maximum smoke limit line. As shown in Figure 3.

### Table 1. Calculation summary of flue gas volume at equivalent extraction volume

| extractionsteam flow (t/h) | extractionsteam Enthalpy(kJ/kg) | extraction steam drainage enthalpy (kJ/kg) | high emperat-ure flue gas temperature (°C) | high temper-ature flue gas flow (t/h) | low tempera-ture flue gas temperature (°C) | low temperat-ure flue gas flow (t/h) |
|---------------------------|----------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| 0                         | 3126.6                           |                                          |                                          |                                          |                                          |                                          |
| 30                        | 3126.6                           | 230.6                                    | 1000                                     | 0                                       | 350                                      | 0                                       |
| 60                        | 3126.6                           | 230.6                                    | 1000                                     | 68                                      | 350                                      | 80                                      |
| 100                       | 3126.6                           | 230.6                                    | 1000                                     | 118                                     | 350                                      | 230                                     |
| 300                       | 3126.6                           | 230.6                                    | 1000                                     | 210                                     | 350                                      | 332                                     |
| 400                       | 3126.6                           | 230.6                                    | 1000                                     | 879                                     | 350                                      | 0                                       |
3.3. **Series mode and parallel mode**

In the series mode, the flue gas-water heat exchanger and the heating station can distribute freely according to different heat proportion to ensure the output of qualified circulating water; In parallel mode, the inlet water flow of the flue gas-water heat exchanger and the heating station can be adjusted freely according to different valve opening to ensure the output of qualified circulating water. The basic thermodynamic characteristic curves of the two are similar.

**Figure 3.** Thermoelectric characteristic curve of unit in short circuit mode of thermal power station

**Figure 4.** Thermoelectric characteristic curve of unit in series mode

Taking the series mode as an example, the planning objective is to seek the boundary of maximum heat supply, maximum load and minimum load. Comprehensive analysis shows that the maximum load of 346MW can be maintained when pure flue gas is used for heating when 0 ~ 100t/h steam extraction; When the working point of the steam turbine is (400t/h, 263MW) under the limit heating condition, the heat supply can still be shared by the flue gas for 100t/h, and the overall working point of the unit is (500t/h, 263MW); When the working point of the boiler is (286t/h, 285MW) under the limit heating condition, the pure condensing 285MW can be converted into the maximum heating capacity of the steam turbine 362t/h according to the equal main steam flow line and the minimum steam inlet line of the low pressure cylinder in Fig. 2. At this time, the load becomes 210MW and the overall working point of the unit becomes (648t/h, 210MW). When the load of de line in Figure 3 is too low, the steam turbine
can only operate in pure condensing state, and it is still the minimum load line in series mode, as shown in Figure 4.

4. Data analysis

4.1. Analysis of maximum heat supply
As shown in Figure 5. Under the three heating modes, the maximum heating capacity of flue gas is 286t/h, followed by the traditional heating station, and the maximum heating capacity can reach 648t/h under the mixed heating mode. This is because this mode makes full use of the heat of flue gas and steam within the boiler and steam turbine limitations, and effectively improves the heating capacity.

![Figure 5. Comparison of maximum heat supply](image)

4.2. Analysis of maximum adjustable power
At lower heating load, the maximum adjustable power of flue gas heating mode and hybrid heating mode are both higher than the live load capacity of traditional heating station mode, but the flue gas heating is limited by the total amount of extractable flue gas, and the heating capacity is lower than that of traditional heating mode; The hybrid heating mode takes into account the advantages of both sides. The maximum electric power in the range of 400t/h steam extraction is 21MW higher than that of the traditional heating mode, and it can still operate stably after exceeding the designed maximum heating capacity of 400t/h. The maximum working point is (648t/h, 210MW), as shown in Figure 6.

![Figure 6. Maximum electric power under different modes with equal heat supply](image)
4.3. Analysis of minimum adjustable power

Under the existing operation mode of "electricity determined by heat", the smaller the minimum output of the unit is, the stronger the grid absorbs renewable energy. The comparison of minimum output under different modes is shown in Figure 7. It can be seen that when the heating load is not too high, the minimum output of flue gas heating mode and mixed heating mode is significantly lower than that of traditional heating station, which is due to the different limiting factors of low load. The low load of boiler side mainly considers the factor of stable combustion, and the extraction of flue gas heating means that the heat input into the boiler is more than that required for actual power generation, and the effect of stable combustion is enhanced; The low load on the turbine side mainly considers the intermediate discharge pressure, which may lead to the failure of steam extraction. Therefore, the minimum output of the traditional heating mode will not be too low. However, with the increase of heating demand, stable combustion is no longer the main limiting factor on the boiler side.

With the increase of flue gas extraction, the ratio of radiant heat and convective heat is easy to be out of balance, causing safety problems. The low load line on the boiler side rises obviously, and the minimum output at about 140t/h will be higher than the heating mode of the heating station under the same heating amount. The hybrid heating mode has both advantages, except that the minimum output of small section (about 220t/h) is higher than that of heat station heating mode, most of the heating sections are the lowest.

Figure 7. Minimum electric power under different modes with equal heat supply

4.4. Peak regulation interval analysis

Figure 8. Peak regulation interval under different modes with equal heat supply
The comparison of peak shaving intervals under different heating modes is shown in Figure 8. It can be seen that the peak shaving range of the hybrid heating mode is higher than the other two modes under any heating capacity. The flue gas heating mode is limited by the total amount of extractable flue gas, and the low load line increases rapidly, resulting in the peak shaving range shrinking rapidly when the heating demand is large. The peak shaving capacity is the worst under the conventional medium and high heating load, but the peak shaving performance is better than that of the heating station mode under the small heating capacity.

5. Conclusion
This paper proposes a heating mode with flue gas-water heat exchanger, and analyzes the overall thermoelectric characteristics of the unit under different heating modes, and compares the data from the dimensions of maximum electric power and minimum electric power under the same heating capacity.

(1) The minimum electric power of flue gas heating mode decreases significantly under small heating demand, and the minimum electric power of hybrid heating mode is significantly lower than that of traditional heating mode in the whole heating range, which effectively improves the ability of power grid to absorb renewable energy, and promotes the profitability of units under the "two rules" mode of power market.

(2) Under the same heating demand, the maximum electric power of the hybrid heating mode can be 21MW higher than that of the traditional heating mode, which is suitable for the scene of less new energy generation and more heat load demand in winter evening.

(3) The maximum heating capacity of hybrid heating mode is significantly higher than that of traditional heating station.

(4) The hybrid heating mode can significantly improve the flexibility of the unit and enhance the thermoelectric decoupling ability.

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