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An Efficient Method for Heat Recovery Process and Temperature Optimization

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Abstract: Flue gas heat loss accounts for a significant component of the overall heat loss for coal-fired boilers in power plants. The flue gas absorbs more heat as the exhaust gas temperature rises, which reduces boiler efficiency and raises coal consumption. Additionally, if the exhaust gas temperature is too high, a lot of water must be used to cool the flue gas for the wet flue gas desulfurization system to function well, which has an impact on the power plant's ability to operate profitably. It is consequently vital to take steps to lower exhaust gas temperatures in order to increase boiler efficiency and decrease the amount of coal and water used. Desulfurization performance may be enhanced and water use can be decreased by reasonable flue gas characteristics at the entry. This study analyzed the unit's energy consumption, investment, and coal savings while proposing four coupling strategies for regulating flue gas temperature and waste heat recovery. A graded flue gas conditioning and waste heat recovery plan was presented under the condition of ensuring high desulfurization efficiency, along with the notion of minimizing energy loss owing to energy inflow temperature difference. Numerical results show that the proposed methods improved the system performance and reduced the water consumption and regulated the boiler temperature.

1 Introduction

The limestone-gypsum wet desulfurization process has high desulfurization efficiency, and is the dominant desulfurization technology for large-capacity desulfurization units, accounting for about 85% worldwide [1–4]. The desulfurization process is also a high-energy-consuming system in thermal power plants. Its total power consumption accounts for 1%~1.6% of the power generation of the whole plant, and the water consumption is about 0.12~0.2 kg/(kW.h) [2]. At present, the flue gas temperature at the inlet of the desulfurization system is generally between 120 and 140°C [3–9], which has a large potential for waste heat recovery. In addition, the high temperature inlet flue gas is not conducive to the progress of SO_2 absorption reaction in the desulfurization tower [10–13], and the water in the limestone slurry in the desulfurization tower evaporates a lot [14]. Therefore, reducing the flue gas temperature at the inlet of the desulfurization tower can improve the desulfurization performance of the desulfurization system and achieve energy saving and consumption reduction [15–21].

Combining the inlet flue gas temperature adjustment with the waste heat recovery of flue gas is the way to maximize the economic benefits [22]. At present, an effective way to utilize the waste heat of flue gas is to add a heating surface in the flue before the desulfurization system, and use the recovered waste heat to heat the feed water of the unit, preheat the cold air, dry the pulverized coal, or use it for cooling and heating [23]. The 1000 MW unit [24] adopted a separate flue system to fully reduce the exhaust gas temperature, installed a low-temperature economizer in the bypass flue of the air preheater, and introduced part of the flue gas to heat the boiler feed water, which improved the unit's efficiency. The Black Pump Power Plant [25] installed a low-temperature economizer after the electrostatic precipitator, and used the waste heat of the flue gas to heat the condensate instead of the No. 3 low-pressure heater. The efficiency of the unit was increased by 0.5 percentage points [26]. Using the waste heat of the flue gas to preheat the air entering the unit can increase the temperature of the cold primary and secondary air entering the air preheater, which is beneficial to the stable combustion in the boiler and improves the efficiency of the boiler [27]. Reference [28] conducted a numerical simulation on the synergistic dust removal performance of the desulfurization tower. The results showed that when the flue gas temperature at the inlet of the desulfurization tower decreased to 85°C, the removal efficiency of the particles in the flue gas of the desulfurization tower changed very little. The waste heat recovery of flue gas has no obvious effect on the synergistic dust removal performance of the desulfurization tower. The power station in [29] adopted the design idea of flue gas heating air. The flue gas temperature at the inlet of the desulfurization tower was reduced from 150°C to 90°C, and the recovered heat was brought into the boiler air heater to increase the boiler inlet air temperature from 25°C to 64°C. Reference [30] used the equivalent enthalpy drop method to conduct thermal analysis on the low-pressure economizer, and proposed the energy counterpart of waste heat utilization, the theory of cascade utilization. The low-temperature economizer was arranged after the induced draft fan and before the desulfurization absorption tower [31], which reduced the flue gas temperature from 125°C to 85°C, and the coal consumption for power supply of the unit decreased by 2.71 g/(kW.h). There are many related studies abroad [32–35].

When combining the flue gas temperature adjustment at the inlet of the desulfurization tower and the optimization of the desulfurization process, the waste heat recovery of the flue gas will involve different flue gas temperature adjustment methods and different waste heat recovery methods. Different temperature adjustment methods and waste heat recovery methods will have varying degrees of influence on the total energy consumption of the desulfurization system, the desulfurization cost, the comprehensive power consumption cost, and the thermal economy of the whole plant [36].

The purpose of this paper is to use different process schemes to adjust the flue gas temperature at the inlet of the desulfurization tower, and to use different schemes for waste heat recovery accordingly. The calculation model of system energy consumption and coal saving is established, and the economic analysis of the proposed desulfurization process is carried out, and the optimal process scheme is obtained by comparison, so as to explore the system with the optimal thermal economy under the condition of ensuring the high-efficiency operation of the desulfurization tower. Scheme to improve the thermal economy of the entire unit.

2 Energy and Coal Consumption Models

2.1 Desulfurization System Parameters

This paper takes the wet desulfurization system of a 660 MW coal-fired unit in my country as the research object, and the operating parameters are shown in Table 1. The unit is equipped with 1 boiler and 1 boiler. The boiler is a 660 MW balanced ventilation with supercritical parameters, and the model is SG-2017/25-YM. The steam turbine is a supercritical, primary intermediate reheat steam turbine produced by Steam Turbine Plant. There are eight stages of extraction steam in the unit. The first three stages of extraction steam are respectively used for three high feeders, the last 4 stages of extraction steam are respectively used for four sets of low feeders, and the fourth stage extraction steam is used as the steam source of the deaerator. The layout of desulfurization system 1 furnace with 1 tower, a booster fan is correspondingly equipped in front of the desulfurization tower, the power plant cancels the configuration of GGH, and installs a conventional low-pressure flue gas cooler to reduce the flue gas temperature at the inlet of the desulfurization tower.

Table 1: Operating parameters

Parameter	Value
Inlet flue gas volume (standard state)	2072415.9 m³/h
Inlet actual flue gas volume	3185015.3 m³/h
Number of layers/layers of spray operation	4
Spray volume per layer	9201 m³/h
Original inlet flue gas temperature	135°C
Liquid to gas ratio	13.32

The acid dew point of the flue gas at the tail of the unit is 74°C. In order to ensure that the flue gas temperature at the inlet of the desulfurization tower is as low as possible and higher than the acid dew point temperature of the flue gas, it is recommended to adjust the flue gas temperature at the inlet of the desulfurization tower to 85°C, which can also ensure a high temperature desulfurization efficiency.

2.2 Auxiliary Engine Energy Consumption Calculation

After installing the flue gas heat exchanger, the energy consumption of the system will change in two aspects. First, the addition of heat exchangers will cause changes in the resistance of the water side and the flue gas side, resulting in changes in the energy consumption of condensate pumps and booster fans. Second, when the process system is changed, some energy-consuming equipment such as fans and water pumps will be added accordingly, which will also significantly affect the total energy consumption of the system.

2.2.1 Booster Fan Energy Consumption

The pressure increase of the booster fan is determined according to the increase of flue resistance during the working process. For the desulfurization system after scheme optimization, adding a heat exchanger in the flue will increase the resistance of flue gas flow and increase the energy consumption of the booster fan. The increase in resistance is Δp (Pa), and the increase in energy consumption of the booster fan is N_{f1}, calculated as follows [37]:

$$N_{f1} = \frac{q_v p}{\eta_f} = \frac{Q_g \Delta p}{\eta_f \times 3.6 \times 10^6} \tag{1}$$

In the formula: η_f is the efficiency of the booster fan; Q_g is the gas flow, m³/h. The energy consumption of the newly added fans in the system scheme is calculated with reference to Eq. (1).

2.2.2 Condensate Pump Energy Consumption

After absorbing heat from the flue gas side, the resistance on the gas removal side will increase, as will the resistance on the water side, which is overcome by the condensate pump. The condensate pump energy consumption [38]:

$$N_w = \frac{\Delta P_w q_w}{3600 \eta_w} \tag{2}$$

where: ΔP_w is the increased resistance on the water side, Pa; q_w is the feed water flow through the flue gas heat exchanger in m³/h; η_w is the efficiency of the condensate pump. The energy consumption of the newly added water pump in the system can be calculated according to Eq. (3):

$$N_h = \frac{\rho g H_h q_L}{3600 \eta_h} \tag{3}$$

where: ρ is the water density; H_h is the total head in m; q_L is the water flow in m³/h and η_h is the efficiency of the pump.

2.3 Unit Coal Consumption Calculation

2.3.1 Boiler Efficiency Model

Boiler exhaust gas temperature is a direct feedback leading to exhaust heat loss, which affects boiler efficiency. The higher the exhaust gas temperature, the greater the heat loss. The expression for boiler efficiency through boiler back balance is:

$$\begin{cases} \eta = [1 - (q_2 + q_3 + q_4 + q_5 + q_6)] \times 100\% \\ q_2 = \frac{(k_1 \alpha + k_2)(T_{py} - T_f)}{100} \end{cases} \tag{4}$$

where: η is boiler efficiency; q_2 is exhaust heat loss; $q_3 \sim q_6$ are other heat loss items of the boiler; k_1, k_2 are the coefficients of coal type; T_{py} is the exhaust gas temperature; T_f is the supply air temperature. When the exhaust gas temperature drops by 20°C, the boiler efficiency can be increased by 1%.

Then the boiler efficiency is calculated by positive balance as:

$$\eta = \frac{q \times 100\%}{7000 \times 4.18 \times b} \tag{5}$$

$$b_n = b(1 - \varepsilon_{ap}) \tag{6}$$

In the formula: q is the heat generated by the boiler; b_n is the standard coal consumption for power supply, the unit is 362 g/(kW.h); b is the standard coal consumption for power generation; ε_{ap} is the power consumption rate of the plant. The standard coal consumption savings of boiler power supply can be obtained through conversion.

2.3.2 Equivalent Enthalpy Drop Method

Based on the principle of the equivalent enthalpy drop method, the waste heat of the flue gas is input into the steam turbine regenerative system as pure heat, and the work amount of the steam turbine extraction steam displaced by this part of pure heat is calculated, that is, the increase in the work done by 1 kg of steam in the steam turbine is calculated. A lot to discuss its thermal economy. The general formula for the equivalent enthalpy drop of the heater is [39]:

$$H_j = \left(h_j - h_c\right) - \sum_{r=1}^{j-1} \frac{A_r}{q_r} H_r \tag{7}$$

where: h_j is the extraction steam specific enthalpy of the j-th stage heater in kJ/kg; h_c is the specific enthalpy of steam turbine exhaust in kJ/kg; H_r is the extraction steam equivalent enthalpy drop of the r-th stage heater in kJ/kg; q_r is the extraction heat of the r-th stage heater in kJ/kg; A_r is the water exotherm γ_r or the heater enthalpy τ_r.

In order to facilitate the calculation of the thermal system, the regenerative heater's steam release heat, feed water enthalpy and drainage heat release are represented by q_j, γ_j, τ_j respectively [40].

$$\begin{cases} q_j = h_j - h_j^{'} \\ \gamma_j = h_{j-1}^{'} - h_j \\ \tau_j = h_{wj} - h_{wj-1} \end{cases} \tag{8}$$

In the formula: h_j is the specific enthalpy of the j-th stage extraction steam in kJ/kg; $h_j^{'}$ is the hydrophobicity specific enthalpy of the j-th level heater in kJ/kg; h_{wj} is the specific enthalpy of the effluent water of the j-th level heater in kJ/kg; h_{wj-1} is the specific enthalpy of the influent water of the j-level heater in kJ/kg.

$$\eta_j = \frac{H_j}{q_j} \tag{9}$$

where η_j is the extraction efficiency of the regenerative heaters at all levels.

The equivalent enthalpy drop increment is expressed as:

$$\Delta H = \Delta q \eta_j \tag{10}$$

The heat recovery from flue gas is expressed as:

$$\Delta q = G_y G_{py} \eta_y \left(t_{en} - t_{ex}\right) \tag{11}$$

In the formula: G_y is the flue gas flow in kg/s; G_{py} is the average specific heat capacity of the flue gas in kJ/(kg $^{\circ}$C); η_y is the heating efficiency of the smoke cooler; t_{en} and t_{ex} are the flue gas temperature at the inlet and outlet of the flue cooler in $^{\circ}$C.

The turbine power increment is expressed as:

$$\Delta P_i = \Delta q \eta_j \tag{12}$$

The coal saving of waste heat recovery is expressed as:

$$b_1^P = \Delta P_i b_n / W \tag{13}$$

In the formula: ΔP_i is the energy consumption increment of the system in kW and W is the unit load in kW.

During waste heat recovery, the heat is recovered to the unit's regenerative system to squeeze out a part of the extraction steam, which will increase the cooling source loss of the steam turbine and reduce the thermal efficiency of the unit. However, after the waste heat of flue gas is recovered, the increase of power generation is realized, which is based on the constant fuel quantity of the unit, so the total thermal economy is increased [41].

3 System Models and Analysis

Four system schemes are proposed, respectively using cold air and main condensate to adjust the flue gas temperature at the inlet of the desulfurization tower, and recovering the waste heat to the boiler air preheater and the unit's regenerative system, which ultimately improves the unit economy. At the same time, the plan also considers the heating of the net flue gas at the outlet to reduce the "white plume" phenomenon around the power plant.

3.1 Scheme A

System model (Scheme) A (Fig. 1) proposes a single-stage air temperature control and air preheater coupling scheme. A first-stage gas-gas heat exchanger is installed at the entrance of the desulfurization tower, and the temperature of the flue gas at the entrance of the desulfurization tower is adjusted by using low-temperature air. A part of the heated air is directly passed into the flue of the desulfurization tower outlet, and mixed with the low-temperature clean flue gas at the outlet to produce the exhaust gas temperature of the chimney, effectively increase the elevation of the flue gas, and avoid the phenomenon of white plume. Another part of the heated hot air is passed into the boiler air preheater, and part of the waste heat is recovered to the boiler system to improve boiler efficiency and realize waste heat recovery.
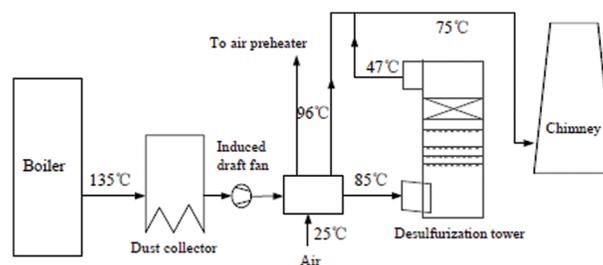
Figure 1: Illustration of system model A

This scheme adopts low-temperature air for heat exchange. Compared with the original GGH net flue gas heat exchange, on the one hand, the heat exchange temperature difference is larger, and the heat exchange efficiency is higher. On the other hand, the leakage of raw flue gas to clean flue gas is avoided, and the emission concentration of clean flue gas is ensured. The other part of the heated air is passed into the boiler air preheater, and the heat recovered from the flue gas is sent to the boiler, which reduces the exhaust gas temperature of the unit, reduces the heat loss of exhaust gas,

improves the boiler efficiency, and better realizes the boiler air preheating coupling of heater and flue gas temperature regulation.

3.2 Scheme B

Scheme B (Fig. 2) proposes a two-stage series water temperature adjustment and waste heat recovery coupling scheme. A two-stage flue gas heat exchanger is set up in front of the desulfurization tower, and the two-stage flue gas heat exchanger is connected in series with working fluid water, and the working fluid after absorbing heat transfers the heat to the unit's regenerative system, which can displace part of the steam turbine extraction steam to increase the output of the steam turbine. In addition, in order to avoid the white plume phenomenon caused by the excessively low flue gas temperature at the outlet of the desulfurization tower, part of the heating steam from the thermal power plant is used to heat the flue gas at the tail of the desulfurization system to ensure the elevation of the flue gas.
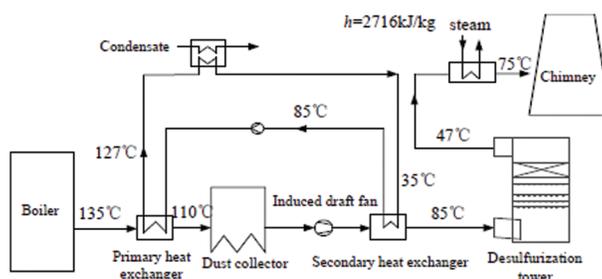
Figure 2: Illustration of system model B

In this scheme, two-stage flue gas heat exchangers are set up. Before the dust collector and the desulfurization tower inlet, respectively, the flue gas temperature at the inlet of the desulfurization tower can be adjusted in stages, and the temperature drop can be distributed reasonably, so as to realize the deep adjustment and ensure the safe operation of the dust collector. After the working water absorbs the heat, all the recovered heat is transferred to the unit's regenerative system through the surface heat exchanger. Because the flue gas temperature after the desulfurization tower is too low, it is necessary to properly raise the temperature before the flue gas is discharged.

In order to avoid low temperature corrosion of the dust collector, the outlet temperature of the flue gas in the first-stage flue gas heat exchanger must be controlled above the acid dew point. The acid dew point of the flue gas is around 74°C, so the operation of the first-stage flue gas heat exchanger is safe.

3.3 Scheme C

Scheme C (Fig. 3) proposes a coupling process of three-stage series flue gas temperature regulation and waste heat recovery. This process uses a three-stage flue gas heat exchanger. The first two-stage heat exchanger is the same as scheme B, but the working water is taken from the condensed water in the regenerative system of the unit, and directly into the regenerative feed water of the unit after the heat exchange is completed. In the system, avoid adverse effects caused by setting heat exchangers. The specific flow direction of the working water is as follows: the working water drawn from the condensate pipe first passes into the secondary heat exchanger, then passes through the primary heat exchanger, absorbs the heat in the flue gas, and continues to pass into the tertiary heat exchanger. The net flue gas at the outlet of the desulfurization tower releases heat and finally returns to the condensate system.

This scheme does not need to use other heat sources to heat the net flue gas, which reduces the loss of other heat sources.
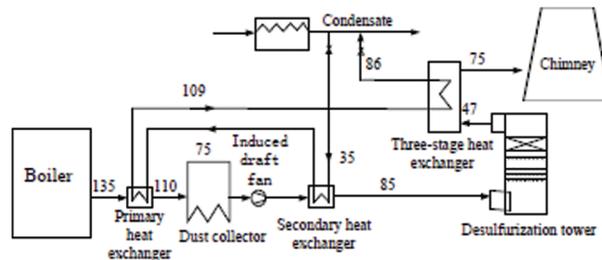
Figure 3: Illustration of system model C

Due to the arrangement of the three-stage flue gas heat exchanger in this scheme, the upper resistance of the flue is larger than that of the two-stage heat exchanger, but the principle of proximity is adopted. Production reduction and other issues. The flue gas temperature is also adjusted in two stages. The medium water after heat exchange is directly fed into the unit's heat recovery system, and the heat is recovered into the system in a mixed manner, which can reduce the irreversible loss of the system and achieve more efficient waste heat recovery and utilization.

3.4 Scheme D

Scheme D (Fig. 4) proposes a scheme for graded adjustment of flue gas temperature at the inlet of the desulfurization tower and graded recovery of waste heat. The three-stage flue gas heat exchanger is also used, and the biggest difference from scheme C is that the working fluid water of the first two-stage flue gas heat exchanger in this scheme is connected in parallel. The working water enters the first and second flue gas heat exchangers respectively, and the working water at the outlet of the first heat exchanger passes into the third heat exchanger to heat up the net flue gas. The working water from the outlet of the secondary heat exchanger is directly returned to the recuperation system of the unit.
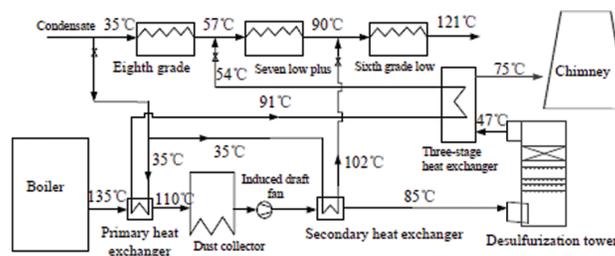
Figure 4: Illustration of system model D

This scheme not only realizes temperature regulation in stages, but also recovers heat in stages. It can effectively reduce the irreversible loss (exergy loss) of the system and maximize the use of waste heat.

4 Simulation Results

4.1 Energy Consumption Characteristics

When calculating the energy consumption of the designed process scheme, the energy consumption changes of the necessary booster fans and the energy consumption changes of newly added energy-consuming equipment are mainly considered.

The energy consumption changes of the four schemes are shown in Figs. 5, and 6 is the heat exchange area required by the heat exchangers arranged in the four schemes, so as to analyze the investment of the schemes. Scheme A reduces the exhaust temperature of the tail flue gas and improves the boiler efficiency of the unit, but the system energy consumption is the largest among the four schemes due to the setting of the air fan and the change of the wind resistance of the flue. In addition, due to the provision of a first-stage gas-air heat exchanger, this type of heat exchanger has a lower heat transfer coefficient than a water-air heat exchanger, so the heat exchange area is the largest. Three-stage heat exchangers are set in the three schemes of B, C, and D. Under the condition that the flue gas temperature adjustment range is the same, the energy consumption increment is not much different.
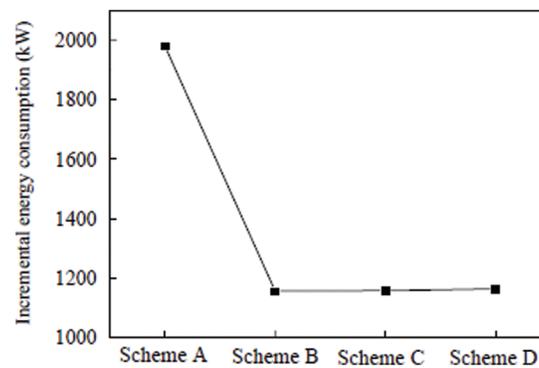
Figure 5: Comparison of energy consumption of the methods
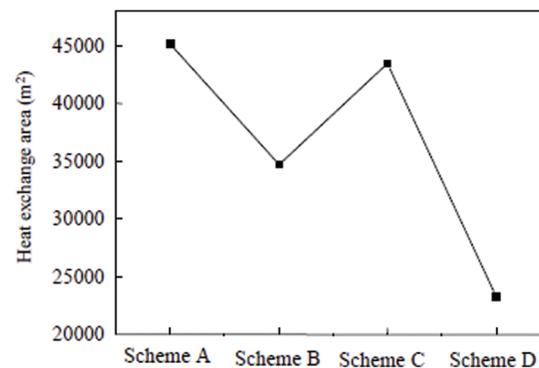
Figure 6: Comparison of heat transfer areas

Scheme D working fluid of the first two heat exchangers is introduced separately, and the temperature drop of the flue gas can be selected flexibly. The adjustment depth of the flue gas temperature of the first and second heat exchangers can be adjusted according to the flow rate of the working fluid and the arrangement of the heat exchanger. Therefore, the total heat exchange area of this scheme is the smallest.

According to the analysis of the energy consumption increment of the system and the heat exchange area, it is comprehensively considered that the scheme D is more conducive to the low energy consumption operation of the system.

4.2 Project Coal Saving Characteristics

In the scheme, the waste heat is recovered into the unit's regenerative system, and sent to the system as pure heat, which reduces the steam extraction of the steam turbine, and can obtain the increase in the generating power of the unit, and then calculate the coal saving according to the coal consumption of the unit. The regenerative extraction steam parameters of the steam turbine are shown in Table 2, and the corresponding equivalent enthalpy drop parameters obtained by calculation are shown in Table 3.

Table 2: Extraction parameters

Heater	Extraction temperature (°C)	Extraction steam specific enthalpy (kJ/kg)	Extraction steam pressure (MPa)
H 1	385.6	3144.2	5.9450
H2	320.0	3027.1	3.6680
H3	446.0	3352.2	1.7760
H4	354.6	3169.0	0.9640
H5	257.0	2978.5	0.4160
H6	191.0	2851.0	0.2260
H7	120.0	2716.0	0.1090
H8	59.7	2455.8	0.0197

Table 3: Drop parameters

Heater	Heat release of steam (kJ/kg)	Hydrophobic heat release (kJ/kg)	Equivalent enthalpy drop (kJ/kg)	Extraction efficiency (%)
H1	2063.8	-	622.1	30.14
H2	2112.9	166.2	546.0	25.84
H3	2592.3	154.3	913.3	35.23
H4	2551.7	142.6	776.3	30.42
H5	2450.0	88.8	607.6	24.80
H6	2453.8	131.3	507.2	20.67
H7	2458.2	139.4	394.5	16.05
H8	2295.5	97.5	140.2	6.11

Fig. 7 shows the coal saving characteristics of the four schemes. Combined with the new equipment in the system and the changes in the energy consumption of the original energy-consuming equipment, the coal consumption and coal consumption for power supply of the unit are finally converted to reflect the economy of the scheme.
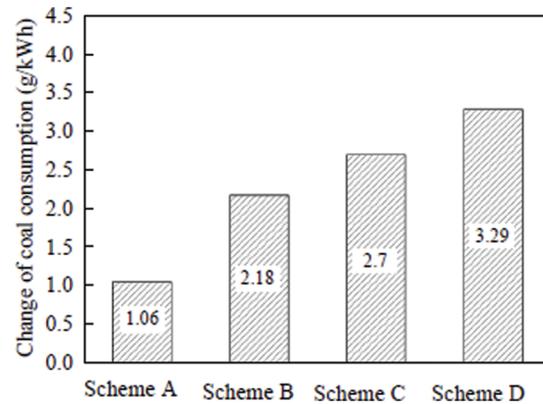
Figure 7: Comparison of coal saving characteristics

Scheme A uses air for waste heat recovery. Due to factors such as heat exchanger efficiency, the recovery capacity is weaker than that of working water, and the amount of waste heat recovery is the lowest. Because of the large amount of induced air, the energy consumption of the system is the highest, so the final coal saving is the least. In scheme B, the waste heat of the flue gas is not used for the heating of the flue gas at the tail, so the amount of waste heat recovery is the largest, but at the same time, steam is used at the tail to heat the flue gas, so this part of the steam does not work in the steam turbine, so the total coal saving is not large. Scheme C uses three-stage heat exchangers in series. Because the tail flue gas needs to be heated, the amount of waste heat recovery is lower than that of scheme B, but the total coal saving is higher than that of scheme B.

For scheme D, the connection method of the heat exchanger is greatly improved. The water at the outlet of the first-stage heater is used to heat the tail flue gas, which does not affect the waste heat recovery of the working fluid of the second-stage heater. The two-stage waste heat recovery is separated and sent to the seventh-stage low-addition and the sixth-stage low-addition in stages. Under the condition of the same flue gas temperature adjustment depth, the economy of the system is maximized. Its final coal saving is the highest among the four schemes.

4.3 Exergy Loss Analysis of Different Waste Heat Recovery Schemes

In the previous waste heat recovery scheme, the heat destination is uneconomical, and the temperature difference at the entry point is large, resulting in large exergy loss, and does not maximize the thermal economy of the system. In view of this situation, according to the first and second laws of thermodynamics, the heat transfer process of the heat exchanger is irreversible, so the heat transfer process must have a reduction in the effective energy of the system, that is, exergy loss. The size of the exergy loss is related to the temperature difference between the heat exchange fluids, and the smaller the temperature difference is, the smaller the exergy loss is. Therefore, the principle of the minimum temperature difference between the media inlet should be followed in waste heat recovery to reduce the effective energy loss of the system. The exergy loss in the heat transfer process of high and low temperature fluids is:

$$\mathrm{d}E_\mathrm{L} = \mathrm{d}E_\mathrm{QH} - dE_\mathrm{QL} = T_0 \left(\frac{1}{T_\mathrm{L}} - \frac{1}{T_\mathrm{H}} \right) \delta Q = T_0 \left(\frac{T_\mathrm{H} - T_\mathrm{L}}{T_\mathrm{L} T_\mathrm{H}} \right) \delta Q \tag{14}$$

where: dE_L is exergy loss; T_0 is the ambient temperature; T_L is the cryogenic fluid temperature; T_H is the high temperature fluid temperature; δQ is the heat exchange.

According to the analysis of energy consumption and coal saving, scheme D has the best economy among the four schemes, and the waste heat recovery scheme has variability. According to the analysis, there are four media import methods in this scheme: 1) All imported into the eighth level low plus; 2) The grades are imported into the seventh, and the eighth grades are low-added; 3) The grades are imported into the sixth grade, and the eighth grades are low-added; 4) The grades are imported into the sixth grade, and the seventh grades are added at a low level. The water temperature of the eighth, seventh, and sixth low-add outlet of the unit is 57°C, 90°C, and 121°C respectively.

Fig. 8 shows the economics and exergy analysis of the four import methods. The results show that the temperature difference between the fluids is the smallest in the six-level and seventh-level low-add confluence methods. The increase in power generation is 5.76 MW, and the coal consumption for power supply is reduced by 3.29 g/(kW·h). Calculate the ratio of exergy loss to waste heat recovery as the exergy loss percentage, and the exergy loss percentage of the obtained scheme. It is 1.05%, and the loss of usable energy is the smallest. This way of importing is the most economical, and maximizes the recovery of waste heat to the unit's heat recovery system.

① All imported into the eighth level low plus；② Graded import seventh and eighth low plus；③Grading into the sixth and eighth low plus；④Grading import sixth and seventh low plus。
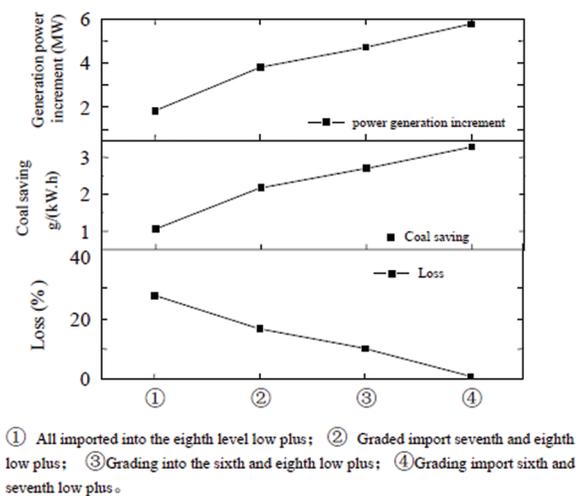
Figure 8: Comparison of the economic parameters of the proposed methods

5 Conclusion

In order to realize the coupling of flue gas temperature regulation and waste heat recovery, under the high desulfurization efficiency, four feasible process schemes are proposed, respectively. Use cold air and working water to adjust the flue gas temperature, and use the waste heat to adjust the flue gas temperature. It is recycled to the boiler air preheater and the unit regenerative system. The economics of the four process schemes, the following conclusions are obtained:

1) Due to working medium and heat exchanger efficiency, among other things, the overall waste heat recovery capacity is limited when utilizing air for flue gas tempering and waste heat recovery, and the investment and energy consumption are the highest.
2) Combined with the heat recovery system, when the condensed water is used as the heat exchange working medium, the total waste heat recovery capacity is high, and the system investment and energy consumption are relatively low. The use of steam to heat the tail flue

gas will significantly reduce the thermal economy of the system, so it should be considered to use the recovered heat to heat the tail flue gas. The four schemes reduce the standard coal consumption of power supply by 1.06, 2.18, 1.91, and 3.29 g/(kW·h) respectively.

3) Using the condensed water of the unit as the working fluid, and grading the waste heat into the regenerative system of the unit can maximize the utilization of the waste heat of the flue gas. When recovering the waste heat of flue gas, the principle of minimum temperature difference at the entry point should be followed to reduce the effective energy loss of the system and maximize the thermal economy of the system. The application of the optimal solution proposed in this paper can reduce the coal consumption of the 660 MW unit by 3.29 g/(kW·h).

The future research will consider the economic analysis of the desulfurization system and evaluate the propose idea.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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