An optimized low-temperature flue gas waste heat utilization system for power plants

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Abstract:

In this paper, an optimized low-temperature flue gas waste heat utilization system (WHUS) is proposed on the basis of the energy cascade utilization principles. In the optimized WHUS, air is preheated by both the exhaust flue gas in the boiler island and the low-pressure steam extraction in the turbine island, thereby part of the flue gas heat in the air preheater can be saved and introduced to heat the feedwater and the high-temperature condensed water. Consequently, part of the high-pressure steam is saved for further expansion in the steam turbine, which obtains additional net power output. Based on the design data of a typical 1000 MW ultra-supercritical coal-fired power plant in China, in-depth analysis of the energy-saving characteristics of the optimized WHUS and the conventional WHUS is conducted. When the optimized WHUS is adopted in a typical 1000 MW unit, net power output increases by 19.51 MW, exergy efficiency improves to 45.46%, and net annual revenue reaches 4.741 million USD. In terms of the conventional WHUS, these aforementioned performance parameters are only 5.83 MW, 44.80% and 1.244 million USD, respectively. The research of this paper can provide a feasible energy-saving option for coal-fired power plants.

Keywords:

Coal-fired power plants, Waste heat utilization, Thermodynamic analysis, Exergy analysis, Techno-economic analysis.

1. Introduction

By the end of 2013, the total installed power capacity in China had reached 1.25 billion kW with the electricity production of 5.25 trillion kWh, both ranked the first in the worldwide. Among these, the coal-fired power plants account for 69% of the total installed power capacity, which generate approximately 78% of the electricity production. At present, this capacity has exceeded 800 million kW, with annual increment of 30-50 million kW. It is widely acknowledged that the coal-fired power generation will continually dominate the power industry in China for a long term [1, 2].

Currently, the increasing fuel price and strict energy-saving environment protection policy imply that more attention should be paid to the improvement of the energy utilization efficiency. An effective energy conservation method for large-scale coal-fired power plants is the in-depth utilization of flue gas waste heat. The most widely adopted approach to utilize this waste heat involves the installation of auxiliary heat exchange equipment, namely, a low-temperature economizer (LTE), in the downstream of the air preheater to heat a portion of the condensed water

[3, 4]. The required heat for this process originates from flue gas instead of steam extraction, as a result, part of the steam extraction from the steam turbine can be saved. The saved steam is able to pass through the following stages of steam turbine and continue to expand for more power output, accompanied by the improvement on the net efficiency.

So far many scholars have carried out productive research on the utilization of the flue gas waste heat. Espatolero *et al.* [5] explored the effects of the flue gas exhaust temperature and the heat exchanger performance on the waste heat recovery, and assessed the effect of energy conservation as induced by the optimization of the boiler island. Chen *et al.* [6] investigated new technologies for exploiting the large amount of low-grade heat available from the flue gas by adopting industrial condensing boilers, and for recovering the latent heat of water vapor in the flue gas.

As for the project application of the flue gas waste heat utilization, the German Schwarze Pumpe power plant with a 2 × 800 MW lignite generation unit implemented a flue gas division system after the electrostatic precipitator and used exhaust energy to heat the condensed water in the regenerative system, the energy conservation effect is significantly improved [7, 8]. In China, several coal-fired power plants with 1000MW unit such as Waigaoqiao 3rd power plant in Shanghai had also adopted the waste heat utilization system (WHUS), in which the flue gas waste heat can be utilized to heat the condensed water, the LTE presents excellent performance as the boiler efficiency is increased by 2 % and the net efficiency of the power generation unit is improved by 0.8 to 0.9 % [9–11].

However, the LTE-based conventional WHUS faces various problems, such as the low-grade flue gas heat and severe material corrosion. These issues limit the energy-saving effects and equipment safety considerably. Thus, in-depth research of the waste heat utilization is of great importance to improve the overall efficiency of the existing power generation units.

In view of these, this study proposes an optimized WHUS, which is based on the comprehensive analysis of the thermodynamic performance of the air preheating process in the boiler island and the regenerative heating process in the turbine island. The optimized WHUS fully realizes the heat and mass transfer processes of different working mediums such as flue gas, steam extraction, air, etc., with energy cascade utilization realized. Besides, the optimized WHUS is analyzed in terms of heat transfer characteristics and energy-saving effects, in combination with a typical ultra-supercritical 1000 MW power generation unit.

2. Methodology of thermodynamic analysis

2.1. Waste heat utilization model

The thermal equilibrium method is commonly used for the thermodynamic analysis in the coal-fired power generation units. In this method, material and thermal balance equations can be listed according to the practical operation condition of the steam turbine. With these basic equations, the required parameters such as the multistage steam extraction flow of steam turbine, the gross power output can be obtained [12]. In this study, the thermal equilibrium method is adopted to perform the corresponding thermodynamic calculation of the flue gas waste heat recycling model. Fig. 1 shows the flow relationship among different working mediums.

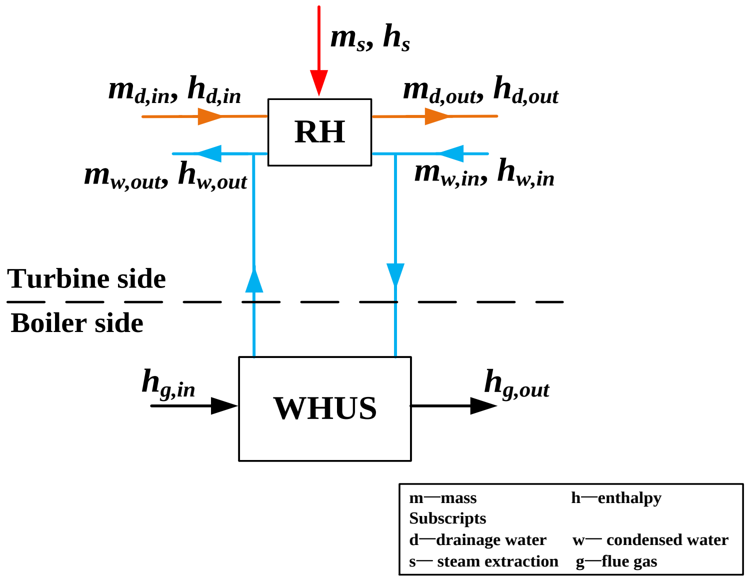


Fig. 1 Simplified schematic diagram of the WHUS

2.2. Net additional power output

When the thermodynamic analysis of the WHUS is conducted, the released heat of the flue gas should be calculated first. The specific formula is as follows:

$$\dot{Q}_1 = \dot{m}_g(h_{g,in} - h_{g,out}) \qquad (1)$$

where $\dot{m}_g$ is the flow rate of the flue gas (kg/s); $h_{g,in}$ and $h_{g,out}$ refer to the input and output flue gas enthalpy, respectively (kJ/kg).

Based on the thermal equilibrium theories, the released heat mentioned above is introduced to economic benefits in the steam turbine regenerative part. Take the drainage heat exchanger as an example, the thermal balance for a specific heater can be expressed as follows if waste heat recovery is disregarded:

$$(\dot{m}_{w,out} h_{w,out} - \dot{m}_{w,in} h_{w,in}) = \dot{m}_s h_s + \dot{m}_{d,in} h_{d,in} - \dot{m}_{d,out} h_{d,out} \qquad (2)$$

When considering the waste heat recovery, for the same heat exchanger, the thermal balance can be expressed as:

$$(\dot{m}'_{w,out} h'_{w,out} - \dot{m}'_{w,in} h'_{w,in}) = \dot{m}'_s h'_s + \dot{m}'_{d,in} h'_{d,in} + \dot{Q}_1 - \dot{m}'_{d,out} h'_{d,out} \qquad (3)$$

where $\dot{m}$, h, and $\dot{Q}_1$ are the mass, enthalpy, and absorbed exhaust heat of the flue gas, respectively; for the subscripts, w, d, and s are the condensed water, drainage water, and steam extraction, respectively; in and out are the inlet and outlet conditions of the heaters, respectively. The exhaust utilization parameters are presented with single quotation marks, whereas the non-utilization parameters are shown without any quotation marks.

Assuming that the thermal system satisfies the stable working conditions before and after the flue gas heat recovery [13], the equations can be presented as ($\dot{m}_{w,out} = \dot{m}'_{w,out}$, $h_{w,out} = h'_{w,out}$, $\dot{m}_{d,in} = \dot{m}'_{d,in}$, $h_{d,in} = h'_{d,in}$, $h_s = h'_s$), and the mass conservation conditions as ($\dot{m}'_{w,out} = \dot{m}'_{w,in} + \dot{m}'_s$, $\dot{m}_{w,out} = \dot{m}_{w,in} + \dot{m}_s$, $\dot{m}'_{d,out} = \dot{m}'_{d,in} + \dot{m}'_s$ and $\dot{m}_{d,out} = \dot{m}_{d,in} + \dot{m}_s$). Thus, the saved steam extraction Δm by adopting the WHUS can be calculated as:

$$\Delta \dot{m} = \dot{m}_s - \dot{m}'_s \tag{4}$$

Based on Formula (4), the additional work of the steam turbine can be calculated as:

$$\Delta P = \frac{\Delta \dot{m} \cdot (h_s - h_0)}{1000} \tag{5}$$

where h_s and h_0 denote the enthalpy of the steam extraction and exhaust steam, respectively (kJ/kg).

According to Formula (5), the net additional power output is calculated as follows:

$$\Delta P_{net} = \Delta P - \Delta P_f \tag{6}$$

where ΔP_f is the increment in the induced fan power with waste heat utilization (MW). As is known that, additional waste heat utilization equipment shall be arranged at the boiler rear flue gas duct for the purpose of recycling the flue gas waste heat, which is bound to increase the flue gas resistance, leading to increase the power consumption of the induced draft fan. The increase in the fan power can be obtained by the following formula:

$$\Delta P_f = \frac{D \cdot \Delta P_r}{1000\eta_f} \tag{7}$$

where ΔP_r is the increase in the flue gas pressure drop (kPa); η_f is the induced draft fan efficiency (η_f = 0.85) [14, 15]; and D is the flue gas flow rate (m^3/s).

2.3. Heat rate reduction

In the power industry, the heat rate is the most commonly metric used to track and report the performance of a thermal power generation units. Heat rate q represents the amount of fuel energy input needed to produce 1 kWh of net electrical energy output. Given the net additional power output ΔP_{net}, the reduction in heat rate is deduced from the following formula [16]:

$$\Delta q = 3600 E_{total} \left[\frac{1}{P_{net}} - \frac{1}{P_{net} + \Delta P_{net}} \right] \tag{8}$$

where E_{total} refers to the total input energy (MW); P_{net} is the net power output (MW), which takes auxiliary power away from the gross power output.

3. Description of the conventional WHUS

3.1. Reference coal-fired power generation unit

In this study, a typical 1000 MW ultra-supercritical power generation unit in China is selected to conduct the case study and quantitative calculation. This power generation unit burns bituminous coal, which contains 56.26% carbon, 3.79% hydrogen, 12.11% oxygen, 0.82% nitrogen, 0.17% sulphur, and 18.1% water, respectively. Main steam pressure and temperature are 26.25 MPa and 600 °C, respectively, and the reheat temperature is 600 °C. The gross work output is 1000MW while the net work output is 942 MW. Table 1 lists the specific parameters of the regenerative heaters (RHs) of the steam turbine.

Table 1. The main parameters for the power generation unit under the THA condition.

Item	Unit	RH1	RH2	RH3	DEA	RH5	RH6	RH7	RH8
Steam extraction temperature	°C	393.0	351.2	482.6	380.5	288.6	192.1	86.1	63.6
Steam extraction pressure	MPa	7.26	5.39	2.29	1.11	0.56	0.23	0.06	0.02
Outlet feedwater temperature	°C	290.0	268.7	219.4	183.8	153.3	122.1	83.3	60.8
Outlet feedwater pressure	MPa	32.70	32.80	32.90	1.09	1.29	1.34	1.39	1.44
Inlet feedwater temperature	°C	268.7	219.4	189.9	153.3	122.1	83.3	60.8	36.2
Inlet feedwater pressure	MPa	32.80	32.90	33.00	1.29	1.34	1.39	1.44	1.53
Drainage water temperature	°C	274.3	225.0	195.5	—	127.6	124.6	86.1	63.6

3.2. Introduction of the conventional WHUS

In the coal-fired power generation unit, a large amount of steam with different parameters needs to be extracted to heat the feedwater and the condensed water, that is, the regenerative process. In this process, the temperatures of the feedwater and the condensed water will be increased, which is beneficial to improve the thermodynamic cycle efficiency. However, the working ability of the steam, which is extracted from the turbine to heat the feedwater and the condensed water, will be destructed since it can no longer continue to expand in the steam turbine. In the conventional WHUS, the exhaust energy of the flue gas is utilized to heat the condensed water, part of the steam extraction is thus saved and can be continue to expand for more power output. As a result, it will raise the gross power output and improve the thermal conversion efficiency.

Fig. 2 depicts the configuration of the conventional WHUS. The LTE is arranged in the downstream of the air preheater in flue gas duct, which is parallel to the RH6. Part of the condensed water at the inlet of the RH6 will enter the LTE and return to the regenerative system after absorbing the flue gas waste heat. Afterward, the condensed water will converge with the main condensed water at the outlet of the RH6. In this way, the 6th-stage steam extraction can be partly saved.

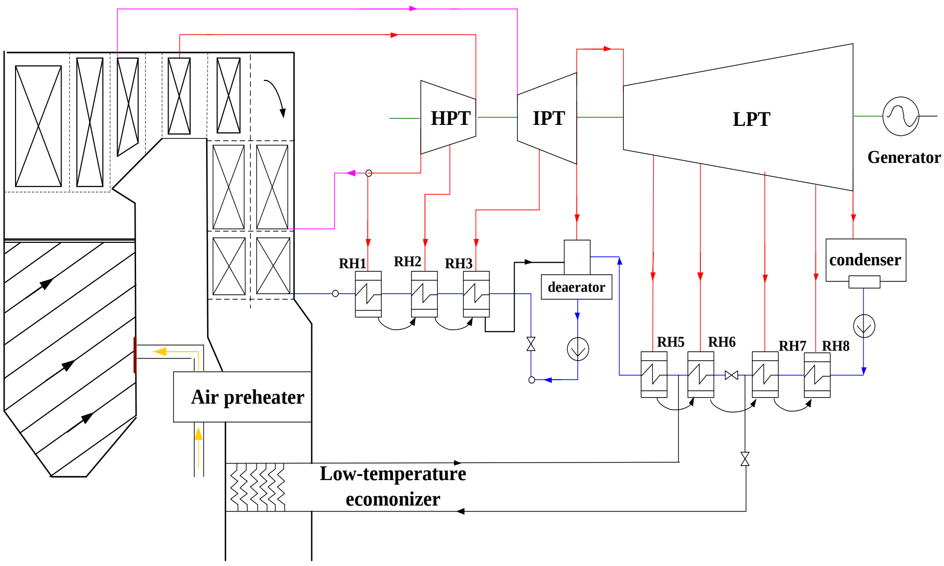


Fig. 2 Schematic of the thermal system of a power plant with the conventional WHUS

Table 2 presents the thermodynamic analysis results of the conventional WHUS. The inlet flue gas temperature of the LTE is equal to that of the exhaust flue gas from the air preheater, which is 131 °C. Meanwhile, due to the relatively low sulfur content of the coal (approximately 0.17%), as well as the acid steam wraparound effect brought by the flying ash, the outlet flue gas temperature of the LTE can be reduced to 100°C without serious corrosion problem.. According to the relevant thermodynamics theories, the smaller the temperature difference between the working mediums, the smaller heat transfer exergy losses. In this case, higher condensed water temperature is preferred, given the fixed flue gas temperature range. In related heat transfer and techno-economic theories, however, a small heat transfer temperature difference increases the heat transfer area and the volume of the heat exchange device. As a result, investment in the heat exchanger is heightened. To balance the thermodynamic performance and equipment investment in the conventional WHUS, LTE adopts the counter-current arrangement and is connected in parallel to RH6. By this arrangement, on the one hand, provided that the engineering constraint is allowed, the condensed water temperature is enhanced as high as possible. As seen in Table 2, considering the flue gas temperature of the LTE is only 131–100 °C, which can only be used to heat the condensed water of RH6 at most (83.3–122.1 °C). On the other hand, the outlet condensed water temperature of LTE is set to 116 °C, slightly lower than 122.1 °C, which ensures the minimum heat transfer temperature difference of the LTE is maintained over 15 °C [17]. Overall, the total investment of the conventional WHUS could be maintained at a relatively acceptable level. Meanwhile, the net power output is increased by 5.83MW, whereas the heat rate of the generation unit is reduced by 42.56 kJ /kWh.

In the LTE, the energy donor is the exhaust flue gas and the energy acceptor is the condensed water of the regenerative system. Therefore, WHUS performance is affected not only by the characteristic of the flue gas, but also by the parameters of the steam cycle. Specifically, power output and economic benefits are not only affected by the quantities of heat released by the flue gas, but also by the parameters of saved steam extraction. In the conventional WHUS, the LTE is installed in the outlet of the air preheater, the inlet flue gas temperature of the LTE is only 131 °C, which can replace the 6th-stage steam extraction at most, as shown in Fig. 3. The 6th-stage steam extraction is characterized by a relatively low working ability since its pressure is only 0.23 MPa, which is the limited factor for improving the energy-saving effects of recycling the flue gas waste heat.

Table 2. The thermodynamic analysis results of the conventional WHUS.

Item	Unit	Conventional WHUS
Inlet flue gas temperature	°C	131
Outlet flue gas temperature	°C	100
Inlet condensed water temperature	°C	83.3
Outlet condensed water temperature	°C	116
Additional auxiliary power consumption	MW	1.25
Gross work output	MW	1007.15
Additional gross work output	MW	7.15
Net work output	MW	947.83
Additional net work output	MW	5.83
Reduction of heat rate	kJ /kWh	42.56

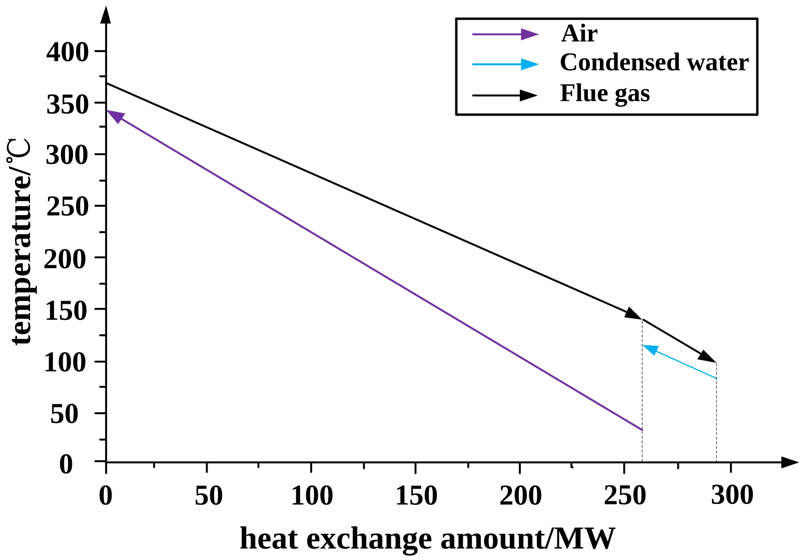


Fig. 3 The heat transfer curve of the conventional WHUS

4. Proposal and performance analysis of the optimized WHUS

4.1. Description of the optimized WHUS

According to the analysis above, to further improve the energy conservation effects of the WHUS, it is essential to enhance the flue gas temperature that entering the LTE. Meanwhile, noting that the logarithmic mean temperature difference of the air preheating process is relatively large (over 60 °C). Thus, to utilize the energy rationally, an optimized WHUS is proposed in this section.

Fig. 4 illustrates the optimized WHUS. This system adds a bypass flue gas duct which is paralleled with the main air preheater. In the bypass flue gas duct, two gas-water heat exchangers are successively installed, approximately one third of the outlet flue gas of the economizer enters the high-temperature gas-water heat exchanger and the low-temperature gas-water heat exchanger of the bypass flue gas duct in sequence, to heat the feedwater (189.9-290 °C) and the condensed water (83.3-153.3 °C), respectively. Since the heat of the flue gas entering the main air preheater reduces in the optimized WHUS, two additional heat exchangers are added to maintain the inlet air temperature of the furnace. Among them, the first-stage heat exchanger utilizes the low-pressure steam extraction to heat the air, while the second one applies the waste flue gas (131-100 °C) to heat the air. The parameters of main heat exchange equipment are shown in Table 3.

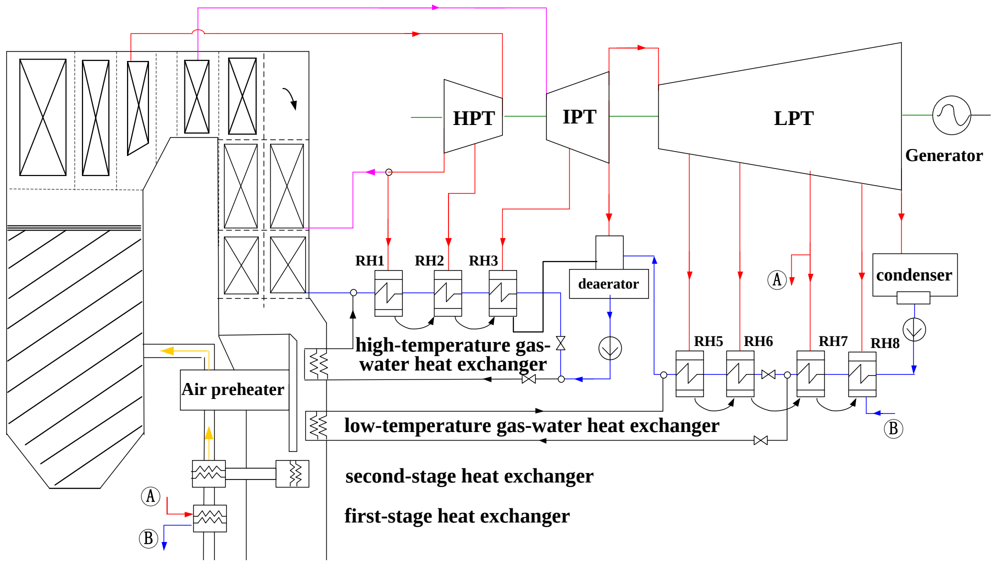


Fig. 4 Schematic of the thermal system of a power plant with the optimized WHUS

Table 3. Main heat exchange equipment parameters.

Item	Unit	High-temperature Gas-water Heat Exchanger	Low-temperature Gas-water Heat Exchanger	First-stage Heat Exchanger	Second-stage Heat Exchanger
Inlet flue gas	°C	372	204.8	—	131
Outlet flue gas	°C	204.8	131	—	100
Inlet water/steam	°C	189.8	83.3	86.1(1*)	—
Outlet water/steam	°C	290	153.3	86.1(0*)	—
Inlet air	°C	—	—	25	60
Outlet air	°C	—	—	60	100
Logarithmic mean temperature difference	°C	39.44	49.58	41.15	35.54

*Note: figures in the bracket indicate the dryness

Fig. 5 presents the heat transfer curve of the optimized WHUS. As indicated both in this figure and in Table 3, the optimized WHUS fully realizes the energy grade match among the exhaust flue gas, air and the condensed water. By adopting two additional heat exchangers, the 7th-stage steam extraction and low-temperature flue gas are utilized to heat the air before it enters the main air preheater, which guarantee the logarithmic mean temperature difference of the air preheating process can be controlled within 36 °C. Subsequently, approximately one third of the flue gas with the temperature of 372-131 °C is saved and introduced into the bypass flue gas duct to heat the feedwater and the condensed water. Part of 1-3th, 5th and 6th-stage steam extractions could be saved and continued to expand for more power output in the steam turbine. Evidently, the energy saving effects of the optimized WHUS is improved remarkably.

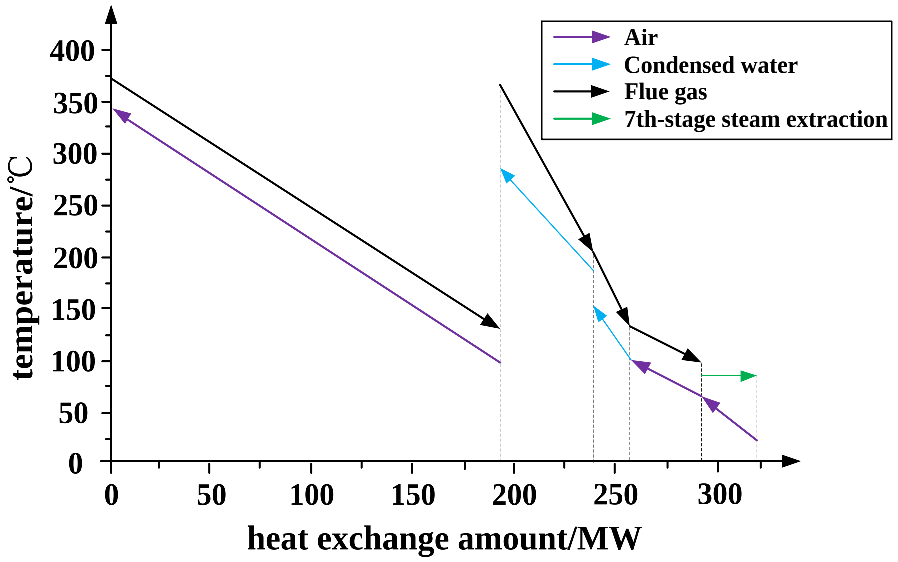


Fig. 5 The heat transfer curve of the optimized WHUS

4.2. Thermodynamic performance results

The thermodynamic analysis comparison between the conventional WHUS (as shown in Figure 2) and the optimized WHUS (as presented in Figure 4) is conducted in Table 4. The gross work output of the optimized WHUS increases by 22.01 MW. This increase is mainly attributed to that the temperature of the flue gas used to heat the feedwater and the condensed water reaches 372-131 °C in the optimized WHUS, which is much higher than that of the conventional WHUS (131-100 °C). The high-grade steam extraction can thus be replaced. As a result, gross work output improves significantly.

However, since several additional heat exchangers are adopted in the optimized WHUS, some pumps and fans are required to overcome the resistance of the water, air and flue gas. As indicated in Table 4, the auxiliary power in the optimized WHUS increases by 2.28 MW. Overall, the increment in net work output is 19.51 MW in the optimized WHUS, and the reduction in heat consumption rate is 143.35 kJ/kWh; whereas for the conventional WHUS, the aforementioned performance parameters are only 5.83 MW and 42.56 kJ/kWh, respectively. Thus, the thermal efficiency of the optimized WHUS is significantly improved.

Table 4. The thermodynamic results of conventional WHUS and optimized WHUS.

Item	Unit	Conventional WHUS	Optimized WHUS
High-temperature gas-water heat exchanger	MW	—	46.13
Low-temperature gas-water heat exchanger	MW	—	19.59
Second-stage heat exchanger	MW	—	34.87
First-stage heat exchanger	MW	—	30.85
Low-temperature economizer	MW	34.87	—
Auxiliary power increment	MW	1.25	2.28
Gross work output	MW	1007.15	1022.01
Additional gross work output	MW	7.15	22.01
Net work output	MW	947.83	961.51
Additional net power output	MW	5.83	19.51
Reduction in heat rate	kJ /kWh	42.56	143.35

4.3. Variation in the steam extraction and work output

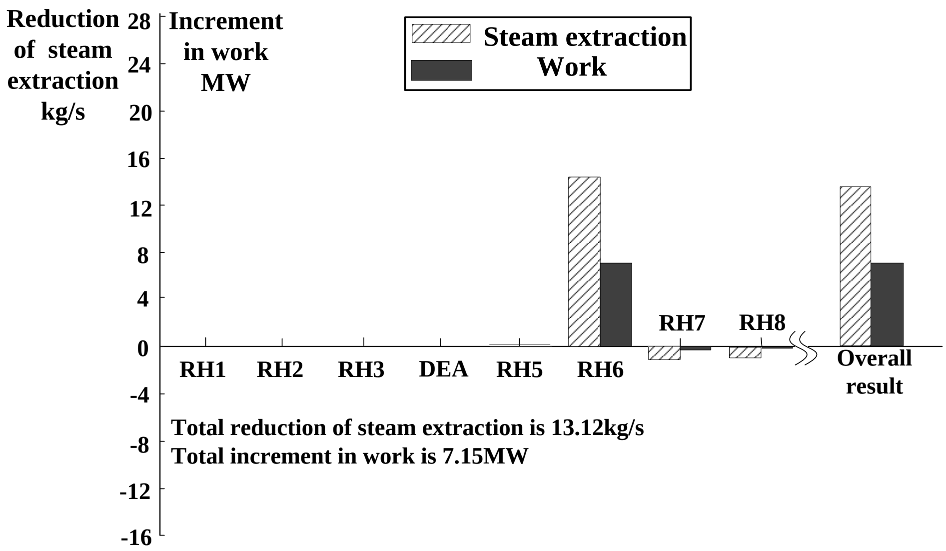
Figure 6 shows the effects of waste heat utilization on the steam extraction and the work output of different systems. The column chart with slash line represents the variation in the multistage steam extractions of the regenerative heaters. When the steam extraction is reduced, the column is located above the *x* axis; conversely, the column is located below the *x* axis if steam extraction is increased. The column chart with shadow denotes the variation in work, if there is an increment in work, the column is located above the *x* axis, and vice versa. The following conclusions can be drawn from Fig. 6:

(1) In the conventional WHUS, by adopting the LTE, the flue gas with the temperature of 131-100 °C is utilized to heat the condensed water from the inlet of the RH6, as a consequence of which, the 6th-stage steam extraction is saved by 14.06 kg/s and the power output is increased by 7.37 MW. Meanwhile, it has to be noted that the 7th and 8th-stage steam extractions show a slight increase, this can be mainly attributed to the fact that the reduction in the 6th-stage steam extraction limits the drainage water flowing into RH7 and RH8 accordingly. However, considering the variation in the 7th and 8th-stage steam extractions is relatively small, the resultant power output variation can almost be neglected. In summary, the total steam extraction of the conventional WHUS decreases by 13.12 kg/s whereas the power output increases by 7.15 MW.

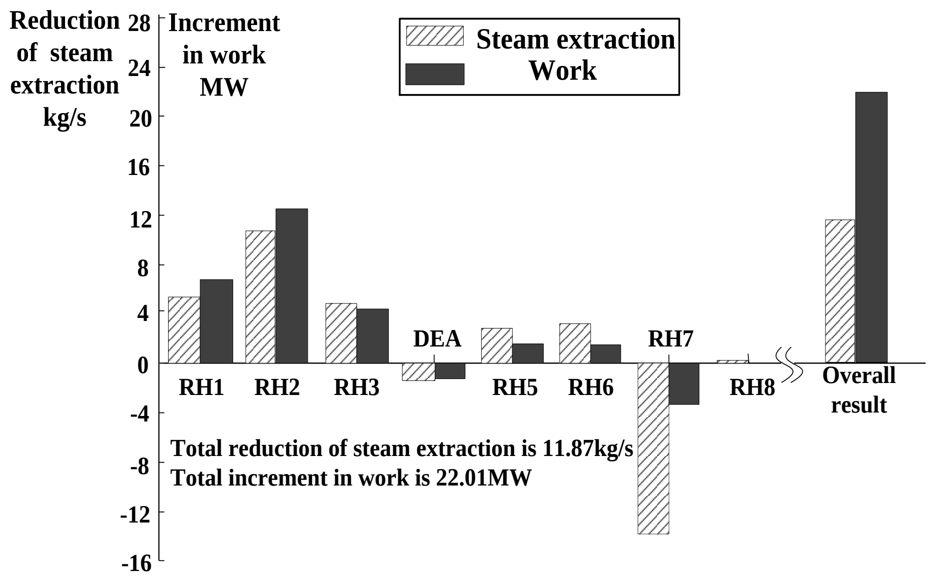
(2) In the optimized WHUS, there are obvious changes in the 1-3th, 5th and 6th-stage steam extractions. The reason is that the gas-water heat exchangers arranged in the bypass flue gas duct utilize part of the flue gas with the temperature of 372-131°C to heat the feedwater of RH1–RH3 and the condensed water of RH5-RH6, As a result, the steam extractions of these regenerative heaters reduce considerably. The 7th-stage steam extraction is increased by 13.72 kg/s, which is utilized to preheat the air in the first-stage heat exchanger. Besides, the steam extraction of DEA is increased whereas the 8th-stage steam extraction is reduced, this is because the drainage water flowing into DEA and RH8 is affected by the steam extraction of prior stage regenerative heater, which will further affect the steam extraction of DEA and RH8. Overall, in the optimized WHUS, the total reduction of steam extraction is 11.87 kg/s whereas the power output increases by 22.01 MW.

(3) In the heat regenerative system, there is a huge working ability difference between the steam extractions from different stages of regenerative heaters. For instance, the working abilities of the 1-3th, 5th and 6th-stage steam extractions are obviously higher than that of the 7th-stage steam extraction. As can be seen from Figure 6, by saving 1 kg steam extraction of RH1, RH2 and RH3, the corresponding additional power outputs are 1.21MW, 1.15MW, and 0.94MW, respectively. Whereas saving 1 kg 6th-stage steam extraction can only improve the power output by 0.45 MW, as for RH7, the power output is only decreased by 0.25 MW if the steam extraction consumption is increased by 1 kg.

(4) The overall reductions in the steam extractions of the conventional WHUS and optimized WHUS varied slightly (13.12 kg/s vs. 11.87 kg/s). And the exhaust flue gas temperature of these two systems is equally set to 100 °C, which means the same amount of waste heat is recovered. Nevertheless, in the conventional WHUS, the flue gas waste heat is used to save the 6th-stage steam extraction, and the results show that its gross work output increment is 7.15 MW. However, the 1-3th, 5th and 6th-stage steam extractions are significantly reduced in the optimized WHUS despite the increase in the 7th-stage steam extraction. Finally the gross work output increment reaches 22.01 MW, which is approximately three times as that of the conventional WHUS. In conclusion, with the reasonable utilization of the low-grade energy from both the boiler island and the turbine island, more high-grade steam extraction is saved in the optimized WHUS, better thermodynamic and waste heat recycling performances can be obtained, given that the same amount of waste heat is recovered in two systems.



(**a**) Conventional WHUS.



(b) Optimized WHUS.

Fig. 6 Effects of waste heat utilization on the steam turbine regenerative heaters

5. Exergy analysis

To reveal the internal phenomena of the optimized WHUS[18-21], an exergy analysis is performed in this section for both the optimized WHUS and the conventional WHUS. The results are listed in Table 5.

As shown in Table 5, the exergy efficiency of the optimized WHUS is 45.46%, which is 0.66% higher than that of the conventional WHUS. Comparing the exergy distribution of the optimized WHUS with the conventional WHUS, it can be found that, the exergy losses of the optimized WHUS is reduced by 10.9MW in the boiler island and 3.96MW in the turbine island. Hence, the reduced exergy losses of the optimized WHUS is mainly attributed to the boiler island.

To be specific, the exergy losses in the boiler island is significantly affected by the air preheating process. This influence is ascribed to the fact that the optimized WHUS utilizes low-pressure steam extraction and low-temperature flue gas to heat the air in sequence. Therefore, the heat transfer temperature difference decreases significantly in the air preheating process. As a result, the heat transfer exergy losses decreases by 14.43 MW. However, by adopting the bypass flue gas duct, the exergy losses in the boiler island increases by 4.39 MW. By taking the exergy losses of other parts in the boiler island into account, the exergy losses in the boiler island of the optimized WHUS is reduced by 10.9 MW compared to that of the conventional WHUS.

As for the turbine island, the variation in exergy losses mainly takes place in the regenerative process. The reason accounting for this is that: in the optimized WHUS, more feedwater and condensed water is heated via the gas-water heat exchangers adopted in the bypass flue gas duct in the boiler island, thereby the water volume flowing through the regenerative system is reduced significantly, and the exergy losses is reduced by 3.97 MW accordingly. Besides, with consideration of the exergy losses in other parts such as condenser and pipeline etc, the total exergy losses in the turbine island of the optimized WHUS is reduced by 3.96 MW, compared to that of the conventional WHUS.

Table 5. Exergy analysis of conventional WHUS and optimized WHUS.

Items	Conventional WHUS		Optimized WHUS	
Unit	MW	%	MW	%
Exergy input				
Fuel input	2248.06	100.00%	2248.06	100.00%
Exergy output				
Gross power output	1007.15	44.80%	1022.01	45.46%
Exergy losses				
exhaust flue gas	156.48	6.96%	156.48	6.96%
Boiler island				
Air preheater	26.80	1.19%	5.86	0.26%
Bypass flue gas duct	—	—	4.39	0.20%
Low-temperature economizer	0.86	0.04%	—	—
Second-stage heat exchanger	—	—	3.05	0.14%
First-stage heat exchanger	—	—	3.46	0.15%
Other equipment	915.92	40.74%	915.92	40.74%
Total exergy losses in the boiler island	943.58	41.97%	932.68	41.49%
Turbine island				
Cylinder stator	66.35	2.95%	66.83	2.97%
Condenser	36.38	1.62%	36.37	1.62%
Regenerative system	26.09	1.16%	22.12	0.98%
Other equipment	12.03	0.54%	11.57	0.52%
Total exergy losses in the turbine island	140.85	6.27%	136.89	6.09%
Exergy efficiency（%）	44.80%		45.46%	

From the analysis above, it is obvious that the optimized WHUS utilizes the low temperature energy in both the boiler island and the turbine island reasonably, thereby realizes the energy grade improvement of the waste heat utilization process. Essentially speaking, the exhaust flue gas temperature of the optimized WHUS keeps the same with that of the conventional WHUS, but the exergy losses of the air preheating is significantly reduced. Finally, the exergy efficiency of the optimized WHUS is improved by 0.66%, which seems very small numerically, noting that the denominator of efficiency calculation is extremely large (2248.06MW), thereby the resultant energy-saving effects are actually rather considerable. As presented in Table 4, given the same fuel input, the additional power output of the optimized WHUS is 19.51 MW, reaching over 3 times as the conventional WHUS (5.83MW), reflecting the remarkable energy-saving benefits of the optimized WHUS.

6. Techno-economic analysis

To further evaluate the energy-saving benefits of the optimized WHUS in actual engineering application, the techno-economic analysis is conducted in the section, the following assumptions are adopted during the analysis: (1)the on-grid power tariff is set at 0.061 USD/kWh; (2) the annual operation hours of the power generation unit is 5000 hours [22]. Here, the annual operation hours stand for the equivalent operation hours of the power generation unit under the rated capacity. Hence, for the power unit that operates below the rated capacity constantly, its annual operation hours are relatively low in spite of the high actual operation hours. Considering that nowadays it is very common for the large-scale coal-fired power units in China to participate in peak load regulation, which means that they are operated below the rated capacity in a long term, thus the annual operation hours of the coal-fired power units in China are comparatively low; (3) the operation and maintenance (O&M) cost accounts for 4% of the total investment annually [23, 24]; and (4) the exchange rate is set to 6.25 CNY/USD.

6.1. Estimation of the total investment cost

Based on the scaling up method [5, 25, 26], the investment of the new added equipment and the related pump are estimated by the following equation:

$$TIC = GDP(CE) \times I_{install,b} \times (\frac{Size_a}{Size_b})^f \times K \tag{9}$$

where *TIC* is the total investment cost of system optimization; $I_{Install,b}$ is the investment cost for the benchmark equipment; $Size_a$ and $Size_b$ are the size parameters of the equipment and the benchmark equipment, respectively; *f* is the size factor; *GDP* is the variation factor; *CE* is the price index factor for the chemical equipment; *K* is the region factor. The detailed reference data are listed in Table 6

Table 6. Reference data for component in the two systems.

Component	Scaling parameter	$I_{Install,b}$(MS)	$Size_b$	f^e	GDP^d	CE^d	K^d	notes
Air preheater	Area	3.82	3.395×10^5 m^2	0.67	1	1	1	a
Heater	Area	0.693	1.315×10^2 m^2	0.67	1	1	1	b
Pump	Outlet pressure	0.093	80 bar	0.67	1	1	1	c

a: Cost is estimated using data from China Electric Power Planning and Design Institute [27].

b: Cost is taken from a feasibility study of flue gas waste heat recovery project in China 2009 [28].

c: Cost is quoted from Moaseri [29].

d: The parameters are based on [15].

e: The parameters are based on [26, 30].

The specific investment costs for added equipment of the optimized WHUS are listed in Table 7, the costs for pipeline and engineering installation are estimated to be 5% and 17% of the total equipment investment cost [31], respectively. For the conventional WHUS, introducing the LTE adds 2.993 million USD to the original total investment, with consideration of other investments such as pumps, pipeline, construction and installation, its TIC is 3.765 million USD. While for the optimized WHUS, as the logarithmic heat transfer temperature difference of the air preheater decreases because of the increasing inlet air temperature, its heat transfer area and investment cost will be increased, thus extra 0.632 million USD is required for the air preheater, as shown in Table 7. Moreover, adopting the gas-water heat exchangers and two-stage heat exchangers introduces 1.911 million USD and 4.175 million USD, respectively. Taking other relevant investments into account, the TIC of the optimized WHUS reaches 8.536 million USD.

Table 7. The investment cost of the added equipment.

Item	Unit	Conventional WHUS	Optimized WHUS
Air preheater	million USD	—	0.632
High-temperature gas-water heat exchanger	million USD	—	1.227
Low-temperature gas-water heat exchanger	million USD	—	0.684
Second-stage heat exchanger	million USD	—	3.416
First-stage heat exchanger	million USD	—	0.759
Low-temperature economizer	million USD	2.993	—
Pumps	million USD	0.093	0.279
Pipeline	million USD	0.154	0.35
Engineering cost of installation	million USD	0.525	1.189
Total investment cost	million USD	3.765	8.536

6.2. Economic performance index

Based on the investment estimation results, this section analyzes the feasibility of the optimized WHUS from the perspective of economic benefits. The net annual revenue (NAR) is calculated based on the dynamic analysis, the construction investment and the operation cost estimation. The specific formula is as follows：

$$NAR = EAI - C_{TIC} - C_{O\&M} \tag{10}$$

where *EAI* is the additional income per year generated by the system optimization, which is calculated as:

$$EAI = \Delta P_{net} h_{eq} C_e \tag{11}$$

where h_{eq} is the equivalent operation hours per year and C_e is the on-grid power tariff.

In addition, the annualized investment capital cost (C_{TIC}) can be calculated as follows [32, 33]:

$$C_{TIC} = TIC \frac{i(1+i)^n}{(1+i)^n - 1} \tag{12}$$

where *i* refers to the fraction interest rate per year, which is set at 8%; and *n* represents the system lifespan, which is presumably 20 years.

Table 8 provides the techno-economic analysis results. The EAI of the optimized WHUS is almost 5.951 million USD, which is more than three times of the conventional WHUS. The C_{TIC} and $C_{O\&M}$ of the optimized WHUS are larger than that of the conventional WHUS, reaching 0.869 million USD and 0.341 million USD, respectively. Nevertheless, the net additional power output in the optimized WHUS is much higher than that in the conventional WHUS and it will affect the NAR majorly. Consequently, the NAR of the optimized WHUS reaches 4.741 million USD per year, which presents its excellent economic performance.

Table 8. Techno-economic analysis results.

Item	Unit	Conventional WHUS	Optimized WHUS
Net additional power output	MW	5.83	19.51
Extra annual income(EAI)	million USD	1.778	5.951
Annualized investment capital cost(C_{TIC})	million USD	0.383	0.869
Operation & maintenance cost($C_{O\&M}$)	million USD	0.151	0.341
Net annual revenue(NAR)	million USD	1.244	4.741

7. Conclusion

In this study, an optimized low-temperature flue gas waste heat utilization system is proposed based on the energy cascade utilization principles. In-depth analyzes on the thermodynamic and techno-economic characteristics of the optimized WHUS are conducted. The following conclusions can be drawn:

(1) In the conventional WHUS, in order to recycle the flue gas waste heat, LTE is adopted and arranged in the downstream of the air preheater in the flue gas duct. Since the inlet flue gas temperature of the LTE is 131 °C, which can replace part of the 6th-stage steam extraction. Combined with the engineering constraints, the heat rate of the power generation unit is only reduced by 42.56 kJ/(kW·h) . Furthermore, the energy-saving effects are limited.

(2) In the optimized WHUS, the low-temperature heat from both the boiler island and the turbine island is utilized reasonably to preheat the air. In this way, not only the inlet air temperature of the air preheater is increased, also the saved high temperature flue gas (372-131 °C) can be introduced to the bypass flue gas duct to heat the feedwater and the condensed water, as a consequence of which, part of the high-pressure steam extraction is saved, leading to the net work output of the optimized WHUS is increased by 19.51 MW, while the heat rate is reduced by 143.35 kJ/(kW·h). The energy-saving effects of the optimized WHUS are remarkable.

(3) In the conventional WHUS, the 6th-stage steam extraction is saved, while in the optimized WHUS, the 1–3th, 5th and 6th-stage steam extractions are saved. In general, the working ability of the high pressure steam extraction is much larger than that of the low pressure steam extraction. Therefore, the resultant energy-saving effects differ distinctly although the total amounts of steam saved by both systems are almost similar.

(4) For the conventional WHUS, the logarithmic mean temperature difference in the air preheating process reaches 60 °C. However, in the optimized WHUS, the logarithmic mean temperature difference is less than 36 °C because the air is successively heated by low-pressure steam extraction and low-temperature flue gas. In this case, the exergy losses of the air preheating process is reduced by 14.43 MW, which becomes the main reason for decreasing the total exergy losses of the optimized WHUS. Ultimately, the exergy efficiency of the optimized WHUS improves to 45.46%.

(5) Techno-economic analysis results show that the total investment of the optimized WHUS is 8.536 million USD, which is doubled compared to that of the conventional WHUS. Nevertheless, the net additional power output in the optimized WHUS is 19.51 MW, which is over three times of

the conventional WHUS. Consequently, the net annual revenue of the optimized WHUS can reach 4.741 million USD per year, which is approximately four times as large as the conventional WHUS.

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