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Energy-Saving Optimization Study on 700°C Double Reheat Advanced Ultra-Supercritical Coal-Fired Power Generation System

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Abstract: 700°C double reheat advanced ultra-supercritical power generation technology is one of the most important development directions for the efficient and clean utilization of coal. To solve the great exergy loss problem caused by the high superheat degrees of regenerative steam extractions in 700°C double reheat advanced ultra-supercritical power generation system, two optimization systems are proposed in this paper. System 1 is integrated with the back pressure extraction steam turbine, and system 2 is simultaneously integrated with both the outside steam cooler and back pressure extraction steam turbine. The system performance models are built by the Ebsilon Professional software. The performances of optimized systems are analyzed by the unit consumption method. The off-design performances of optimization systems are analyzed. The results show that: the standard power generation coal consumption rates of optimization systems 1 and 2 are decreased by 1.88 $g\cdot(kW\cdot h)^{-1}$, 2.97 $g\cdot(kW\cdot h)^{-1}$ compared with that of the 700°C reference system; the average superheat degrees of regenerative steam extractions of optimized systems 1 and 2 are decreased by 122.2°C, 140.7°C (100% turbine heat acceptance condition), respectively. The comparison results also show that the performance of the optimized system 2 is better than those of the optimized system 1 and the 700°C reference system. The power generation standard coal consumption rate and the power generation efficiency of the optimized system 2 are about 232.08 $g\cdot(kW\cdot h)^{-1}$ and 52.96% (100% turbine heat acceptance condition), respectively.

Keywords: 700℃, advanced ultra-supercritical (A-USC), double reheat cycle, extraction steam superheat degree, unit consumption method, system optimization

1. Introduction

Advanced ultra-supercritical (A-USC) power generation technology is one of the most effective technical solutions to improve the coal power generation efficiency as well as reduce the pollutant emissions [1–5]. 600°C double reheat USC technology has been widely used and provided a solid foundation for developing 700°C A-USC technology [6–9]. Countries around the world are actively developing 700°C A-USC technology due to the lower pollution emissions and the higher power generation efficiency that can reach up above 50% [1]. The main problem encountered in the development of 700°C A-USC is the integration and energy-saving optimization of thermal cycle system except for the high-temperature nickel-based alloy materials [4]. The steam parameters of 700°C A-USC thermal system are further improved, which results in the obvious increase

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Nomenclatures

Abbreviation		SST	Small steam turbine
A-USC	Advanced Ultra-supercritical	THA	Turbine heat acceptance condition
BEST	Back pressure Extraction Steam Turbine	**Symbols**	
DEA	Deaerator	B	Coal flow rate/t·h^{-1}
HPC	High-pressure cylinder	b	Coal consumption rate/g·(kW·h)$^{-1}$
IPC	Intermediate-pressure cylinder	b_i	Additional unit consumption of each equipment in power plant/g·(kW·h)$^{-1}$
LPC	Low-pressure cylinder	I_i	Exergy loss for equipment i/kJ·kg^{-1}
OSC	Outside steam cooler	LHV	Lower heating value/kJ·kg^{-1}
RH	Reheater	P	Power generation of the unit/MW
SH	Superheater	T_0	Environment temperature/K
SHPC	Super high-pressure cylinder	η	Power generation efficiency/%

in superheat degrees of the extraction steam of the regenerative system compared with those of 600°C USC unit [10–12] and great exergy losses in regenerator system. Therefore, it is of great significance to deeply study the regenerative system energy-saving optimization design method of 700°C A-USC double reheat power generation.

Some researchers have studied the regenerative system energy-saving optimization on 600°C–700°C A-USC coal-fired power generation systems. Both the outside steam cooler (OSC) and the back pressure extraction steam turbine (BEST) are usually used to reduce superheat degrees of extraction steams. The method of installing OSC has been widely used in current 600°C USC units, and the BEST has also been applied to the construction of 600°C double reheat USC units [8, 9]. Yang [10] studied a 1000 MW 600°C single reheat unit using BEST in Jiahuwan engineering application, which could reduce the power plant equipment investment and decrease the coal consumption rate by 1.0–1.4 g·(kW·h)$^{-1}$. Li [13] proposed adding two outer steam coolers in a double reheat USC unit and the heat consumption rate can be further reduced by 80.7 kJ·(kW·h)$^{-1}$ based on the conventional double reheat system. Fu [14] proposed different arrangement modes of OSCs for a 600°C 1000-MW USC unit. The coal consumption rates can be reduced by 0.632 g·(kW·h)$^{-1}$ and 1.12 g·(kW·h)$^{-1}$ when the OSC is arranged at the second stage regenerative heater and the second stage and the fourth stage regenerative heaters, respectively. Duan [8, 9] proposed using the BEST to replace the 3–6 stages regenerative heaters to reduce the superheat degrees of extraction steam for 600°C double reheat unit, in which the average superheat degree can be reduced by 102°C under 100% turbine heat rate acceptance (100%THA) operation condition and the coal consumption rate was reduced by 2.0 g·(kW·h)$^{-1}$. Zhou [15] proposed applying the BEST to replace the 2–7 stages regenerative heaters and to reduce the superheat degree. The power generation efficiency of the OSC scheme is 0.34% higher than that of the reference unit and the power generation efficiency of the BEST scheme is 1.87% higher than that of the reference unit. Xu [16] investigated two superheat utilization schemes of extraction steam in a double reheat USC unit and used thermodynamic analyses method. One scheme adopted OSCs and the other employed BEST. The result showed that the power generation efficiency of the OSC scheme and the BEST scheme increased by 0.16% and 0.67%, respectively. Zhao [17] studied the exergy distribution in a turbine system for a 1000 MW 600°C double reheat USC power plant by the exergy balance method which could provide a reference for unit optimization. Fan [18] proposed a novel cycle integrating steam, water and air processes based on the systematic combination of flue gas heat recovery and bleeding steam cascade energy utilization and the cycle net efficiency was increased by 0.61%. Yang [19] proposed to add an air preheater to improve the inlet air temperature based on the energy consumption method. The power generation coal consumption rates decreased by 1.5 g·(kW·h)$^{-1}$. Some researchers studied the optimization of regenerative system in 650°C–700°C A-USC unit. Yang [11] established the model for 700°C double reheat A-USC and used the BEST to reduce the superheat degrees from the second to the seventh stages regenerative steam extractions, in which the power generation efficiency was up to 52.42%. Shui [20] discussed the influences of steam pressure on the unit efficiency for a 650°C single reheat USC regenerative system, in which the heat consumption rate of the power unit was less than 6940 kJ·(kW·h)$^{-1}$. Lin [21] proposed a new 1000-MW 700°C single reheat A-USC unit by integrating the steam-air heaters to reduce the air-preheating exergy loss and the power supply efficiency increased by 0.82%.

However, few people have studied the optimal selection of the replaced regenerator stage number and location of BEST in 700°C double reheat A-USC, and few have simultaneously studied the combination of the

BEST and OSC to profoundly reduce the coal consumption. To solve the problem that the high superheat degrees of regenerative steam extractions in 700°C A-USC system, based on the principle of energy cascade utilization and energy grade matching, two optimized systems of 700°C double reheat A-USC power plants are proposed in this paper and a 660-MW 600°C USC double reheat unit in practice and a 700°C traditional A-USC double reheat unit are used as reference systems for comparison. The thermodynamic model is established and the exergy consumption analysis is carried out to reveal the thermal performances of new optimized systems.

The main contents are as follows:

(1) Because of high superheat degrees of 1 to 8 stages extraction steam of 700°C A-USC double reheat coal-fired power plant, five schemes integrating BEST with different stage numbers and locations are proposed and the optimized system 1 is obtained. The results show that the superheat degrees of regenerative extraction steam are obviously reduced.

(2) Six schemes integrated with the OSCs are proposed and the optimized system 2 is obtained to further decrease the superheat degrees of regenerative extraction steam of the optimized system 1.

(3) Compared with systems of other literatures, the superheat degrees of regenerative extraction steam and the coal consumption rates of power generation of both optimized systems 1 and 2 are significantly reduced.

(4) Energy consumption distributions of different systems are revealed.

2. Description of 700°C Double Reheat A-USC Reference System and Model Validation

2.1 Description of 700°C A-USC reference system

The 700°C A-USC double reheat reference power plant is selected and the system flowchart, as well as the main design parameters based on the literature data [11], are shown in Fig. 1 and Table 1, respectively. The *T-s* figure of the 700°C reference system is shown in Fig. 2. Initial parameters of the unit are 35 MPa/700°C/720°C/720°C, and ten-stage regenerative feed water heaters are adopted. The coal consumption rate of power generation is 235.48 g·(kW·h)$^{-1}$ under 100%THA operation condition. The compositions of coal are shown in Table 2.

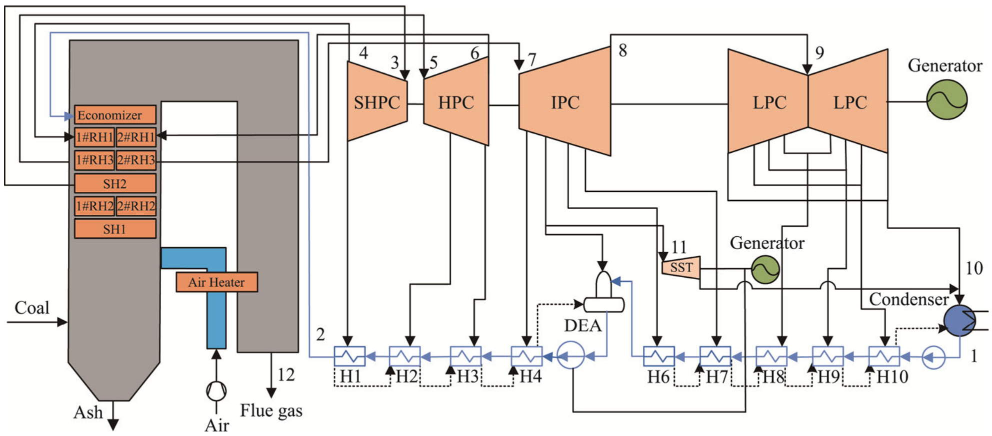


Fig. 1 Flowchart of the 700°C A-USC reference system

Table 1 Design parameters of the 700°C A-USC reference system

Items	Pressure /MPa	Temperature /°C	Mass flow rate/t·h^{-1}	Items	Pressure /MPa	Temperature /°C	Mass flow rate/t·h^{-1}
1 Condenser outlet	0.0045	31.0	942.5	7 IPC inlet	3.4	720.0	1113.7
2 Economizer inlet	37.8	324.2	1416.0	8 IPC outlet	0.27	320.3	887.4
3 SHPC inlet	35.0	700.0	1416.0	9 LPC inlet	0.26	320.1	887.4
4 SHPC outlet	13.1	520.0	1416.0	10 LPC outlet	0.0045	31.0	778.2
5 HPC inlet	12.0	720.0	1324.0	11 SST inlet	0.76	473.0	84.9
6 HPC outlet	3.7	514.4	1113.7	12 Exhaust flue gas	0.098	120.0	2011.2

Table 2 The compositions of coal

Ultimate analysis/%					Proximate analysis/%		Lower heating value (LHV)/kJ·kg^{-1}
C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}	M_{ar}	A_{ar}	23 440
61.7	3.7	8.56	1.12	0.6	15.5	8.8	

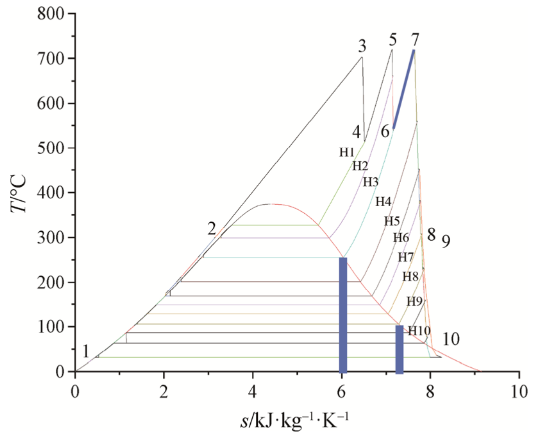


Fig. 2 *T-s* diagram of the 700°C A-USC reference system

Table 3 Steam extraction superheat degrees of regenerative heaters in reference systems

Extraction steam stage	700°C double reheat A-USC reference system		
	Pressure/MPa	Temperature /°C	Superheat degrees/°C
1	13.08	520.6	189.4
2	8.66	657.1	356.7
3	3.66	508.1	263.0
4	1.60	593.6	392.2
5	0.80	481.8	313.2
6	0.48	409.0	260.4
7	0.268	233.0	105.0
8	0.13	254.0	148.3
9	0.064	178.8	92.4
10	0.024	93.0	29.9
Extraction steam stage	**600°C double reheat USC system [8]**		
	Pressure/MPa	Temperature /°C	Superheat degrees/°C
1	10.28	418.3	105.3
2	5.84	536.7	262.9
3	3.28	445.5	206.6
4	1.89	548.0	338.5
5	1.10	468.2	284.3
6	0.69	396.1	232.0
7	0.38	315.6	174.3
8	0.13	201.6	94.1
9	0.04	84.5	10.9
10	0.016	55.6	0.0

The steam extraction superheat degrees comparisons of the 700°C reference system and the 600°C double reheat USC reference system in Ref. [8] under 100%THA load are shown in Table 3. The extraction steam superheat degrees of the 700°C reference system are higher than those of the 600°C USC system. The average superheat degree of 1–8 stages extraction steam of the 700°C reference system is 253°C, and the highest superheat degree is as high as 392.2°C at the fourth stage. However, the 600°C USC system's average superheat degree is 41°C lower than that of the 700°C reference system. The large heat exchange temperature differences corresponding to the regenerative heater for 700°C reference system have a great impact on the unit performance. Therefore, there is still room for further energy saving and energy consumption reduction.

2.2 Model simulation and assumptions

The Ebsilon Professional (EB) commercial software, which is widely used to optimize the thermal cycle process in power generation system, is used to simulate the energy equilibrium and system performances for the studied cases of 700°C A-USC units [8–9, 11, 15]. The software calculates the system thermal balance based on the first law of thermodynamics and simulates the variable working conditions of the power generation unit based on the Friuli Greig formula, which can be expressed as follows:

$$\frac{G_1}{G}=\sqrt{\frac{p_{01}^2-p_{21}^2}{p_0^2-p_2^2}}\sqrt{\frac{T_0}{T_{01}}} \tag{1}$$

where, G, T_0, p_0 and p_2 are the steam mass flow rate, temperature, pre-stage and post-stage pressures of the steam turbine at the design load condition, t/h, °C, MPa and MPa, respectively; G_1, T_{01}, p_{01} and p_{21} are the steam flow rate, temperature, pre-stage and post-stage pressures of the steam turbine at variable load conditions, t/h, °C, MPa and MPa, respectively.

In the prototype model, some assumptions are as follows:

(1) Regenerative steam extraction pressures and pipeline pressure drops at different conditions are based on that in Ref. [11];

(2) The pressure drops of SHPC, HPC, IPC and LPC heaters are 3.0%, 5.0%, 5.0% and 5.0%, respectively;

(3) The pressure drops of the first reheater, the second reheater, as well as pipelines are 6.4%, 6.4% and 10.2%, respectively;

(4) The absolute pressure drop of the boiler inlet feed water is 1.5 MPa;

(5) The isentropic efficiencies of SHPC, HPC, IPC and LPC are 0.89, 0.90, 0.935 and 0.9 (100%THA), respectively;

(6) The generator efficiency is 0.99; feed water pump efficiency is 0.85; the BEST isentropic efficiency is 0.90 (100%THA);

(7) Each system's power output (electricity) is set at 660 MW (100%THA).

2.3 Calculation model and validation

The data of a typical N660 MW-30 MPa-600°C/ 620°C/620°C double reheat USC power plant from

Table 4 Extraction steam parameters comparison of literature [8] values with simulation results of 600°C reference USC

Extraction stage	Pressure/MPa	Temperature/°C		Mass flow/t·h^{-1}	
		Literature [8]	Simulation results	Literature [8]	Simulation results
1	10.280	417.5	418.3	182.0	182.4
2	5.836	336.2	336.7	120.8	121.0
3	3.279	445.0	445.5	73.6	73.8
4	1.888	347.5	348.0	46.2	46.3
5	1.096	468.0	468.2	133.0	133.2
6	0.685	395.5	396.1	45.2	45.6
7	0.375	315.2	315.6	64.0	63.9
8	0.132	201.0	201.6	61.5	61.8
9	0.036	84.2	84.5	34.0	33.9
10	0.016	55.4	55.6	36.5	36.8

Ref. [8] are chosen to validate the model's reliability. The comparisons of extraction steam parameters between design values and simulation results of the N660 MW-30 MPa-600°C/620°C/620°C USC plant are listed in Table 4. The errors are less than 1%.

2.4 Thermal performance calculation method

The unit consumption analysis method is a kind of exergy analysis method [22, 23]. It can directly show the exergy loss of each equipment in the form of energy consumption distribution, which is easy to be understood. It reveals the energy consumption distribution characteristics of each unit, process and the overall system, which provides a clear guidance for the system optimization.

For the 700°C A-USC power generation system, the input exergy can be expressed as follows:

$$F \cdot e_F = P \cdot e_P + \sum_{i=1}^{k} I_i \tag{2}$$

where, e_F, e_P represent the exergy per unit of coal and electricity, kJ/kg, kJ·(kW·h)$^{-1}$, respectively; F and P represent the coal consumption and power generation of the system, kg, kW·h. Assuming that the system has k equipment or processes, I_i represents the exergy loss of the i-th equipment, kJ. Further deducing the above formula, the general expression of the actual unit fuel consumption of 700°C A-USC system can be obtained as follows:

$$b = \frac{F}{P} = \frac{e_P}{e_F} + \sum_{i=1}^{k} \frac{I_i}{P \cdot e_F} = b_{\min} + \sum_{i=1}^{k} b_i \tag{3}$$

where, b is the total fuel consumption rate of the process, kg·(kW·h)$^{-1}$; $b_{\min}$ is the theoretical minimum fuel unit consumption, which is the fuel consumption per kW·h without any exergy destruction, kg·(kW·h)$^{-1}$; b_i is the additional fuel consumption rate of the i-th equipment due to the exergy destruction in the process, kg·(kW·h)$^{-1}$.

The theoretical minimum fuel consumption rate for power generation is as follows:

$$b_\mathrm{e}^{\min} = e_P / e_F = 122.9\ \mathrm{g}\cdot(\mathrm{kW}\cdot\mathrm{h})^{-1} \tag{4}$$

Additional exergy loss of the i-th equipment is as follows:

$$I_i = \sum E_{i,\mathrm{in}} - \sum E_{i,\mathrm{out}} \tag{5}$$

$\sum E_{i,\mathrm{in}}$ is the total exergy flowing into the device, kW; $\sum E_{i,\mathrm{out}}$ is the total exergy flowing out of the device, kW.

The calculation formula for the additional unit consumption rate of the i-th equipment is as follows:

$$b_i = \frac{I_i}{P \cdot e_F} = 122.9 \frac{I_i}{P} \tag{6}$$

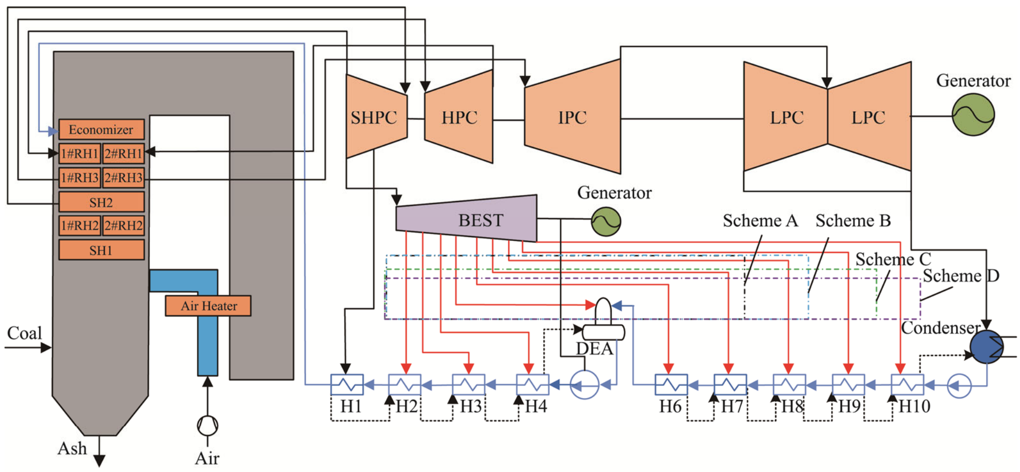
Power generation efficiency η is calculated as follows:

$$\eta = 122.9 / b \tag{7}$$

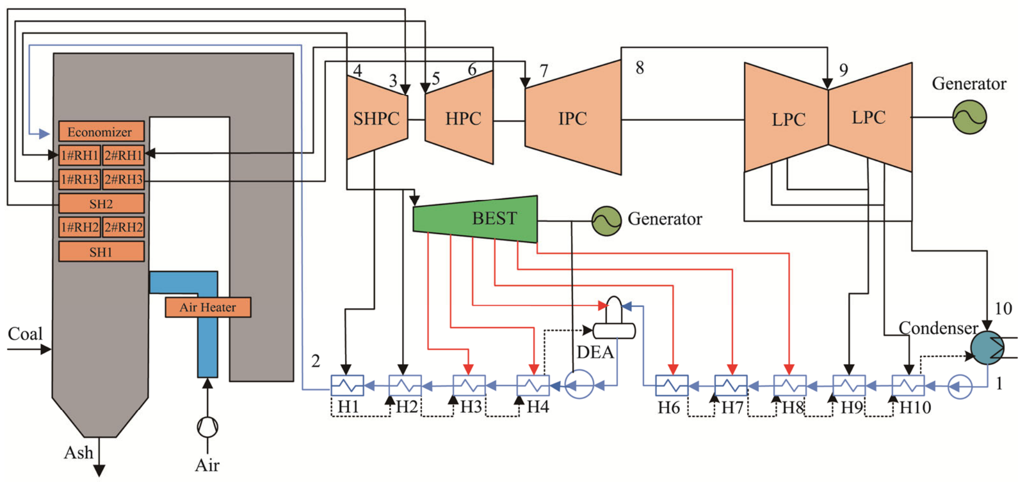
3. Optimization Thermal Systems of 700°C Double Reheat A-USC

3.1 700°C double reheat thermal system with BEST (system 1)

Due to the relative high superheat degrees for the 1–8 stages extraction steam, an optimized system integrated with BEST is proposed to further reduce superheat degrees and improve the power generation efficiency. Ref. [11] proposed to replace the 2–7 stages regenerative steam extraction with BEST, in which the steam extractions of 2–7 stages regenerators are from the BEST instead of being extracted from the original HPC and IPC steam turbines. This paper further studies how to optimize the replaced steam extraction stage number and location of BEST. Therefore, five thermal systems with BEST are proposed and the flowcharts are shown in Fig. 3. Scheme A is to replace the 2–7 stages regenerative extraction steam by BEST which is similar to the



(a) The thermal system configurations of Scheme A, Scheme B, Scheme C and Scheme D for 700°C A-USC integrated with BEST



(b) The thermal system configuration of 700°C A-USC integrated with BEST replacing 3–8 stages

Fig. 3 Flowcharts of system 1 with different schemes

literature [11]; scheme B is to replace the 2–8 stages regenerative extraction steam by BEST; scheme C is to replace the 2–9 stages regenerative extraction steam by BEST; scheme D is to replace the 2–10 stages regenerative extraction steam by BEST, and scheme E is to replace the 3–8 stages regenerative extraction steam by BEST. The inlet steam of BEST is part of the SHPC cylinder exhaust steam. The BEST can drive the feedwater pump directly, and the excess shaft power can also be used for power generation. According to the actual operating data in Ref. [10], the isentropic efficiency of BEST in this scheme is set as 90% under 100%THA condition.

The thermal performances of five different schemes are shown in Table 5. It can be seen that power generation coal consumption rate of scheme E is the lowest. Therefore, it is selected as the optimized system 1. The power generation coal consumption rate is 233.6 $g\cdot(kW\cdot h)^{-1}$, 1.88 $g\cdot(kW\cdot h)^{-1}$ lower than that of the 700°C reference unit and 1.2 $g\cdot(kW\cdot h)^{-1}$ lower than that of scheme A. The comparison result sequence of the main steam mass flow is scheme E>scheme A>700°C reference unit. However, the BEST extraction steam mass flow rate of scheme E is lower than that of scheme A. In scheme E, 324.3 $t\cdot h^{-1}$ exhaust steam from the SHPC enters BEST instead of reheat steam, resulting in the ratio of the first reheat steam mass flow to the main-steam mass flow is decreased from 93.5% to 60.6%. The comparisons of superheat degrees and extraction steam mass flow rate of cylinders for the 700°C reference system, scheme A and scheme E (100%THA) are shown in Fig. 4. The superheat degrees of scheme E have been decreased obviously after using BEST, which can effectively reduce the irreversible loss. The average superheat degree of scheme E at 100%THA is 75.8°C, which is 139.2°C lower than that of the reference system and is 26.64°C lower than that of the scheme A. The superheat degrees of extraction steam in H8, H9, and

Table 5 Thermal performances of different schemes of system 1

Items	700°C Reference system	Scheme A	Scheme B	Scheme C	Scheme D	Scheme E
Power output/MW	660	660	660	660	660	660
Main-steam flow rate/t·h^{-1}	1419.9	1449.7	1441.3	1408.7	1419.1	1458.7
BEST extraction steam pressure/MPa	/	7.32	7.32	7.32	7.32	7.32
BEST extraction steam flow rate/t·h^{-1}	/	367.1	407.9	416.3	513.0	324.3
Feedwater temperature/°C	323.5	323.5	323.5	323.5	323.5	323.5
Condenser flow rate/t·h^{-1}	865.2	825.2	822.6	835.0	828.4	838.4
Fuel consumption/t·h^{-1}	200.41	200.01	199.86	200.50	201.50	199.14
Standard coal consumption/t·h^{-1}	160.49	160.15	160.05	160.9	161.36	159.47
Power generation coal consumption rate/ g·(kW·h)$^{-1}$	235.48	234.80	234.69	235.20	236.12	233.60
Power generation efficiency/%	52.19	52.23	52.37	52.12	52.05	52.61

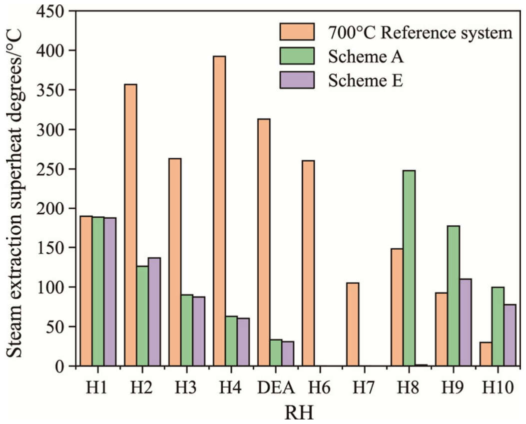


Fig. 4 The superheat degrees comparison of 700°C reference system, scheme A and scheme E (100%THA)

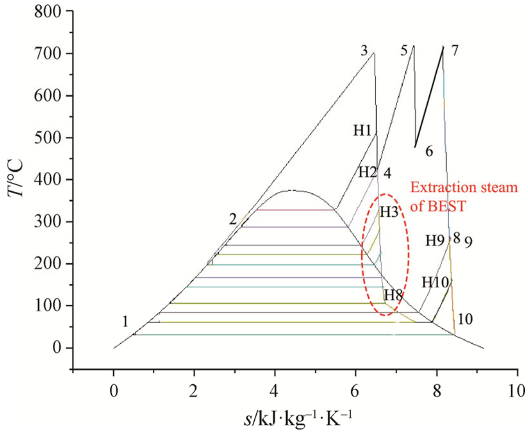


Fig. 5 *T-s* diagram of the optimized system 1

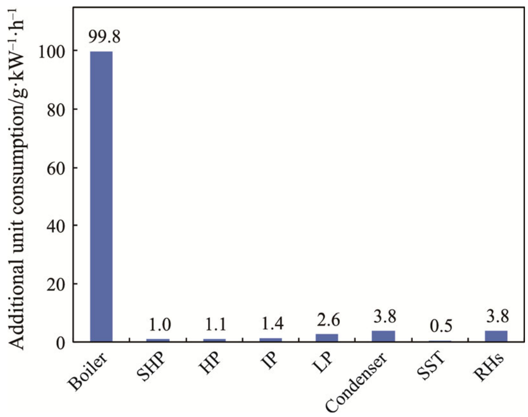


Fig. 6 Additional unit consumption distributions of 700°C reference unit in 100%THA condition

H10 in schemes A and E are higher than those in the reference system. The main reason is the LP parameters of the reference system are different from those of schemes A and E. The extraction steam pressures of double reheat steam of schemes A and E are optimized by genetic algorithm in EB. The inlet enthalpies of LP in schemes A and E are higher than that of the reference system resulting in the higher superheat degrees in H8, H9, and H10 in schemes A and E. The enthalpy of LP in schemes A and E is 3370 kJ/kg, while the enthalpy of LP in the reference system is 3111.7 kJ/kg.

Fig. 5 shows the *T-s* diagram of the optimized system 1. It can be seen that the entropy increase of system 1 is decreased obviously than that of the 700°C reference system (Fig. 2) from H3 to H8. The heat required for the reheat process is reduced compared with Fig. 2.

Fig. 6 shows the additional unit consumption distributions of the 700°C reference unit in 100%THA condition and Fig. 7 shows additional unit consumption differences of subsystems between the optimized system 1 and the 700°C reference unit in 100%THA condition. The comparisons of extraction steam mass flow rates of cylinders for the 700°C reference system, scheme A and scheme E (100%THA) are shown in Fig. 8. It can be seen than the additional unit consumption of boiler is the biggest among the unit consumption distributions. The additional unit consumptions of HPC, IPC, condenser and RHs are decreased while the additional unit consumptions of boiler, SHPC, LPC are increased in the optimized system 1. That's because the superheat degrees of H3-H8 are decreased; meanwhile, the extraction steam mass flow rates of HPC, IPC and condenser of optimized system 1 are lower than those of the 700°C reference unit but the extraction steam mass flow rate of SHPC of optimized system 1 is higher than that of the 700°C reference unit. It can be seen that the comparison sequence of the overall extraction steam mass flow is 700°C reference unit>scheme A>scheme E. Schemes A and E don't extract steam from HPC and IPC cylinders resulting in the additional unit consumption decrease of HPC and IP. The SHPC extraction steam mass flow rate of scheme E is higher than that of the 700°C reference unit but the LPC steam extraction steam mass flow rate is lower than that of the 700°C reference unit. However, as shown in Fig. 7, the additional unit consumption of LP in the optimized system 1 is higher than that of 700°C reference unit. That is because the inlet enthalpy of LP in optimized system 1 is higher than that of the reference system although the LP steam extraction steam mass flow

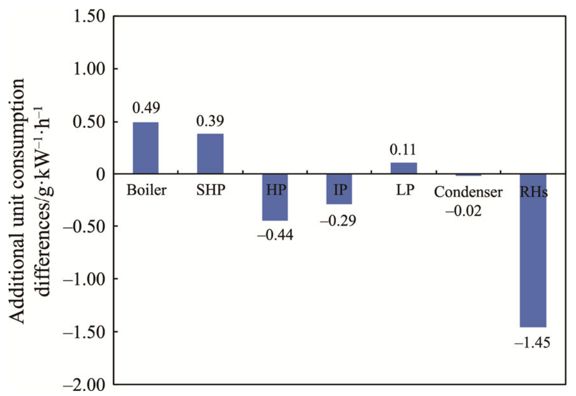


Fig. 7 Additional unit consumption differences of subsystems between the optimized system 1 and 700°C reference unit in 100%THA condition

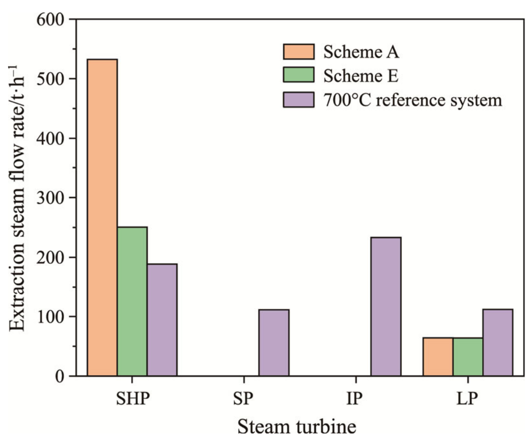


Fig. 8 Comparison of the extraction steam flow rate of 700°C reference system, scheme A and scheme E (100%THA load)

rate is lower than that of the 700°C reference unit. The additional unit consumption of the boiler is increased because the ratio of the first reheat steam mass flow to the main-steam mass flow is decreased and the heat required for the reheat process is reduced.

3.2 700°C double reheat thermal system simultaneously integrated with both OSCs and BEST (system 2)

Although the optimized system 1 has reduced the average superheat degree of RHs, the superheat degrees of the first, the second and the ninth stages regenerative extraction steam are still relatively high (as shown in Fig. 4). Therefore, new systems integrated with the OSCs based on the optimized system 1 are proposed (system 2).

How to rationally arrange the position of OSC is carried out by adopting 6 different combinations. The first scheme is to add an OSC in front of the 1st stage regenerator; the second scheme is to add an OSC in front of the 2nd stage regenerator; the third is to add an OSC in front of the 9th stage regenerator; the fourth is to add two OSCs in front of the 1st+2nd stages regenerators; the fifth is to add two OSCs in front of the 1st+9th-stages regenerators; the sixth is to add three OSCs in front of 1st+2nd+9th stages regenerators. The comparisons of thermal performances of different schemes are shown in Table 6. The coal consumption rates of 1st stage regenerator with OSC scheme, 1st+2nd stages regenerators with OSC scheme and 1st+2nd+9th-stages regenerator with OSC are the lowest among these schemes under the same load of 660 MW. Because of a slight difference in coal consumption rate among these three schemes, the scheme of 1st+2nd stages regenerators with OSC scheme is selected as the optimized system 2 based on the economic performance considerations. Fig. 9 shows the flowchart of the optimized system 2. The coal consumption rate for power generation of the optimized system 2 is 232.08 g·(kW·h)$^{-1}$, which is 1.52 g·(kW·h)$^{-1}$ lower than that of the optimized system 1. The main-steam mass flow rate of the optimized system 2 is increased by 69.8 t/h than that of the optimized system 1, but the BEST extraction steam mass flow rate of the optimized system 2 is 6.9 t/h lower than that of the optimized system 1.

Fig. 10 shows the superheat degrees of the reference unit, the optimized system 1 and the optimized system 2 (100%THA). The superheat degrees of 1st stage and 2rd stage regenerators are decreased obviously. Average steam extraction superheat degrees of the optimized system 1, the optimized system 2, and the 700°C reference system in variable load conditions are shown in Fig. 11. The average superheat degrees of these three systems are 198°C, 76°C and 49°C, respectively. The

Table 6 Comparison of thermal performance indexes in all schemes of system 2

Items	700°C Reference system	Optimized system 1	System 2					
			1st stage regenerator adding OSC	2nd stage regenerator adding OSC	9th stages regenerator adding OSC	1st+2nd stages regenerators adding OSC	1st+9th stages regenerators adding OSC	1st+2nd+9th stages regenerators adding OSC
Power output/MW	660	660	660	660	660	660	660	660
Main-steam flow rate/t·h^{-1}	1419.9	1458.7	1505.4	1475.14	1457.62	1528.5	1502.82	1528.85
Feed water temperature/°C	323.5	323.5	336.84	326.24	321.49	343.5	336.74	344.19
Fuel consumption/t·h^{-1}	200.41	199.14	198.68	199.92	200.19	198.15	198.69	198.11
Standard coal consumption/t·h^{-1}	160.49	159.47	159.11	160.10	160.31	158.69	159.12	158.65
Coal consumption rate for power generation /g·(kW·h)$^{-1}$	235.48	233.60	232.84	234.66	235.16	232.08	232.89	231.87
Power generation efficiency/%	52.19	52.61	52.78	52.37	52.26	52.96	52.77	53.00

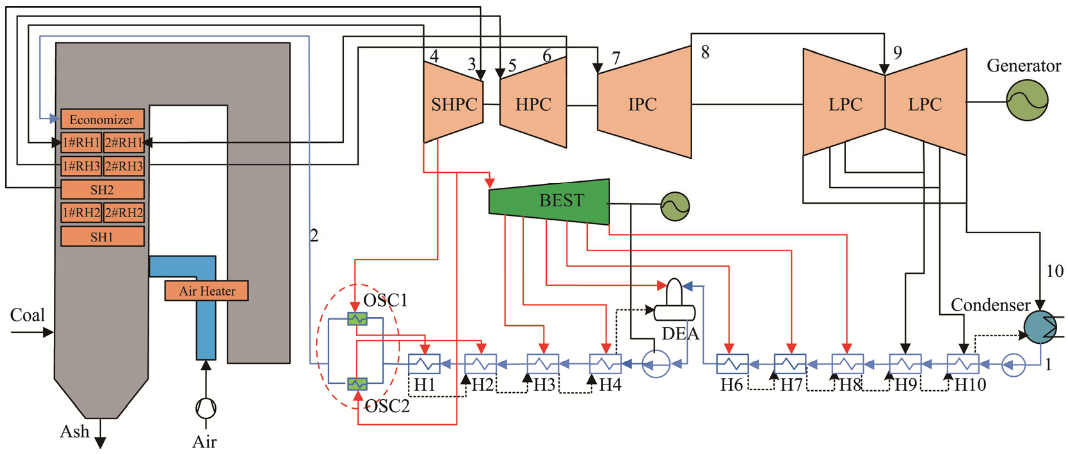


Fig. 9 Flowchart of the optimized system 2

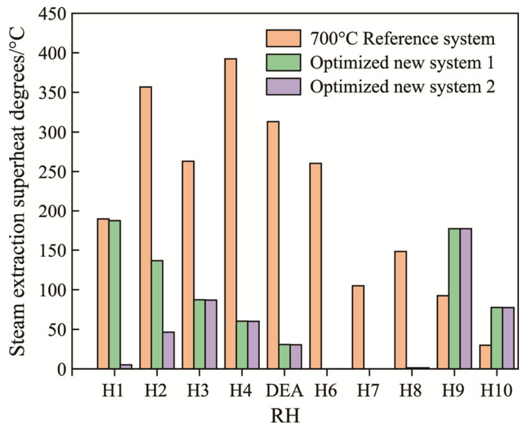


Fig. 10 The superheat degrees comparison of the reference unit, the optimized system 1 and the optimized system 2 (100%THA)

average superheat degree of the optimized system 2 is decreased by 27°C than that of the optimized system 1 (100%THA). With the decrease of the operating load, the superheat degree of the extraction steam is gradually increased. For example, in the 700°C reference unit, the superheat degree of the first stage regenerative heater of the unit is 187°C under 100%THA operation condition, and reaches up to 268°C under 40%THA operation condition, with an increase of 81°C. The average steam extraction superheat degrees of two optimized systems are decreased by 122.2°C and 149.5°C (100%THA), respectively. The optimized system 2 can effectively decrease the steam extraction superheat degrees.

Fig. 12 shows the additional unit consumption differences of subsystems between the optimized system 2 and the optimized system 1 in 100%THA condition. The comparisons of feedwater temperatures between the optimized system 1 and the optimized system 2 are shown in Fig. 13. It can be seen that the additional unit consumptions of boiler and RHs are decreased while the additional unit consumptions of SHPC, OSC are

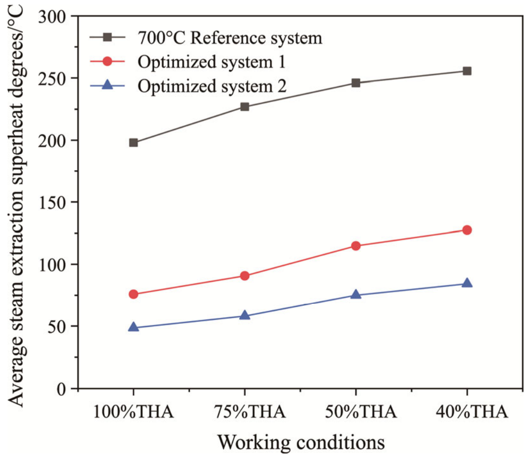


Fig. 11 Average steam extraction superheat degrees of the optimized system 1, the optimized system 2, and reference system in variable conditions

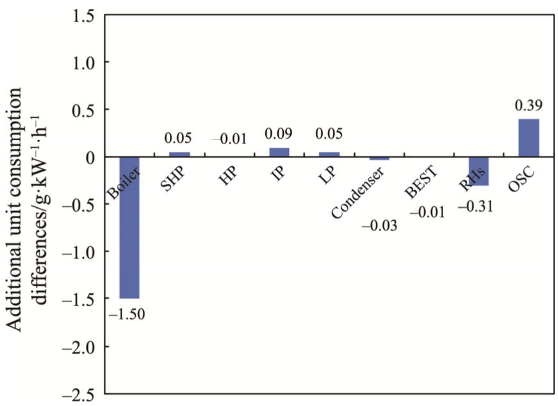


Fig. 12 Additional unit consumption differences of subsystems between the optimized system 2 and the optimized system 1 in 100%THA condition

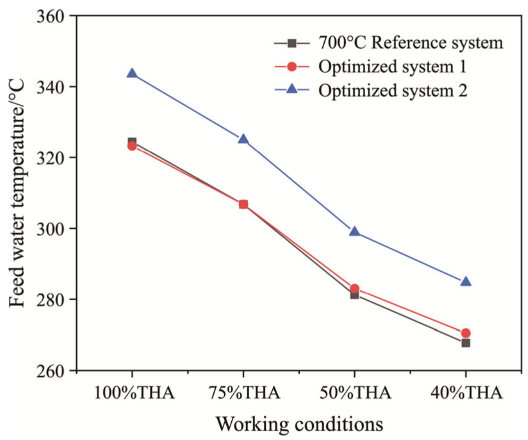


Fig. 13 The feedwater temperatures of the reference system, optimized system 1, and the optimized system 2 in variable conditions

increased. That's because the superheat degrees are decreased and the average feedwater temperature of the optimized system 2 is higher than those of the optimized system 1 and the 700°C reference system. The temperature of the feedwater entering the boiler (100%THA) of the optimized system 2 is increased by 20°C, which reduces the heat exchange temperature difference of the boiler. The extraction steam mass flow rate of the 1st stage regenerator is increased from 165.1 t/h to 183.7 t/h and the extraction steam mass flow rate of the 2rd stage regenerator is increased from 126.7 t/h to 140.3 t/h resulting in the increase of SHPC additional unit consumptions.

In order to illustrate the advantages of the optimized system in this paper, these references about 600°C/ 650°C/700°C USC coal-fired power generation units are discussed for comparative study on the thermal performances which include the power generation consumption rate, increment of the reduced coal consumption rate and the steam parameters. Table 7 shows the comparison of thermal performances with other different systems, including 600°C double reheat USC system in Ref. [8], 650°C single reheat A-USC system in Ref. [20], 700°C double reheat A-USC system in Ref. [11] and three systems in this paper. The scheme proposed in Ref. [8] is 660-MW 600°C double reheat USC system integrated with BEST from the third stage to the sixth stage. The scheme proposed in Ref. [11] is 1000-MW 700°C double reheat A-USC system integrated with BEST from second stage to the seventh stage. The scheme proposed in Ref. [20] is 1000-MW 650°C single reheat A-USC system without integrated with BEST. Compared with that of the 600°C double reheat USC system [8], the coal consumption rate of 700°C double reheat A-USC power plant is further decreased due to the increases of both steam temperature and steam pressure. For example, the coal consumption rates of 700°C reference unit, optimized system 1 and optimized system 2 are decreased by 21.7 $g\cdot(kW\cdot h)^{-1}$, 23.6 $g\cdot(kW\cdot h)^{-1}$, 25.12 $g\cdot(kW\cdot h)^{-1}$, respectively compared with Ref. [8], under 100%THA operation condition. The main steam mass flow rates of 700°C reference unit, optimized system 1 and optimized system 2 are decreased than 600°C double reheat USC system [8] based on the same output. Compared with that in Ref. [11], the coal consumption rates of 700°C optimized system 1 and optimized system 2 are decreased by 0.85 $g\cdot(kW\cdot h)^{-1}$ and 2.37 $g\cdot(kW\cdot h)^{-1}$, respectively under 100%THA operation condition because of the optimization of regenerator stage number and location of BEST and the adding of OSCs. Compared with the 650°C single reheat A-USC system in Ref. [20], the coal consumption rates of 700°C optimized system 1 and optimized system 2 are decreased by 3.3 $g\cdot(kW\cdot h)^{-1}$ and 4.82 $g\cdot(kW\cdot h)^{-1}$, respectively under 100% THA operation condition.

Table 7 Comparison of thermal performance with other different systems

Items			600°C double reheat USC system in Ref. [8]	650°C single reheat A-USC system in Ref. [20]	700°C double reheat A-USC system in Ref. [11]	700°C reference system	The optimized system 1	The optimized system 2
Power output		MW	660	1000	1000	660	660	660
Main steam	Mass flow	$t \cdot h^{-1}$	1688.1	2643.9	2013.8	1419.9	1458.7	1528.9
	Pressure	MPa	31	35	35	35	35	35
	Temperature	°C	600	650	720	700	700	700
First reheat steam	Mass flow	$t \cdot h^{-1}$	1506.5	/	1379.0	1327.5	884.1	875.0
	Pressure	MPa	9.8	7.4	8.23	12	6.5	6.5
	Temperature	°C	620	650	720	700	720	720
	Mass flow rate ratio	%	89.2	/	0.685	93.5	60.6	57.2
Double reheat steam	Mass flow	$t \cdot h^{-1}$	1312.5	/	1379.0	1116.5	884.1	875.0
	Pressure	MPa	3.0	/	1.48	3.4	1.5	1.5
	Temperature	°C	620	/	720	720	720	720
	Mass flow rate ratio	%	77.8	/	0.685	78.6	60.6	57.2
BEST inlet	Mass flow	$t \cdot h^{-1}$	366.4	/	/	/	324.3	317.4
	Pressure	MPa	11.1	/	/	/	7.36	7.36
	Temperature	°C	419.1	/	/	/	425.9	425.9
	Mass flow rate ratio	%	21.7	/	/	/	22.2	20.8
Rated back pressure		MPa	0.0045	0.0049	0.0045	0.0045	0.0045	0.0045
Power generation consumption rate		$g \cdot (kW \cdot h)^{-1}$	257.2	236.9	234.45	235.48	233.60	232.08
Increment		$g \cdot (kW \cdot h)^{-1}$	/	20.3	22.75	21.72	23.6	25.12

4. Off-Design Performance Analysis

4.1 Coal consumption rate analysis

In order to reveal the actual operation performances of different systems, the off-design performances are deeply investigated and the coal consumption rates of different systems are shown in Fig. 14. Fig. 15 shows the fuel saving amount of the optimized system 1, the optimized system 2 compared with the 700°C reference unit. It shows that under all working conditions, with the decrease of operating load, the coal consumption rates are gradually increased for those systems and the performances of optimized systems 1 and 2 are better than that of the reference system at each working condition. The coal consumption rate of 700°C double reheat A-USC power plant is decreased obviously compared with that of the 600°C double reheat USC system [8]. When the load is reduced, the fuel saving amount effects of the optimized system 2 are gradually reduced. For example, the coal consumption rate of 700°C optimized system 2 is decreased by 24.74 $g \cdot (kW \cdot h)^{-1}$ under 100%THA operation condition and decreased by 20.97 $g \cdot (kW \cdot h)^{-1}$ under 40%THA operation condition.

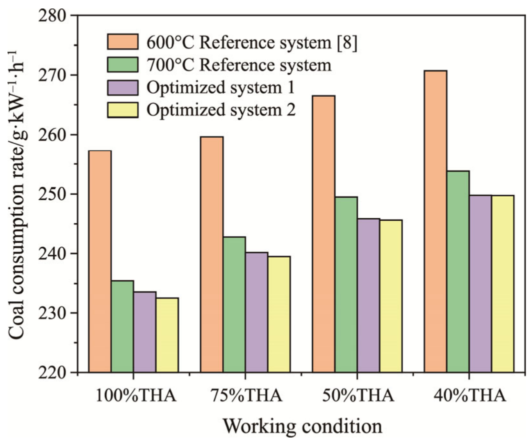


Fig. 14 The coal consumption rates of different systems in variable conditions

4.2 Additional coal consumption analysis of boiler

Fig. 16 shows the boiler additional unit consumptions for different systems under variable load operation conditions. It can be seen that as the load decreases, the boiler additional unit consumptions of different systems gradually increase; the order of the boiler unit consumptions for different systems from small to large is: the optimized system 2<the optimized system 1<700°C reference unit<600°C reference unit. The boiler additional unit consumption of 700°C A-USC power plant is decreased by more than 18 $g \cdot (kW \cdot h)^{-1}$ under 100%THA operation condition than that of the 600°C double reheat USC system [8]. Therefore, the boiler

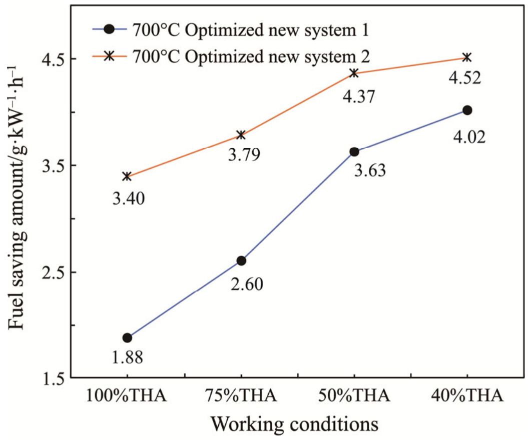


Fig. 15 The fuel saving amount of optimized system 1 and 2 compared with the 700°C reference unit in variable conditions

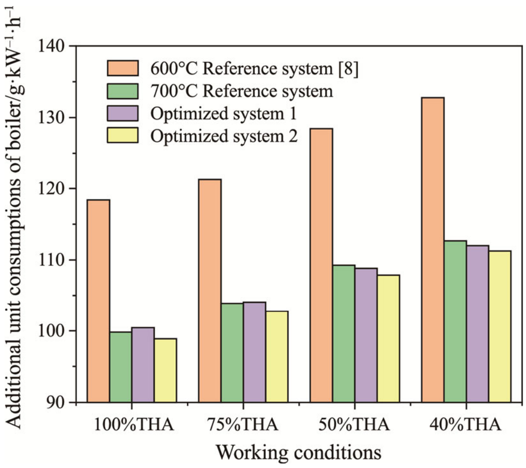


Fig. 16 Additional unit consumptions of boiler in variable load conditions

energy saving amount of 700°C A-USC power plant accounts for more than 80% to the overall energy saving amount. That's because the improvement of steam parameters decreases the heat transfer temperature difference between steam and flue gas. The boiler additional unit consumption of the 700°C optimized system 2 is lower than those of the optimized system 1 and 700°C reference unit because that the utilization of the OSC in system 2 can increase the feed water temperature.

4.3 Additional unit consumption analysis of steam turbine

Table 8 shows the total additional unit consumptions of steam turbines and each cylinder (SHPC, HPC, IPC, LPC), SST, and BEST of different systems under variable operating conditions. It shows that the total additional unit consumptions of the steam turbines for the optimized system 1, and the optimized system 2 are lower than that of reference unit, and the total additional unit consumption of steam turbine decreases with the decrease of operating load.

4.4 Additional unit consumption analysis of regenerative heaters (RHs)

Fig. 17 shows the additional unit consumptions of regenerative heaters for different systems under variable load operation conditions. It can be seen that the RHs additional unit consumptions for different systems decrease with the decreasing of operating load. The RHs additional coal consumption of 700°C reference system are greater than that of 600°C reference system [8] because of the higher superheat degree. The RHs additional unit consumptions of the 700°C optimized

Table 8 Additional unit consumptions of cylinders in variable load conditions, $g\cdot(kW\cdot h)^{-1}$

Working condition	Systems	SHPC	HPC	IPC	LPC	SST	BEST	Additional unit consumptions of cylinders
	700°C Reference system	0.97	1.07	1.35	2.62	0.52	/	6.53
100%THA	The optimized System 1	1.35	0.63	1.06	2.91	/	0.46	6.41
	The optimized System 2	1.39	0.62	1.06	2.89	/	0.46	6.42
	700°C reference system	0.98	1.09	1.37	2.62	0.39	/	6.45
75%THA	The optimized System 1	1.35	0.64	1.08	2.87	/	0.45	6.39
	The optimized System 2	1.36	0.64	1.08	2.86	/	0.45	6.39
	700°C reference system	0.99	1.10	1.39	2.52	0.30	/	6.3
50%THA	The optimized System 1	1.32	0.67	1.11	2.75	/	0.42	6.27
	The optimized System 2	1.31	0.66	1.11	2.75	/	0.42	6.25
	700°C reference system	0.99	1.11	1.41	2.46	0.27	/	6.24
40%THA	The optimized System 1	1.31	0.68	1.13	2.69	/	0.40	6.21
	The optimized System 2	1.29	0.68	1.13	2.70	/	0.40	6.20

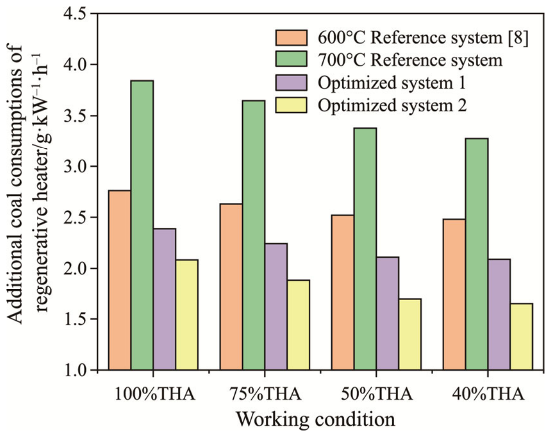


Fig. 17 Additional unit consumptions of RHs in variable conditions

system 1 and system 2 are all lower than that of the 700°C reference unit and the RHs additional unit consumption of the optimized system 2 is lower than that of the optimized system 1 because of the adding of 2 stages OSCs.

5. Conclusions

To further reduce the higher superheat degrees of regenerative steam extractions, two optimized 700°C double reheat advanced ultra-supercritical coal-fired power generation systems are proposed and analyzed by using the unit consumption analysis method. The main conclusions are as follows:

(1) The coal consumption rate of the 700°C double reheat A-USC power plant is decreased over 21.7 $g\cdot(kW\cdot h)^{-1}$ than that of the 600°C double reheat USC system due to the increases of both steam temperature and steam pressure.

(2) In view of the high superheat degrees of 1 to 8 stages extraction steam for 700°C reference system, five schemes integrated with BEST are proposed and the optimized system 1 is obtained. The calculating results show that the coal consumption rate of the optimized system 1 with the BEST to replace 3–8 stages extraction steam is the lowest, and 1.88 $g\cdot(kW\cdot h)^{-1}$ lower than that of the 700°C reference unit due to the obvious reduction of superheat degrees of extraction steams, which effectively reduces the irreversible loss.

(3) The optimized system 2 integrated with OSCs at 1st and 2nd stages regenerators on the basis of optimized system 1, has a further decreased coal consumption rate with 232.08 $g\cdot(kW\cdot h)^{-1}$, which is 1.52 $g\cdot(kW\cdot h)^{-1}$ lower than that of the optimized system 1.

(4) The performances of optimization systems 1 and 2 are better than that of the 700°C reference unit under all working conditions. With the decrease of operation load, the boiler unit consumption rate of optimized system 2 is the lowest due to the utilization of OSCs. Total additional unit consumption rates of steam turbines in the optimized systems 1 and 2 are lower than that of the 700°C reference unit. Total additional unit consumption rate of steam turbine and regenerative heater decrease with the decrease of operation load. The additional unit consumption rates of regenerative heaters for the optimized systems 1 and 2 are lower than that of 700°C reference unit.

Acknowledgements

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