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SYSTEM STUDY ON POWER PLANT BASED ON SUPERCRITICAL WATER GASIFICATION OF COAL

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ABSTRACT

Clean coal technology is a key way to ensure the energy security and sustainable development of China. Supercritical water gasification of coal is a representative clean coal technology, which can be integrated within thermal power plants. In this study, adapted layouts of power generation system based on supercritical water gasification of coal were proposed to further enhance the system energy efficiency. Models of adapted systems were developed by Aspen Plus, and their performance was simulated. The results showed that the efficient system layout increased the energy efficiency by 8.72%-pts to 48.24% in contrast to its comparison layout. This improvement is mainly due to the 40% decrease of exergy destruction in superheater of the systems through adaption, as well as higher inlet parameters of turbine.

Keywords: supercritical water gasification, power generation system, simulation study, performance comparison of systems

NONMENCLATURE

Abbreviations	
HP	High-pressure turbine
LP	Low-pressure turbine
HR	Heat regenerator
SCWG	Supercritical water gasification
SCWGC	SCWG of coal
Symbols	
H	Enthalpy
S	Entropy
T	Temperature
P	Pressure
e_x	Exergy of stream
$W_{L,ex}$	Exergy destruction of device
η_{ex}	Exergy efficiency of device

1. INTRODUCTION

Coal, accounting for 60.4% of energy consumption in China in 2017 [1], is the most essential primary energy in this country. The development of coal utilization technology plays an important role in energy security and economic development in China. Supercritical water gasification of coal (SCWGC) is a novel clean utilization technology of coal, aiming at efficient energy conversion and restriction of pollution emission.

Supercritical water gasification (SCWG) of organic material was proposed in 1978 to produce syngas with high heat value [2]. Due to the excellent characteristics of supercritical water, SCWG can be conducted efficiently with coal [3-4] and biomass [5]. During SCWG process, elements such as N and S deposit as inorganic salts, which benefits the air pollution control [6].

Since coal is a widespread energy source, SCWGC has become revolutionary technology which may has deep influence on the energy utilization of world. Some scholars have focused on the researches of SCWGC. Experiments of continuous gasification of coal were conducted [7], and the effects of parameters like temperature, pressure and catalysts were studied [8-10].

It's a proper choice to combine SCWGC with power generation system due to the high quality of electricity. But the amount of studies on SCWGC power generation were very limited. Guo [11] proposed a theoretical power generation system based on SCWG, which illustrated the feasibility of SCWGC power generation. And Chen [12] established a system featuring a relatively high efficiency with the existence of CO_2 capture.

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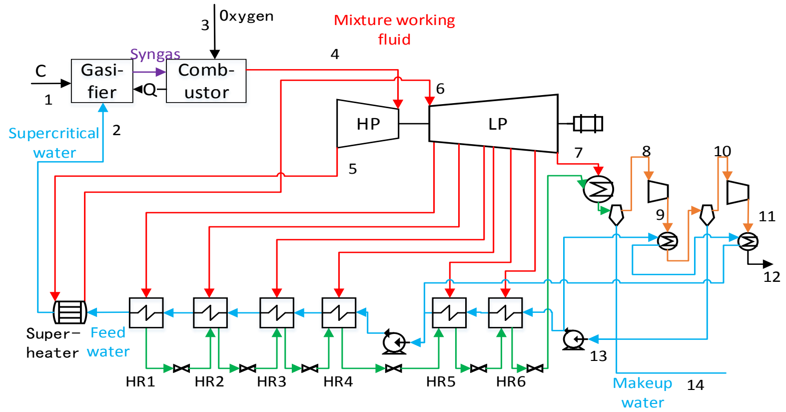

Fig.1 Flow Sheet of System SCED

In previous SCWGC power generation, the outlet stream of combustor with a high temperature was adopted to directly heat feed water. This design caused severe exergy destruction in heat exchange process, which accounted for a relatively large percentage of total value of the system. In this article, novel system was constructed mainly by adapting the location of superheater to reduce this irreversible loss. The effect of adaption was measured by simulation and evaluating the efficiency difference. This job was conducted on theory level and some restrictions of device and materials were ignored.

2. DESCRIPTION OF SYSTEM

In system proposed in reference [12], superheater was considered as the main restriction of efficiency since it caused severe exergy destruction. The system in Fig.1 was designed aiming to reduce its value, and it was called system with control of exergy destruction in superheater (SCED). The recovery of waste heat in cold end was also considered in it. Its comparison system, whose settings of superheater is shown in Fig.2, was only adapted to deal with the waste heat, and it hence was called system with recovery of waste heat (SRWH).

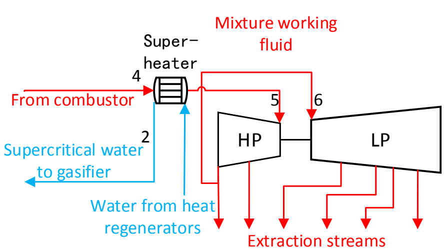

Fig 2 Flow Sheet of Superheater Part in System SRWH

In SCED system, coal, oxygen and supercritical water was converted into a mixture of H_2O and CO_2 through gasification and combustion process. The mixture was first guided to high-pressure turbine (HP) to generate power and the outlet stream of HP, whose temperature was relatively low, was used to perform the task of heating feed water. After the heat exchange, the mixture continued power generation in low-pressure turbine (LP). The back pressure of LP was 10kPa and two stages of compressors were arranged to increase the pressure to 1bar of CO_2 for its capture. The heat released from condensers after compressors was used to heat feed water and they were in parallel with HR5 and HR6.

For SRWH system, the layout except the part shown in Fig.2 was same as SCED system. The difference existed in that the mixture from combustor entered superheater to conduct heat exchange process first in SRWH system, and then flowed into turbines to generate power.

3. STUDY ON SYSTEM LAYOUTS

3.1 Simulation models

Process simulation software Aspen Plus was selected to simulate the behavior of proposed power generation systems. To simplify the operation, carbon was used to replace coal to avoid nonconventional component. The models provided by the software itself such as RStoic, Compr, MHeatX and Flash2 were adopted to simulate related processes.

The property method for working fluid with high temperature and high pressure was RKSMHV2, representing RKS equation of state integrated with modified Huron-Vidal mixing rule [13]. For streams under normal conditions, Peng-Robinson property method is a general solution.

The power consumption of compressors and pumps as well as power output of turbines were calculated by Aspen Plus. After that, the efficiency of the systems was calculated by following equations.

$$\eta = \frac{P_{\text{turbine}} - P_{\text{compressor}} - P_{\text{pump}} - P_{\text{oxy}}}{\dot{m}_C h v_C}$$

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η is the efficiency of system. $P_{turbine}$, P_{bottom}, $P_{compressor}$ and P_{pump} are the power output of turbines, power output of bottom cycle, power consumption of compressors and power consumption of pumps, respectively. $\dot{m}_C$ is the mass flow rate of carbon and hv_C is the heat value of carbon. P_{oxy} could be calculated using $P_{oxy} = \dot{m}_{oxy}\gamma_{oxy}$, where $\dot{m}_{oxy}$ is mass flow rate of oxygen and γ_{oxy} is the power consumption of unit-mass oxygen production. The value of γ_{oxy} was assumed as 0.31 kWh/kg.

3.2 Key parameters

The parameters of carbon, oxygen and makeup water as well as necessary internal parameters of system were specified in Aspen Plus and parameters of all streams in the system were calculated by the software. The parameters of main streams of systems are listed in Table 1 and Table 2.

The key parameters of heat regeneration subsystems of the two systems are listed in Table 3 and Table 4.

4. RESULTS AND DISCUSSION

4.1 Energy analysis of systems

The energy flow diagram of the SCED systems is shown in Fig.3. The energy input of the system was heat value of carbon, which were 32.76MW. The energy taken into systems by oxygen and makeup water was ignored. As can be seen in Fig.3, the total power output of turbine in system SCED was 20.03MW, among which 0.85MW was consumed by compressors, 0.41 MW was consumed by pumps and 2.97 MW was consumed by air separation unit. So ultimate efficiency of SCED was 48.24%. It could be calculated using same method that its comparison system, SRWH, had efficiency of 39.52%.

The comparison of power generation and consumption is shown intuitively in Fig.4. The SCED system had higher turbine output and the power consumption of the two systems were almost same. So SCED system showed higher efficiency. The high ability to generate power was mainly given by high inlet parameters of turbine since the mixture from combustor with high temperature and high pressure entered HP directly to generate power after the adaption of layout.

4.2 Analysis of superheater

Table 1 Parameters of Main Streams in System SCED

	T/ ℃	p/bar	Mass flow/kg·h^{-1}
1	25	250	3600
2	650	250	40000
3	25	250	9590.85
4	1494.51	250	53190.85
5	1172.13	65	53190.85
6	315.57	65	53190.85
7	45.62	0.1	34232.21
8	25	0.1	15080.88
9	141.80	0.35	15080.88
10	30	0.35	13795.86
11	125.20	1	13795.86
12	107.42	1	13795.86
13	25.16	0.1	40000
14	25	0.1	605.01

Table 2 Parameters of Main Streams in System SRWH

	T/ ℃	p/bar	Mass flow/kg·h^{-1}
1	25	250	3600.00
2	650	250	40000.00
3	25	250	9590.85
4	1494.51	250	53190.85
5	723.25	250	53190.85
6	391.76	32.02	48722.35
7	45.96	0.1	36545.87
8	25	0.1	15080.88
9	141.80	0.35	15080.88
10	30	0.35	13795.86
11	125.20	1	13795.86
12	107.42	1	13795.86
13	25.16	0.1	40000.00
14	25	0.1	605.01

Table 3 Main Parameters of Heat Recovery Subsystem in System SCED

Parameters	HR1	HR2	HR3	HR4	HR5	HR6
Inlet pressure of stream extractions (bar)	55.43	32.02	15.00	5.81	4.11	1.11
Extraction ratio	0.108	0.084	0.069	0.059	0.015	0.021
Outlet temperature of feed water (°C)	260.0	225.3	188.3	149.5	106.1	65.8

Table 4 Main Parameters of Heat Recovery Subsystem in System SRWH

Parameters	HR1	HR2	HR3	HR4	HR5	HR6
Inlet pressure of stream extractions (bar)	55.43	32.02	15.00	5.81	4.11	1.11
Extraction ratio	0.084	0.071	0.062	0.055	0.018	0.022
Outlet temperature of feed water (°C)	260.0	225.3	188.3	149.5	106.1	65.8

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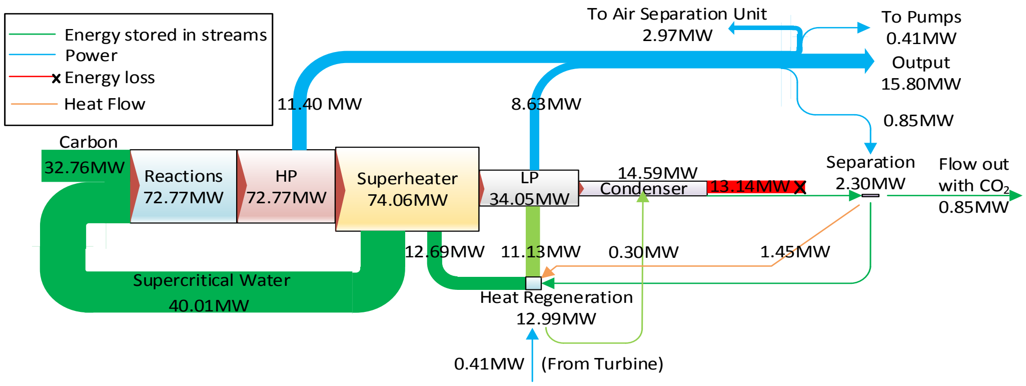


Fig 3 Energy Flow Diagram of System SCED

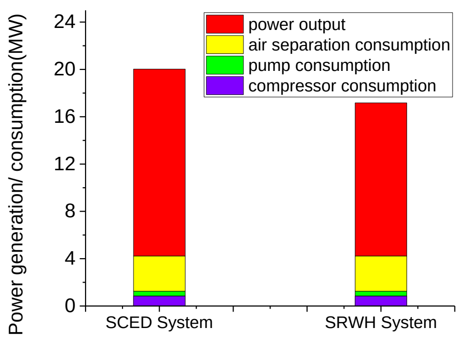


Fig 4 Power Generation and Consumption of Two Systems

Another main reason for the improvement of system is the decrease of exergy destruction in superheater. Superheater was established to heat the feed water in order to provide supercritical water for the gasification process. Due to the relatively high temperature difference between two working fluid, large amounts of exergy destruction existed in superheater. The value of exergy destruction was reduced by changing the sequence of superheater and HP. Exergy analysis

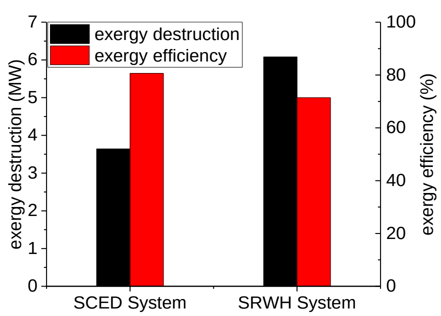
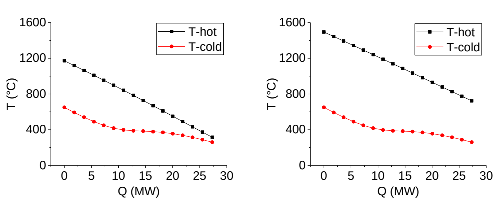


Fig 5 Exergy Destruction and Efficiency of Superheaters



(a) SCED (b) SRWH

Fig.6 T-Q Diagram of Superheaters

referred to superheaters was conducted to measure the effect of this adaption.

Fig.5 shows the results of the exergy calculation of superheaters. The superheater in system SCED had lower exergy destruction of 3.64MW and higher exergy efficiency of 80.7% than that in system SRWH. The exergy destruction of SCED accounted for approximately 60% of the value in SRWH, demonstrating the effect of adaptation in hot end. Fig.6 shows the T-Q diagrams of the two superheaters and the temperature difference can be seen clearly. The inlet temperature of hot side of decreased from 1494.5°C to 1172.1°C while that of cold side kept constant. So the superheater in system SCED had less irreversible available energy loss and hence showed better performance.

4.3 Discussion about the layout of systems

The results of simulation and calculation showed that system SCED achieved an efficiency of 48.24% while that value of system SRWH was 39.52%. The efficiency difference pointed out the effect of the sequence exchange of superheater and HP in hot end since it allowed mixture with high temperature and pressure to generate power, which followed the principle of cascade utilization of energy and enhanced the power output of turbine. Also it had less exergy destruction as the inlet temperature of hot side decreased, so more available energy entered LP, which benefited the system performance.

This study was conducted from the angel of theoretical analysis and some problems on the level of device manufacture were ignored. For superheater, the horrible temperature condition made it difficult to manufacture such a heat exchanger for SCED system. But in SRWH, the superheater might be designed as a part of the combustor which was more possible to be realized. For HP turbine, the inlet temperature and pressure of HP in SCED system was 1494.5°C and 250bar, respectively.

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The technology of gas turbine might be adopted to deal with the high temperature, but the high pressure might become new problem. For LP turbine, the exhaust stream of LP had high humidity, which may cause damage to the blades at last stages of LP. These disadvantages may restrict the application of SCED system. So although SCED system showed high efficiency, there was still challenges on its way of further development.

5. CONCLUSION

Aiming at restriction of high exergy destruction in superheater in SCWGC power generation system, system layout study was conducted in this article. System SCED was constructed to deal with this problem while system SRWH was established as its comparison. The main difference between the systems depended on the location of superheater, and the layouts in the cold end were designed according to the outlet parameters of the two different superheaters.

System SCED featured superheater behind HP with an exergy destruction of 3.64MW in superheater, which was 40% lower than its comparison system SRWH. System SCED also had higher inlet parameters of HP, which enhanced the power output of turbine. These advantages gave system SCED relatively high efficiency of 48.24% while system SRWH showed efficiency of 39.52%. The results showed the effect of the adaption of the layout in hot end, but the new system of SCED may face challenges in device manufacture. Related future researches will be conducted continuously and make contributes to the application of SCWGC power generation.

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