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Thermodynamic Analysis of a novel Chemical Recuperative Power Plant based on Supercritical Water Coal Gasification

Xiaodong Xue[1,2], Changchun Liu[2,3], Wei Han[2,3*], Zefeng Wang[2,3]

1 North China Electric Power University, Beijing 102206, China

2 Institute of Engineering Thermophysics, Chinses Academy of Sciences, Beijing 100190, China

3 University of Chinese Academy of Sciences, Beijing, 100190, China

ABSTRACT

Clean and efficient coal utilization technology becomes increasing attention. Supercritical water coal gasification technology has the advantages of low gasification temperature and clean production. In this paper, a novel integrated system of supercritical water coal gasification and power generation is proposed. The innovation of the proposed system is to use the high-temperature flue gas of gas turbine to provide heat for the supercritical water coal gasification process instead of oxidation of coal. The results show that the net power generation efficiency of the proposed system is 53.80% and the exergy efficiency is 52.53%, which are approximately 4.90 and 4.78 percentage points higher than that of the reference system, respectively. Finally, the chemical energy and heat of syngas is converted to power through comprehensive cascade utilization. This work provides a quite promising approach for the clean and highly efficient coal utilization.

Keywords: Supercritical water coal gasification; Power generation; Cascade utilization; Energy level

NONMENCLATURE

Abbreviations	
AGR	acid gas removal unit
ASU	air separation unit
COMB	combustor
COMP	compressor
CON	condenser
EUD	energy utilization diagram
FER	flue gas energy recovery
GEN	generator
GF	gasifier
GT	gas turbine
HE	heat exchanger
HHV/LHV	high/low heating value
SCW	supercritical water
SEP	separator
SER	syngas energy recovery
SH	syngas heat exchanger
SP	supplemental water pump
ST	steam turbine
TUR	turbine
RV	pressure release valve
VP	vacuum pump
SCWG	supercritical water gasification
LP/HP	low/high pressure pump
LT/HT	low/high pressure steam turbine
LPD/HPD	low/high pressure steam drum
Symbols	
A	energy level
E	exergy, kW
H	energy, kW
Q	heat, kW
T	temperature, °C
W	power, kW
m	mass flow, kg/h
η	efficiency, %

1. INTRODUCTION

Coal still plays an important role in the primary energy consumption, however the traditional direct coal-fired power generation makes a huge loss of chemical energy and causes serious environmental pollution. The clean, high-efficiency and low-carbon application technology of coal has become very important and will occupy an extremely important position in the future energy [1]. The gasification process can realize clean conversion of coal [2]. However, the traditional coal gasification needs pure oxygen as gasifying agent, and the preparation of pure oxygen needs air separation unit with high energy consumption, which reduces the efficiency of the system. Therefore, an urgent need exists for development of more cleaner and efficient coal conversion and utilization processes.

Coal gasification in supercritical water was generally considered as the most promising clean utilization technology of coal [3], which can convert coal to syngas, while the pollutants containing S and N deposit as solid residual and can be discharged from the gasifier [4]. Currently, there are many researches on coal gasification in supercritical water in the world, which are mainly focused on production of hydrogen, methane and methanol from coal gasification [5,6].

However, at present, there are few studies on the combustion of syngas for power generation by directly coupling with the combined cycle after coal gasification in supercritical water. In this paper, a novel power generation system based on coal gasification in supercritical water using gas turbine exhaust gas to provide heat for the gasification process is proposed and analyzed, which can completely avoid the coal combustion directly and better match the gasification heat generated in the process of coal gasification in supercritical water with the heat in the combined cycle to realize the comprehensive cascade utilization of chemical energy and physical energy. The net power generation efficiency and exergy destructions are studied and compared with other mature technologies.

2. SYSTEM DESCRIPTION

2.1 Specific description of the proposed system

The general layout of power generation system integrated coal gasification in supercritical water is illustrated in Fig. 1. The gasification products mainly include H_2, CH_4, CO and CO_2. The syngas from the GF is heat exchanged in turn in the heat exchangers SH1 and SH2, then the pressure is reduced by RV, and finally the water in the syngas is separated from the SEP. Secondly, the syngas enters the COMB and combusts after mixing from the air from the COMP, and then enter the TUR. The flue gas after power generation in TUR, still has a very high temperature, in order to better utilize this part of the sensible heat, so that the flue gas into the GF, supply heat for gasification process. After that, the flue gas from GF goes to the combined cycle to produce high temperature and high-pressure steam, and then enters the HT and LT to generate electricity. Finally, the water condensed by CON passes through VP and LP.

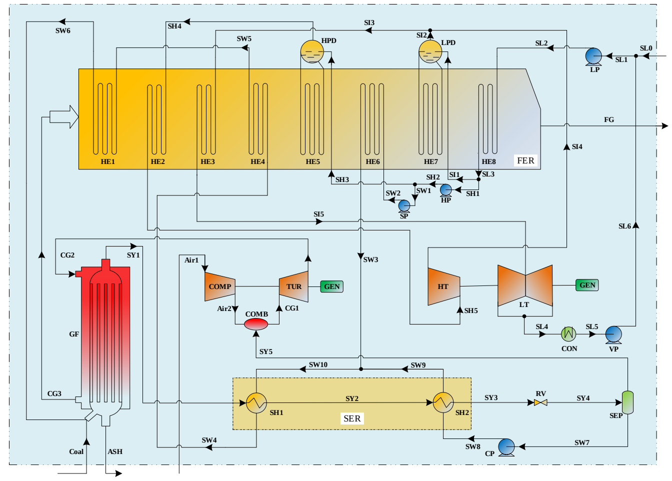

Fig. 1. The schematic diagram of the proposed system

2.2 Specific description of the reference system

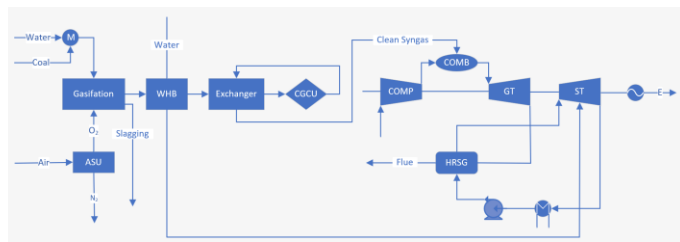

Fig. 2. The schematic diagram of the reference system

In this paper, the integrated gasification combined cycle (IGCC) based on the GE entrained flow gasifier is selected as the reference system [7]. The schematic diagram of the reference system is illustrated in Fig. 2. The pulverized coal with a coal concentration of 63% is mixed with 98% pure O_2 from the air separation unit (ASU) and enters the GE gasifier, where a gasification reaction takes place to convert the chemical energy of the coal into the chemical energy of syngas at the temperature of 1346 °C and pressure of 3 MPa. Then, the produced high-temperature syngas is introduced to the waste heat boiler for syngas heat recovery to generate steam for power generation. Afterward, the syngas is desulphurized and purified in acid gas removal unit (AGR) and then combusted in the COMB for power generation.

2.3 Performance evaluation

The fuel input by the supercritical water gasification power generation system is coal, and the output product is electricity. In this paper, net power generation efficiency and exergy efficiency are used to evaluate the energy utilization level of the system. The net power generation efficiency of proposed system is defined as:

$$\eta_{\text{net}} = \frac{W_{\text{GT}} + W_{\text{ST}} - W_{\text{pump}}}{m_{\text{coal}} \cdot LHV_{\text{coal}}} \quad (1)$$

where, W_{GT}, W_{ST} and W_{pump} refer to the sum power output of gas turbine, the sum power output of steam turbines and the sum power consumption of pumps, respectively. The LHV_{coal} denotes the low heating value of the flue coal, and m_{coal} is the coal mass flow consumed by the system.

The exergy generation efficiency of the system is defined as:

$$\eta_{\text{ex}} = \frac{E_{\text{GT}} + E_{\text{ST}} - E_{\text{pump}}}{m_{\text{coal}} \cdot e_{\text{coal}}} \quad (2)$$

where, E_{GT}, E_{ST} and E_{pump} refer to the sum exergy output of gas turbine, the sum exergy output of steam turbines and the sum exergy consumption of pumps, respectively.

3. RESULTS AND DISCUSSION

3.1 System simulation

Table 1 Energy balance of the studied systems

Items	Proposed system	Reference system
Mass flow of coal, kg/s	62.77	62.77
Energy input, MW	1858.59	1858.59
Net power output, MW	1000.00	908.98
Power generation, MW	1012.42	973.31
Gas turbine	829.26	608.96
Steam turbine	183.16	364.35
Self-power consumption	12.42	64.32
Pumps	12.42	3.70
Compressor		19.96
ASU		40.66
Net power efficiency, %	53.80	48.91

When the proposed system and reference system consume the same amount coal, the energy balance data of the reference system are also listed in Table 1. When the coal consumption is 62.77 kg/s, the corresponding energy is 1858.59 MW. At this time, the power generation of the reference system is 908.98 MW, in which the power generation of gas turbine and steam turbine is 608.96MW and 364.35MW respectively. The self-power consumption of the reference system is 64.32MW, which mainly occurs in the ASU and COMP, which are 40.66MW and 19.96MW respectively. In the case of consuming the same amount of coal, the power generation of the proposed system can produce the electricity of 1000.00MW. The power generation of gas turbine and steam turbine is 829.26MW and 183.16MW respectively. The power generation of the steam turbine has decreased from 364.35MW to 183.16MW, which is mainly due to the fact that a large part of the flue gas exhaust heat of gas turbine in the proposed system is used to provide gasification heat and prepare supercritical water. In view of the excellent gasification characteristics of supercritical water, the ASU and COMP are removed in the proposed system, and its self-power consumption is greatly reduced. However, in the reference system, the high temperature syngas is cooled to 900℃ by spraying water in the gasifier, and then the sensible heat of the syngas is recycled to drive Rankine cycle to generate electricity. Finally, the net power generation efficiency of the proposed system is 53.80%, which is 4.90 percentage points higher than the reference system.

3.2 Performance improvement mechanism analysis

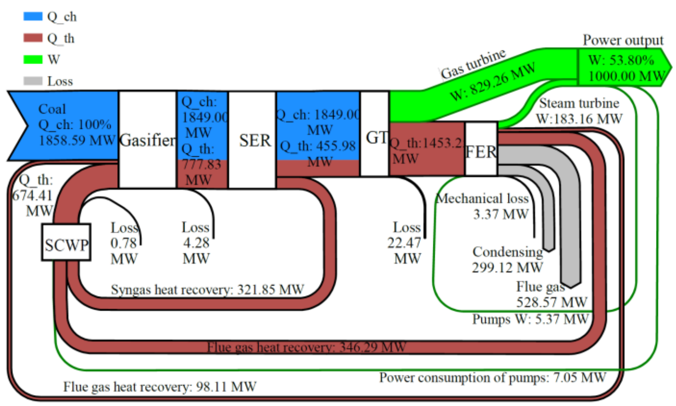

Fig. 3. Energy flow chart of the proposed system

The energy flow charts of the proposed systems is presented in Fig. 3. When the input energy of the proposed system is 1858.59MW, the chemical energy of syngas reaches 1849.00MW, and the corresponding cold gas efficiency is as high as 99.48%. Through supercritical water coal gasification, the proposed system converts more chemical energy of coal into the chemical energy of syngas. In the syngas from the gasifier of the proposed system, in addition to the chemical energy of syngas, there is also a part of the heat energy produced by the coal conversion process and the heat energy of supercritical water, which is 777.83MW. In the syngas energy recovery unit, part of the thermal energy of the syngas is recovered to heat supercritical water, and the other part follows the syngas into the gas turbine. In the proposed system, the chemical energy and thermal energy carried by the syngas entering the gas turbine are 1849.00MW and 455.98MW respectively. The gas turbine power generation of the proposed system is much higher, mainly due to a substantial increase in the chemical energy of the input gas turbine. In the FER of the proposed system, 23.83% of the flue gas waste heat is recovered for the preparation of supercritical water, 6.75% of the flue gas waste heat is recovered for gasification heat, so the steam turbine can only generate 183.16MW electricity. Finally, the net power generation capacity of the proposed system reaches 1000.00MW, which is 10.03% higher than that of the reference system (908.83MW).

3.3 Exergy analysis

The exergy balances of the studied systems are presented in Table 2. The total exergy of the input two studied systems is 1903.66MW, the output exergy of the reference system is 908.98MW, and its exergy efficiency is 47.75%; the output exergy of the proposed system is 1000.00MW, and its exergy efficiency is up to 52.53%, which is 4.78 percentage points higher than that of the reference system. The exergy destruction of the proposed system and the reference system are 903.66MW and 994.67MW respectively.

Table 2 Exergy balance of the studied systems

Items	Proposed system	Reference system
Exergy input, MW	1903.66	1903.66
Exergy output, MW	1000.00	908.98
Exergy destruction, MW	903.66	994.67
Fuel conversion process, MW	557.28	602.96
Gasification	34.71	301.95
Combustion	522.57	301.00
Heat exchange process, MW	67.30	107.01
Heat exchange of syngas	20.90	44.78
Heat exchange of flue gas	46.40	62.23
Power generation, MW	99.39	121.95
Compressor	23.46	26.97
Turbine	50.57	46.11
Steam turbines	22.62	43.12
Pumps	2.75	0.91
Oxygen compressor		4.84
Other losses, MW	179.68	162.75
Flue gas	99.22	58.12
Condensation	14.20	28.50
Throttle valve	66.26	
Syngas purification		41.95
ASU		34.18

In the fuel conversion process, the total exergy destruction occurred in the gasification process of the proposed system is 34.71MW, accounting for approximately 1.82% of the total exergy input, and the exergy destruction of this part of the proposed system is lower than 88.50% of the reference system. In the proposed system, the exergy destruction of the gas turbine combustor is 522.57MW, while that of the reference system is 301.00MW. The reason is that the gasification process of the proposed system recovers the sensible heat of the flue gas, which converts part of the heat energy of low energy level into the syngas chemical energy of high energy level, resulting in a higher chemical energy of syngas.

4. CONCLUSIONS

In this paper, a novel integrated system of supercritical water coal gasification and power generation is proposed. The innovation of the proposed system is to use the high-temperature heat of flue gas of gas turbine to drive the gasification process. The net power generation efficiency and exergy efficiency of the system are used as evaluation indexes, combined with EUD analysis, to reveal the cause of exergy destruction and the mechanism of performance improvement of the system. Through simulation calculations, the results show that the net power generation efficiency of the novel supercritical water coal gasification system is 53.80% and the exergy efficiency is 52.53%, which are approximately 4.90 and 4.78 percentage points higher than that of the traditional coal gasification system, respectively. Finally, the comprehensive cascade utilization of fuel chemical energy and physical energy is realized, providing a quite promising approach for the clean and highly efficient coal utilization.

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