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A HIGH-EFFICIENCY POWER GENERATION SYSTEM BASED ON SELF-SUSTAINING SUPERCRITICAL WATER COAL GASIFICATION

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ABSTRACT

An innovative high-efficiency power generation system is developed and investigated in this paper. Based on self-sustaining supercritical water coal gasification, the thermal energy of the syngas is cascade utilized according to its temperature and pressure, both sensible and latent heat of the syngas can be recycled into the system, and thereby the net power efficiency can be about five percentage points higher than that of the traditional GE gasification based power plant. The exergy analysis shows that the exergy efficiency of the proposed system reaches 49.17%, which is 10.72% higher than that of the reference system, and the improvement in exergy efficiency of the proposed system mainly comes from the exergy destruction decline of the syngas energy recovery process and the gas compression process. The syngas combustion process is the highest exergy destruction process with a value of 183.77 MW in the proposed system. Further improvement in the system performance of the proposed system lies in the utilization of syngas.

Keywords: Power generation; SCWG; Coal gasification; Cascade utilization; Combined cycle; Self-sustaining

NONMENCLATURE

Abbreviations

AGR	acid gas removal unit
ASU	air separation unit
BUR	burner
CC	combined cycle
COMB	combustor
COMP	compressor
CON	condenser
CP	circulation water pump
FHE	flue gas heat exchanger
GEN	generator
GT	gas turbine
HEX	heat exchanger
HHV	high heating value
HPST	high-pressure syngas turbine
HRSG	heat recovery steam generator
LHV	low heating value
LPST	low-pressure syngas turbine
RH	reheater
RV	pressure reducing valve
SCW	supercritical water
SCWG	supercritical water gasifier
SEP	separator
SER	syngas energy recovery
SHE	syngas heat exchanger
SP	supplemental water pump
WHR	waste heat recovery
LB/IB/HB	low/mid/high pressure evaporator
LE/IE/HE	low/mid/high pressure economizer
LP/IP/HP	low/mid/high pressure pump
LS/IS/HS	low/mid/high pressure superheater
LT/IT/HT	low/mid/high pressure turbine

Symbols

E	exergy, kW
m	mass flow, kg/h
Q	heat, kW
T	temperature, °C
W	power, kW
η	efficiency, %

1. INTRODUCTION

Coal acts as one of the most important primary energy worldwide, accounts for approximately 38% of the global power generation [1]. A large amount of pollutants, such as NO_x and SO_x, are produced during the conventional coal utilization process [2]. Thus, gasification is employed as an alternative coal utilization method for pollutant emission control. The supercritical water (SCW) coal gasification has got increased attention thanks to its efficient and clean performance [3].

The SCW possesses special chemical and physical properties such as low viscosity, high diffusion rates, insoluble for inorganic compounds, and miscible with organic and no-polar compounds without limitations [4]. Nowadays, studies on the application of the SCW are mainly focused on the waste treatment and low calorific value fuel conversion [5]. Compared to conventional gasification methods, the SCW gasification advantages in a great fuel adaptability, easy pollutants controlling, higher hydrogen yield, and easy energy recovery [6]. A common concern lies in the heat source of the SCW preparation and gasification. One way is burning coal in air [7], however, the extra emission weakens the environmental performance of the new coal utilization technology, which is against the original intention of developing this technology. Injecting pure oxygen into the gasifier can ensure self-sustaining of the gasification process [8], the main problem of this approach lies in the large extra investment in air separation unit (ASU) and the huge energy consumption of the air separation process. Partial syngas burning combined with syngas heat recovery is a promising approach to overcome the above problems.

The main contributions of this study including: (1) an innovative self-sustaining SCW coal gasification based high-efficiency power generation system is developed and investigated, a net power efficiency of 50.5% was obtained with a power output of 300 MW; (2) the syngas thermal energy is cascade utilized according to its temperature and pressure, both sensible and latent heat of the syngas can be recycled into the system; and (3) a comparison study with a GE entrained flow gasifier based IGCC power plant is conducted to address the excellence thermal performance of the proposed SCWG based IGCC power plant.

2. SYSTEM DESCRIPTION

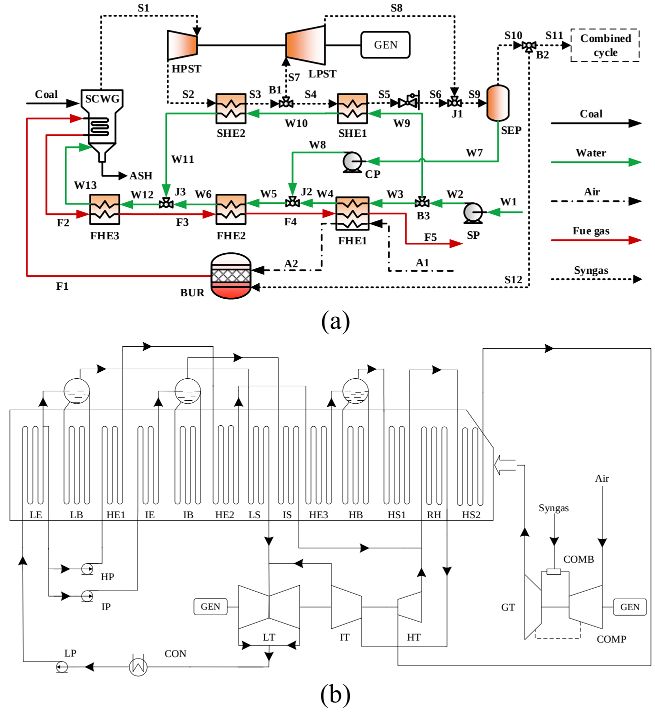
2.1 Description of the proposed system

The general layout of the self-sustaining SCW coal gasification based power generation system is illustrated in Fig. 1. The complex flow chart main composes of four parts: the coal gasification process, the syngas energy recovery (SER) process, the SCW preparation process and the CC subsystem. At the first stage of the system, the coal is converted into a hydrogen-rich syngas by the SCW in the supercritical water gasifier (SCWG), and the heat required for gasification is provided by burning syngas in the burner (BUR).

Then, the SER process is performed. The produced syngas is first used to produce power in a high-pressure syngas turbine (HPST) considering its high power generation ability; next, it is adopted to preheat the high-pressure water in the syngas heat exchanger #2 (SHE2); then, it is divided into two streams (S4 and S7) for the purpose of better temperature match in the syngas heat exchanger #1 (SHE1). One part (S4) passes through the SHE1 to preheat the high-pressure water (W9) and the other part (S7) is introduced into the low-pressure syngas turbine (LPST) to produce power; after that, the syngas from the SHE1 is transformed into a low-pressure syngas by a pressure reducing valve (RV) and mixed with the low-pressure syngas from the LPST; finally, the condensate in the mixed low-pressure syngas is separated in the separator (SEP), part of the syngas is burned in the BUR to provide heat for coal gasification while the other part is introduced into the CC to produce power. In this way, both sensible and latent heat contained in the syngas is recycled into the system. The high-temperature flue gas produced by burning syngas is first used to provide heat for coal gasification; then, used to produce SCW and preheat water in the flue gas heat exchanger #3 and #2 (FHE3 and FHE2) in sequence; finally, used to preheat water and air in the flue gas heat exchanger #1 (FHE1).

For the preparation of SCW, the low-temperature supplemental water (W1) is divided into two streams (W3 and W9) after being pressurized by a supplemental water pump (SP). One part of the high-pressure water (W9) is preheated by the high-temperature syngas in the SHE1 and SHE2 in sequence; the other part (W3) is first preheated by the flue gas in the FHE1, then mixed with the high-pressure recycle water (W8) from the circulating water pump (CP), resulting in stream W5. The mixed stream W5 is further heated in the FHE2, then, mixed with the stream W11 from the SHE2 resulting in W12 to produce SCW in the FHE3. It should be noted that in the absence of circulating water and syngas heat prior to system startup, all pressurized water passes through FHE1, FHE2 and FHE3 in sequence, and all required heat for SCW production are provided by syngas burning.

The CC adopted in this study is a triple-pressure reheat CC, as presented in Fig. 1 (b). S represents superheater, B stands for evaporator, T represents turbine, P represents pump, E represents economizer, and RH represents reheater. L, I and H refer to low, mid and high pressure, respectively. The ambient air is compressed into the combustor (COMB) to burn the syngas, and the produced hot tail gas is fed into the GT to produce power. The tail gas from the GT than passes through the heat recovery steam generator (HRSG) before being rejected to the ambient. The heat remained in the tail gas is recovered to produce steam by the HRSG, and the produced steam is applied to generate power in steam turbines.



(a)

(b)

Fig. 1 (a) the schematic diagram of the self-sustaining SCWG-based power generation system and (b) the flow chart of the combined cycle.

2.2 Description of the reference system

A GE entrained flow gasifier based IGCC power plant is selected as the reference system [9], as this type gasifier is one of the most common gasifier types that can be used to gasify solid or liquid fuels with high efficiency. The simplified flow chart of the reference system is illustrated in Fig. 2. A 98% pure oxygen is first prepared by an ASU. Then, a pulverized coal-slurry with a coal concentration of 63% is pumped into the gasifier by oxygen. In the gasifier, the coal is converted into a syngas with a temperature of 1346 °C. The high-temperature syngas is sent to the waste heat recovery (WHR), the heat exchanger (HEX) and the acid gas removal unit (AGR) in sequence. The heat of the syngas is recovered to generate steam in the WHR and to preheat cold clean gas in the HEX. The preheated clean syngas is introduced into the CC for power generation finally.

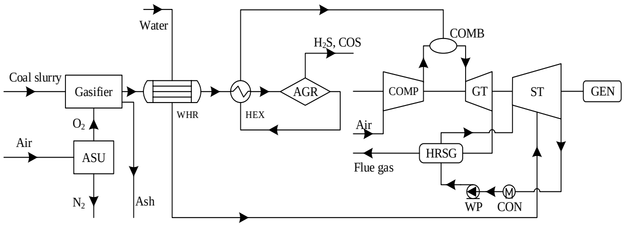


Fig. 2 the flow chart of the reference system.

2.3 Evaluation criteria

To calculate the power generation efficiency of the GT

$$\eta_{\mathrm{GT,\,en}}=\frac{W_{\mathrm{GT}}-W_{\mathrm{compressor}}}{m_{\mathrm{syn}}\cdot LHV_{\mathrm{syn}}} \tag{1}$$

where W_{GT} and $W_{\mathrm{compressor}}$ represent the power production of the GT and the power consumption of the compressor. m_{syn} is the mass flow of the syngas being introduced into the CC, and the LHV_{syn} denotes the low heating value of the syngas.

To calculate the power generation efficiency of the CC

$$\eta_{\mathrm{CC,\,en}}=\frac{W_{\mathrm{GT}}+W_{\mathrm{STUR}}-W_{\mathrm{CC,\,pump}}-W_{\mathrm{compressor}}}{m_{\mathrm{syn}}\cdot LHV_{\mathrm{syn}}} \tag{2}$$

where W_{STUR} represents the sum power output of the HT, the IT and the LT. $W_{\mathrm{CC,\ pump}}$ refers to the sum power consumption of the HP, the IP and the LP.

To calculate the net power generation efficiency of the proposed system,

$$\eta_{\mathrm{net,\,en}}=\frac{W_{\mathrm{turbine}}-W_{\mathrm{pump}}-W_{\mathrm{compressor}}}{m_{\mathrm{coal}}\cdot LHV_{\mathrm{coal}}} \tag{3}$$

where W_{turbine} and W_{pump} refer to the sum power output of turbines and the sum power consumption of pumps. m_{coal} represents the coal mass flow consumed by the proposed system, and LHV_{coal} is the low heating value of the consumed coal.

To obtain the exergy efficiency of the GT, the CC and the proposed system, a slight change is introduced into the equations above:

$$\eta_{\mathrm{GT,\,ex}}=\frac{W_{\mathrm{GT}}-W_{\mathrm{compressor}}}{E_{\mathrm{CC,\,ex}}} \tag{4}$$

$$\eta_{\mathrm{CC,\,ex}}=\frac{W_{\mathrm{GT}}+W_{\mathrm{STUR}}-W_{\mathrm{CC,\,pump}}-W_{\mathrm{compressor}}}{E_{\mathrm{CC,\,ex}}} \tag{5}$$

$$\eta_{\text{net, ex}} = \frac{W_{\text{turbine}} - W_{\text{pump}} - W_{\text{compressor}}}{E_{\text{coal, ex}}} \tag{6}$$

where $E_{\text{CC, ex}}$ and $E_{\text{coal, ex}}$ denote the exergy of the syngas being introduced into the CC and the exergy of the coal input of the proposed system.

3. RESULTS AND DISCUSSION

3.1 *Base*-case *results*

The base-case of the self-sustaining SCW gasification based power generation system with a capacity of 300 MW has been disclosed. The energy flow chart of the proposed system is presented in Fig. 3. The only energy input of the proposed system is the thermal energy (about 594.10 MW) contained in the gasified coal. The coal is transformed into a hydrogen-rich syngas after being injected into the SCWG, the thermal energy remained in the syngas is then recovered by syngas turbines and heat exchangers, the HHV and LHV of the produced syngas at the SEP outlet is 10.21 MJ/kg and 8.03 MJ/kg respectively. After that, about 37.1% of the produced syngas is burned for heating and almost 62.9% of it is sent to the CC for power generation. In total, almost 67.03% of the consumed thermal energy is converted into power through turbines; then, about 24.5% of the produced power are consumed by the pumps and compressor in the proposed system.

The LHV based GT efficiency in the proposed system is 47.7%, which is much higher than the value of 36.17% reported by Liu [10] with the same pressure ratio and the GT inlet temperature. This result main comes from the variation of the fuel for the GT, the syngas consumed in the proposed system has a much higher initial temperature (around 175 °C) and inert gas composition, such as CO_2 and H_2O. On the one hand, the high inlet fuel temperature decreases the heat demand for fuel preheating, the fuel consumption of the GT decreases correspondingly. On the other hand, the pressurized inert gas in the syngas replaced part of the air to cool the GT; therefore, the amount of air compressed by the compressor decreases; corresponds, the power consumption of the compressor decreases. Both the decreased fuel input and compressor power consumption realized an increased LHV based GT efficiency. The LHV based efficiency of the CC in the proposed system reaches 65.81% thanks to the excellent GT performance. Considering a large amount of water latent heat is brought into the CC by the high-temperature syngas, the HHV based GT efficiency and CC efficiency are a better choice to evaluate the performance of the GT and CC in the proposed system, with a value of 37.50% and 51.70% respectively. The net power generation efficiency of the proposed system reaches 50.50%, which is much higher than the value of 35-43% for major coal-based IGCC projects worldwide [11].

The reference system is conducted at the same amount of coal consumption. The detailed energy consumption and generation of the proposed system and the proposed system are summarized in Table 1. The total power produced in the proposed system is 398.25 MW, which main contains three parts: the power produced by syngas turbines from the pressure energy recovery of the syngas (58.73 MW), the power produced by the GT (271.95 MW) and the power produced by steam turbines (67.56 MW). The GT is the dominant power generation component of the proposed system, taking 68.29% of the gross system power generation, followed by the steam turbines (16.97%), then the syngas turbines (14.75%). The power produced in the reference system can be divided into two groups: the power produced by the GT (321.53 MW) and the power produced by the steam turbines (113.52 MW). The power produced by the GT in the reference system is 15.42% higher than that in the proposed system. These results main due to all produced syngas in the reference system are introduced into the CC, while only 62.9% of the produced syngas in the proposed system is sent to the CC. The power produced by steam turbine in the proposed system is almost half of that in the reference system, however, the power generation of the syngas turbine once again reduced the power generation gap between the two systems. The self-power consumption of the proposed system is 98.25 MW, which is mainly consumed by the pumps (3.28 MW) and compressor (94.97 MW). The power consumption of pumps in the proposed system is almost three times that in the reference system. The result mainly comes from the high-power consumption of the SCW pumps. The power consumption of the compressor in the proposed system is 45.97% lower than that in the reference system. The low power consumption of the proposed system not only benefits from the low air-to-fuel ratio in the GT but also the omitted oxygen compression process for gasification. The energy consumption of the ASU is 24.31 MW in the reference system, which drops the system efficiency by 4.09 percentage points. The proposed system gets rid of the ASU thanks to the excellent performance of the SCW. Finally, the net power output of the proposed system and reference system is 300 MW and 270.94 MW, respectively, and the net power efficiency of the proposed system is higher than that of the reference system by 4.89 percentage points.

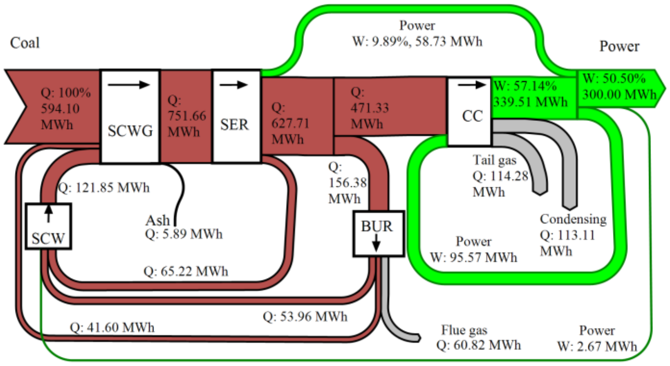


Fig. 3 Energy flow chart of the proposed system.

Table 1 Thermodynamic performances of the self-sustaining SCWG-based power generation system

Items	Proposed system	Reference system
Coal input, MW	594.10	594.10
Power generation, MW	398.25	435.05
Syngas turbines, MW	58.73	--
GT, MW	271.95	321.53
Steam turbines, MW	67.56	113.52
Self-power consumption, MW	98.25	164.11
Pumps, MW	3.28	1.17
Compressor, MW	94.97	138.63
ASU, MW	--	24.31
Net power output, MW	300	270.94
Net power efficiency, %	50.50	45.61

3.2 Exergy analysis

The exergy balances of the studied systems are presented in Table 2. The total exergy input of the proposed system by coal is 610.16 MW, in which 49.17% are finally converted into power, and the remained exergy with a value of 310.16 MW is destructed. With the same amount of exergy input, only 44.41% of it is finally converted into power in the reference system. The exergy destruction can be categorized into 11 parts by combining several components into one group according to its function, they are: the exergy destructed in coal gasification process, the exergy destructed in SER process, the exergy destructed in SCW preparation process, the exergy destructed in combustion process, the exergy destructed in gas compression process, the exergy destructed in the syngas purification process, the exergy destructed in the air separation process, the exergy destructed in the HRSG, the exergy destructed in the turbines, the exergy destructed in condensing process and the exergy loss in the exhaust including the flue gas and tail gas. The gasification process and combustion process are the two highest exergy destruction process for both the proposed system and reference system. The exergy destructed in the gasification process is much lower than that destructed in the combustion process for the proposed system, while it is exactly the opposite for the reference system. This result owes to the different heating methods of the gasification process of the two systems. The heat demand of the gasification process is provided by burning produced syngas in the proposed system, while it is provided by carbon oxidation process inside the gasifier in the reference system. The exergy destructed in the SER process is 10.22 MW in the proposed system, the value is less than half of that in the reference system. This result is not only due to the low average heat transfer temperature difference in the heat recovery process but also due to proper pressure energy recovery. The increased SCW preparation process brings an extra exergy destruction of 22.33 MW in the proposed system. However, it is because of this increased process that avoids the exergy destruction of the air separation process with a value of 24.31 MW and the syngas purification process with a value of 9.16 MW. The exergy destruction of the HRSG is 10.50 MW in the proposed, which is about 1 MW lower than that in the reference system, this is due to the low proportion of the syngas being introduced into the CC. The exergy destruction of turbines in the proposed system (7.79 MW) is almost half of that in the reference system, this is due to the low proportion of power generated by steam turbines which have a relatively lower efficiency. Similarly, the exergy destruction of the condensing process in the proposed system is also lower than that in the reference system. The exergy loss caused by exhaust in the proposed system is almost six times that of the exhaust in the reference system, mainly due to the fact that, in contrast to the pure oxygenation in the reference, a large amount of nitrogen is introduced into the proposed system. As a consequence, the improvement in exergy efficiency of the proposed system mainly comes from the exergy destruction decline of the SER process and the gas compression process.

Table 2 Exergy balance of the studied systems.

Items	Proposed system	Reference system
Exergy input	610.16	610.16
Exergy output (power)	300	270.94
Exergy destruction and losses	310.16	339.22
Coal gasification process	50.38	129.24
SER process	10.22	24.03
SCW preparation process	22.33	--
Combustion process	183.77	105.59
Gas compression process	5.07	11.13
Syngas purification process	--	9.16
Air separation process	--	24.31
HRSG	10.50	11.46
Turbines	7.79	14.00
Condensing	5.38	7.92
Exhaust loss	14.71	2.38
Exergy efficiency, %	49.17	44.41

4. CONCLUSIONS

An innovative high-efficiency power generation system is developed and investigated in this paper. Based on self-sustaining SCW coal gasification, the net power efficiency of the proposed system reaches 50.5% with a power output of 300 MW. To make full use of the thermal energy of produced syngas, the syngas thermal energy is cascade utilized according to its temperature and pressure. Besides, after the energy recovery process, the syngas is directly sent to the burner and CC without further condensing, which leads to a lower compressor power consumption and a higher net power efficiency.

Due to the energy cascade utilization and advanced integration of the proposed system, the simulation results show that the exergy efficiency reaches 49.17%, which is about five percentage points higher than that of the reference system. Compared to the reference system, the improvement in exergy efficiency of the proposed system mainly comes from the exergy destruction decline of the syngas energy recovery process and the gas compression process. The distribution of exergy destruction in the system are revealed for further optimizing the performance of the system. The exergy analysis results indicated that the combustion process is the highest exergy destruction process with a value of 183.77 MW in the proposed system, followed by the gasification process (50.38 MW), then the SCW preparation process (22.33 MW). A great performance improvement potential lies in changing the syngas utilization process.

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