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Zero/negative carbon emission coal-steam gasification power generation system via biomass heating

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ABSTRACT

The coal-steam gasification method has been proven to be suitable for power generation. However, the low concentration of CO2 generated in the external coal combustion heating process causes significant CO2 capture energy consumption. As a carbon-neutral fuel, biomass combined with coal-steam gasification could contribute to a reduction in CO2 emissions. In this work, using the typical herbaceous biomass as the heating fuel, the energy efficiency and carbon emissions of the biomass-heating-coal-gasification power generation system (BHCG) are systematically studied. The results indicate that the coupling utilization of biomass and coal can significantly improve the emission reduction characteristics of fossil energy systems. In the no-carbon capture scenario, the power efficiency of BHCG is 50.66 %, which is 5.31% higher than GE gasification power generation system. When the carbon capture process is introduced, the power efficiency of BHCG is 46.40 % with -133.90 kg CO2/MWh. The biomass heating coal-steam gasification method can utilize the negative carbon utilization of fossil fuels and has high energy efficiency.

Keywords: coal gasification, biomass, external-heating, energy efficiency, carbon emission, CCS

NONMENCLATURE

Abbreviations	
BHCG	Biomass-heating-coal-gasification power generation system
IGCC	Integrated coal gasification combined cycle
CGE	Cold gas efficiency
CWS	Coal-water slurry
WHB	Waste heat boiler
ASU	Air separation unit
COG	Coke oven gas
LHV	Lower heating value

1. INTRODUCTION

Currently, fossil fuels account for 70% of the world's energy generation, of which coal accounts for 43% of the total fossil energy consumption. In this way, fossil fuels, especially coal, will still play a significant role in the future world energy system. Under the background of the carbon-neutral vision, seeking the clean and efficient utilization method of coal has become the focus of current research[1]. Compared with the direct combustion of coal, coal gasification technology has been proven to have higher energy efficiency and lower carbon emissions[2].

Previous studies have proven that coal-steam gasification technology is suitable for power generation

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because of its high cold gas efficiency (CGE). The process of coal-steam gasification could be described as below: the gasification coal is first introduced into a pyrolizer to generate coke oven gas and coke. Then the high-temperature coke and steam reacted in the gasifier to generate syngas. The coking process and coke-steam gasification process are endothermic reactions at around 1000-1100 °C, which need to be heated by external heat sources[3]. And coal direct combustion heating was widely used in coal-steam gasification in previous research[2]. Coal-steam gasification uses steam instead of pure oxygen as the gasification agent. Therefore, the high energy consumption of air separation units is avoided. Additionally, the sensible heat of syngas is recovered and converted into high-energy-level chemical energy through the thermochemical regenerative process, which enhances the CGE.

However, for the external coal-fired combustion of the coal-steam gasification process, the direct combustion of coal will cause serious pollutant emissions. And the emission of low-concentration CO2 flue gas will cause high carbon capture energy consumption. On the other hand, coal, as a high-energy-level fuel, is directly burned as a heating source at about 1200 °C, which is unmatched in energy level. The direct combustion of coal wastes its high-quality chemical energy.

To solve this problem, biomass is introduced into coal-steam gasification process. As the fourth largest energy source after fossil fuels, biomass is the only renewable carbon neutral carbonaceous fuel[4, 5]. From the perspective of low carbon, using biomass as heating fuel can achieve zero carbon emission of external combustion heat source, avoiding high carbon capture energy consumption of low concentration flue gas. From the thermodynamic point of view, the energy level of biomass is lower than coal, and it is more suitable to be used as a fuel for heating combustion. Therefore, integrating biomass combustion and coal-steam gasification is expected to have high energy efficiency and low carbon emissions.

From this perspective, this paper proposed a power generation system based on coal-steam gasification via biomass external combustion heating (BHCG). The power generation system based on the traditional coal gasification and biomass direct-fired power plants are used as reference systems. And the power efficiency improving ratio and emission reduction potential of the proposed system is comprehensively analyzed.

2. PROCESS DESCRIPTION

2.1 The coal-steam gasification power generation system via biomass heating

The schematic diagram of BHCG is shown in Fig. 1. In the proposed system, coal, as the gasification raw material, enters the coke oven for the coking reaction after pretreatment. Then the high-temperature coke from the coke oven enters the gasifier and reacts with the steam to produce carbon monoxide, hydrogen, and a small amount of carbon dioxide. The sensible heat of the high-temperature coke oven gas (COG) and syngas is recovered through a heat exchanger. The COG and syngas enter the desulfurization unit for desulfurization after cooling to about 50 °C. Finally, the purified synthetic gas enters the combined cycle for power generation.

The heat required for coal-steam gasification in the system is provided by biomass combustion. Biomass raw materials have the characteristics of low energy density, high water content, and poor pulverization, so they are not suitable for direct fired in the combustion chamber. Through biomass molding technology, the dried biomass is crushed and molded into high calorific value particulate or briquette fuel and optimizes the combustion performance. Therefore, the corn straw briquette material is selected as the external combustion fuel in this work [6]. The heat energy required for biomass drying is provided by burning part of the biomass briquette fuel. Additionally, the power consumption required by BHCG (e.g., the pretreatment of raw materials, coal-steam gasification process, and external combustion of biomass) is provided by itself.

2.2 The traditional GE gasification power generation system

The traditional coal gasification power generation system based on GE gasification technology (IGCC) is selected as the reference system I. As shown in Fig. 2, the coal-water slurry (CWS) is mixed with high-purity oxygen from the air separation unit and enters the gasifier at high speed through the processed nozzle. The CWS is broken by oxygen flow and undergoes violent severe oxidative exothermic reaction at high temperature, providing heat for gasification reaction. The sensible heat of high-temperature syngas is recovered through a waste heat boiler (WHB). The high-temperature and high-pressure water steam generated by the WHB enters the steam turbine for power generation. The cooled syngas is desulfurized through the desulfurization unit. Then the purified syngas enters the combined cycle for power generation.

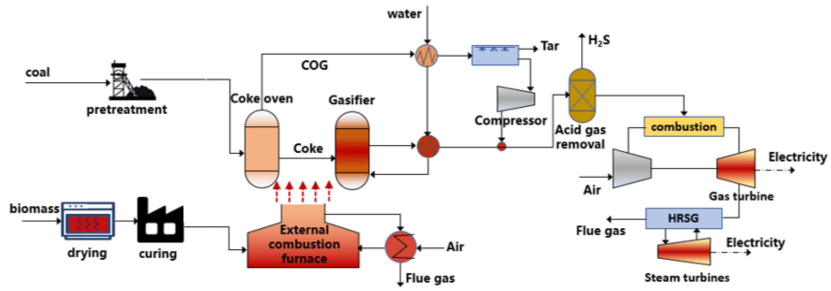

Fig. 1. The coal-steam gasification power generation system via biomass heating

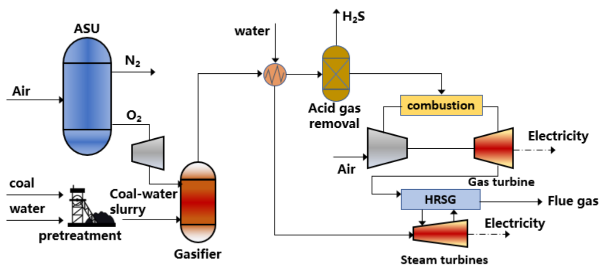

Fig. 2. The GE gasification power generation system

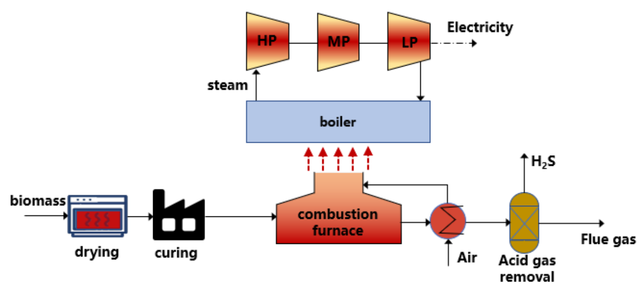

Fig. 3. The biomass direct combustion power generation system

2.3 The biomass direct combustion power generation system

As reference system II, the schematic diagram of the biomass direct combustion power generation system is shown in Fig. 3. The biomass briquette fuel of the external heating part of BHCG is used as the fuel of the biomass direct fired power generation system[4]. Compared with traditional coal-fired power plants, biomass direct fired power generation system adds biomass pretreatment process. The biomass briquette is burned in the combustion chamber and heats the boiler to produce high-temperature and high-pressure water vapor. Then the steam drives the steam turbine to generate electricity. The heat and electricity required for biomass pretreatment are provided by the biomass direct combustion power generation system.

2.4 Carbon capture process

Previous studies have shown that for IGCC, applying the pre-combustion carbon capture can efficiently achieve low energy consumption of CO2 capture [7]. The CO in the syngas generates CO2 and H2 through the water gas shift reaction (WGS). As a result, CO2 and H2 become the main component of the syngas, and the CO2 concentration can exceed 40%. Such concentration of CO2 could be captured with low energy consumption by using the Selexol method.

And for the combustion process, research has proven that post-combustion capture technology based on chemical absorption is the most mature carbon capture technology with the best comprehensive benefits [8]. Therefore, post-combustion capture technology is used in this work to capture the CO2 discharged by the combustion process. It is worth noting that the utilization of biomass is zero carbon emission. Therefore, the carbon capture of the biomass combustion process is an additional emission reduction for the system and could be served as negative emissions. In other words, the system can achieve negative emissions when the CO2 captured from biomass combustion exceeds the CO2 discharged from coal utilization.

3. KEY DESIGN PARAMETERS AND SYSTEM CRITERIA

3.1 Key design parameters for three systems

The specific processes of the proposed system and the reference systems are simulated by Aspen Plus V 11.0. And the PR-BM is selected as the global method during the simulation. The bituminous coal and corn stalk briquette fuel are selected as the input fuels for the systems. The results of proximate and final properties and final composition analyses for these two fuels are presented in Table 1[6].

Table. 1. The industrial and ultimate analysis of bituminous coal and corn stalk briquette fuel

Fuels	Industrial analysis (wt%)				Ultimate analysis (wt%)					LHV(MJ/kg)
	V	FC	A	M	C	H	O	N	S	
Coal	30.80	56.81	8.79	3.60	71.63	4.53	10.28	0.84	0.33	26.6
Biomass	71.45	17.75	5.93	4.87	39.04	6.16	42.76	1.05	0.19	16.8

Table. 2. Experimental results of coal coking

Products distribution(wt%)							
COG	31.9	Coke	59.3	Tar	1.5	H_2O	7.3
COG component (Vol %)							
H_2	51.7	O_2	1.7	N_2	9.0	CH_4	11.6
CO_2	3.5	CO	21.9	C_2H_4	0.5	H_2S	0.1
Char ultimate analysis (wt %)							
C	91.86	H	1.38	O	0.14	N	0.87
S	0.44	ASH	5.31				

RYield and RGibbs reactors are used to simulate the process of coal-steam gasification. The coal coking process is simulated by the RYield reactor. First, pre-treated coal undergoes the coking reaction in isolation of air under atmosphere pressure at 1000 °C to generate coke oven gas, coke, and a small amount of tar. As shown in Table 2, the product distribution of coal coking is determined by experiments. The sensible heat of high-temperature COG is recycled through a WHB. The tar and sulfur in COG are removed through the purification units. The high-temperature coke from the coke oven enters the gasifier and reacts with the steam at 1100 °C and 20 bar to produce synthesis gas mainly composed of CO and H2. According to the experimental data, the steam-to-coke mass ratio (S/C) is set as 1.12. After desulfurization, the syngas enters the gas turbine for power generation together with the COG. The unconventional component coke is converted into conventional components by the RYield reactor, and the coke-steam gasification process is simulated by the RGibbs reactor.

For the GE gasification process, the combination of RYield and RGibbs reactor is used to simulate the GE gasifier. With oxygen of more than 95% purity as the agent, the coal-water slurry of 66.5wt% coal concentration generates syngas mainly consisting of CO and H2 through a series of complex reactions in the gasifier, including pyrolysis, gasification, combustion, etc. The operating conditions of the GE gasification are 1346 °C and 20 bar. The sensible heat from the synthesis gas is recovered through the WHB. Then the purified syngas enters the combined cycle for power generation.

The combustion process involved in the external combustion heating and biomass direct combustion power generation system is realized through the combination of RYield and RStoic reactors. The biomass briquette fuel is converted into corresponding elements through the RYield reactor first. Then the violent oxidation reaction takes place in the RStoic reactor and generates a lot of heat. For BHCG, the heat generated by the combustion is supplied to the coal-steam gasification process. And such heat is used to produce high-temperature steam for power generation for the biomass direct combustion power generation system.

In the low carbon scenario, the system requires to equip with the carbon capture process. For the gasification process, the CO contained in the syngas is converted into CO2 and H2 through the WGS reaction. Then the mixture rich in CO2 and H2 is separated into pure H2 and high-concentration CO2 via the pre-combustion carbon capture unit. The pure H2 enters the combined cycle to generate electricity. And the CO2 is captured and further processed. Two-stage REquil reactors (high-temperature and low-temperature reactors) are applied to simulate the WGS process with a CO conversion rate exceeding 96%. Meanwhile, the CO2 concentration of the syngas after shifting is around 40%, and the Selexol technology is applied to capture the CO2. Additionally, the chemical absorption method based on AMP absorbent is adopted to capture CO2 generated by biomass combustion. The power consumption required for the carbon capture process is provided by the power output from the system. And the heat consumption required is provided by extracting steam from the low-pressure cylinder of the steam turbine. The other key design parameters for the systems are shown in Table 3.

Table. 3. Other key design parameters

Process	description
Pretreatment	Coal for 0.022 kWh/kg Biomass for 0.068 kWh/kg
ASU[9]	0.48 kWh/Nm^3 O_2
Pyrolizer	T=1000°C P=1bar
Gasifier	T=1100°C P=20bar
Desulphurization	0.538 kWh/kg H_2S
Combustion	T=1200°C P=1bar heat loss:9%
WHB	Triple-pressure reheat steam: 126/25/5.5 bar, Steam temperature: 566 °C, Isentropic efficiency of ST: 0.88/0.89/0.87
Gas turbine	Pressure ratio:16.7; gas turbine initial temperature:1327 °C; isentropic efficiency of GT: 0.92

Carbon capture	Pre-combustion: Selexol technology Post-combustion: AMP based chemical absorption

3.2 Evaluation criteria

The power efficiency, power efficiency improvement ratio (PEIR), and specific CO2 emissions are the systematic evaluation criteria in this work.

The power efficiency is defined as:

$$\eta_i = \frac{p_i}{E_i} \quad (1)$$

where p_i is the power output (MW) of the system i. the E_i represents the energy input (MW) of the coal and biomass.

The PEIR is defined as Eq. 2, which reflects the increase of power generation of the new system compared with the reference system under the premise of consuming the same fuel.

$$PEIR = \frac{P_{BHCG} - E_{IGCC} * \eta_{IGCC} - E_{Bio} * \eta_{Bio}}{E_{IGCC} * \eta_{IGCC} - E_{Bio} * \eta_{Bio}} \quad (2)$$

where P_{BHCG} is the power output (MW) of BHCG. The E_{IGCC} and η_{IGCC} is the energy input of coal (MW) and power efficiency of IGCC. And the E_{Bio} and η_{Bio} is the energy input of biomass (MW) and power efficiency of biomass direct combustion power generation system.

The specific CO2 emission is calculated as Eq. 3, which represents the CO2 emissions per unit of electricity produced. Where N_{CO_2} is the CO2 emitted by the system (kgCO2/MWh).

$$SCE_i = \frac{N_{CO_2}}{P_i} \quad (3)$$

4. RESULTS AND DISCUSSION

4.1 No carbon capture scenario

The simulation results are obtained based on strict conservation of mass and energy. As shown in Table 4, in the no carbon capture scenario, the results show that the power efficiency of BHCG is superior to that of the two reference systems. The coal-steam gasification process in BHCG has a higher CGE of 90.14%, while that of GE gasification is 79.80%. Furthermore, BHCG avoids the high-power consumption of air separation. As a result, the power efficiency of BHCG is 50.66%, which is nearly 5.31% higher than that of IGCC. Besides, the power efficiency of BHCG is 18.23% higher than that of the biomass direct combustion power generation system.

In terms of carbon emissions, since the input fuel with more than 20% energy ratio of is replaced by biomass, the specific CO2 emissions of BHCG are significantly decreased compared with IGCC. The specific CO2 emission decreased from 617.09 to 445.86 kgCO2/MWh, a decrease of 27.75%. On the other hand, the biomass direct-fired power generation system uses carbon-neutral fuel entirely, so its carbon footprint is zero. Therefore, the biomass-based system has significant advantages in low-carbon over the other two.

The PEIR is calculated to reveal the performance improvement of BHCG compared with the traditional coal and biomass utilization systems. The results show that under the same energy input and coal/biomass ratio, the proposed system could produce 21.84% more electricity than the reference systems. In other words, coupling biomass heating and coal-steam gasification can significantly improve the utilization efficiency of fuels.

Table. 4. Simulation results of BHCG and two reference systems (without carbon capture)

	BHCG	GE gasification	Biomass direct combustion
Energy input-coal MW	539.57	761.82	0
Energy input-biomass MW	222.43	0.00	760.00
Total input MW	762.00	761.82	760.00
Electricity MW	386.00	345.51	246.49
Energy efficiency	50.66%	45.35%	32.43%
Specific CO2 emission kgCO2/MWh	445.86	617.09	0

4.2 Carbon capture scenario

The carbon capture process was introduced into the systems in the low-carbon scenario. And the power efficiency changes of the carbon capture-equipped systems are calculated and shown in Fig. 4. The results show that the energy efficiency of the systems decreases due to the energy consumption of carbon capture. The power generation of IGCC is decreased to 320.04 MW when the carbon capture rate is 90%. The carbon capture process reduces the power efficiency of IGCC by 3 points. In contrast, as part of the coal input of BHCG is replaced by biomass, the net CO2 emissions are relatively low. As a result, the amount of CO2 captured in the proposed system is lower. Therefore, the carbon capture energy consumption of the proposed system is lower, and the power efficiency is reduced from 50.66% to 48.42%, with only 2 points decreased.

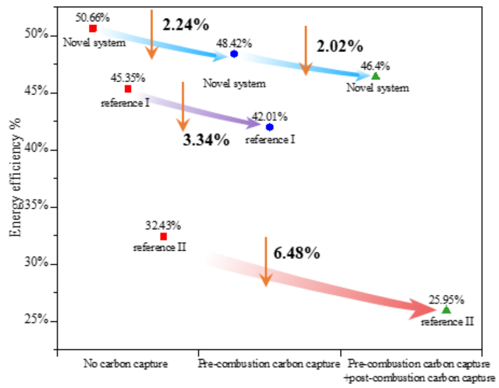

Fig. 4. Power efficiency changes of the systems before and after being equipped with carbon capture processes

In terms of carbon emission, the specific CO_2 emission of IGCC equipped with Selexol technology is 67.06 $kgCO_2/MWh$. The Selexol technology has good economic benefits when the capture rate is 90%. When the capture rate continues to increase, the energy consumption of carbon capture will be significantly increased. As a result, the economy will be worse. Therefore, IGCC, which takes fossil fuels as the total input, cannot achieve zero or even negative carbon emissions.

Additionally, although the biomass direct combustion power generation system is zero carbon emission, the power efficiency is significantly lower than IGCC. However, BHCG inputs are coal and biomass. When the captured CO_2 from biomass combustion is greater than the CO_2 emitted by coal-steam gasification, BHCG is carbon negative. The calculation results show that the power efficiency of BHCG is 46.40% when the pre-combustion and post-combustion capture rates are 90%. And the specific carbon emission of the proposed system is -133.90 $kgCO_2/MWh$. In a word, BHCG can achieve negative carbon emissions and has a far higher power efficiency than biomass direct combustion power plants with zero carbon emissions.

5. CONCLUSIONS

A method of coal-steam gasification heating by biomass external combustion is proposed. This paper takes the power generation system based on the proposed method as an example, and the power efficiency and carbon emission are comparatively analyzed. The results show that BHCG can improve power efficiency by 5.31% and reduce carbon emissions by nearly 30% compared with the GE gasification power generation system. BHCG can output half more power than the biomass direct-fired power generation system with the same energy input. -133.90 $kgCO_2/MWh$ negative carbon emissions of BHCG could be achieved when the carbon capture process is introduced. And the energy efficiency is 46.40%, which is still higher than that of IGCC without the carbon capture process. On balance, the novel method effectively integrates coal and biomass, which makes coal utilization achieve negative carbon emissions, and significantly improves the energy efficiency of biomass.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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