



Exergy analysis of a coal/biomass co-hydrogasification based chemical looping power generation system



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ABSTRACT

Power generation from co-utilization of coal and biomass is very attractive since this technology can not only save the coal resource but make sufficient utilization of biomass. In addition, with this concept, net carbon discharge per unit electric power generation can also be sharply reduced. In this work, a coal/biomass co-hydrogasification based chemical looping power generation system is presented and analyzed with the assistance of Aspen Plus. The effects of different operating conditions including the biomass mass fraction, R_b , the hydrogen recycle ratio, R_{hr} , the hydrogasification pressure, P_{hg} , the iron to fuel mole ratio, R_{if} , the reducer temperature, T_{re} , the oxidizer temperature, T_{ox} , and the fuel utilization factor, U_f of the SOFC (solid oxide fuel cell) on the system operation results including the energy efficiency, η_e , the total energy efficiency, η_{te} , the exergy efficiency, η_{ex} , the total exergy efficiency, η_{tex} and the carbon capture rate, η_{cc} , are analyzed. The energy and exergy balances of the whole system are also calculated and the corresponding Sankey diagram and Grassmann diagram are drawn. Under the benchmark condition, exergy efficiencies of different units in the system are calculated. η_{te} , η_{tex} and η_{cc} of the system are also found to be 43.6%, 41.2% and 99.1%, respectively.

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1. Introduction

In the new century, coal is still the dominant fuel on the earth [1]. Great demand on coal, however, will cause severe environmental pollution and tremendous carbon discharge. In addition, over dependence on coal will also make the energy structure of one country fragile since coal will definitely run out one day. In recent years, with the advent of fear about environment pollution, climate change and coal resource exhaustion, investigations have been strongly focused on power generation from biomass [2]. Compared to coal, biomass is less intensive in carbon and pollutants discharge. Actually, biomass is carbon neutral, because the amount of carbon released during the thermal process of biomass will almost equal the amount of carbon captured during the photosynthesis process [3]. However, biomass is usually season-dependent and its calorific value is also very low. Hence, it is unrealistic to thoroughly substitute biomass for coal for power generation. One good compromise is the technology of co-utilization of coal and biomass [4].

With this method, part of coal consumption can be compensated by biomass, so the coal service time can be prolonged and, in the meantime, the carbon and pollutants discharge can be reduced. Hence, power generation from co-utilization of coal and biomass is proposed in this work for clean power generation. Gasification is an efficient way for the clean conversion of coal and other solid carbonaceous fuels [5]. Thereinto, hydrogasification has attracted more and more attentions recently for its unique advantages. For example, the carbon methanation reaction is strongly exothermic so no additional heat is required to maintain the gasification temperature; the direct product of hydrogasification is methane so no additional methanator is required; the efficiency of hydrogasification is usually higher than the other gasification technologies and can reach to 80%; no catalyst is required for the hydrogasification process [6,7]. Hence, the hydrogasification technology is chosen in this work to convert coal and biomass into syngas. CLP (chemical looping process) is a novel method to convert carbonaceous fuels with carbon capture and it was firstly proposed by Richter and Knoche in 1983 [8,9]. Compared to the traditional oxy-fuel combustion, CLP utilizes the lattice oxygen contained in the oxygen carriers rather than the gaseous. Thus, the air separation

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device which is electricity-intensive can be avoided by using the CLP technology [10]. In addition, pure hydrogen can be produced by the CLP technology, so no gaseous carbonaceous fuel like CH₄ or CO which usually takes a great part in the syngas will be brought into the SOFC (solid oxide fuel cells). Consequently, the internal reformer in the SOFC can be removed and the carbon deposit issue can also be thoroughly avoided [11]. In addition, research has found that most Fe based oxygen carriers present higher melting point, better mechanical strength, lower environmental impact and lower cost than the others [12]. Thus, CLP with pyrite as the oxygen carrier is proposed in this work to generate pure hydrogen with carbon capture. With all the proposed technologies mentioned above, a coal/biomass co-hydrogasification based chemical looping power generation system is developed in this work with the assistance of Aspen Plus. Actually, this system is developed based on the ZEC (zero emission coal) system [13]. The novelty of this system compared to the ZEC system includes two folds. First, since coal is non-renewable and dirty while biomass is renewable and relatively clean and carbon neutral, co-hydrogasification of coal and biomass technology is adopted. Second, the iron based CLH (chemical looping hydrogen) generation process is added to generate almost pure hydrogen from the syngas. This is because in the original ZEC system, hydrogen is generated by methane reforming. Although the hydrogen concentration can be improved in the reformers, there will still be large amount of CH₄ and small amount of CO in the syngas entering the SOFC. CO will form carbon deposit through the disproportionated reaction and CH₄ will form carbon deposit through the cracking reaction, which is harmful for the long term operation of SOFC. With the addition of the CLH process, not only the carbon deposit issue can be avoided but the SOFC structure can also be simplified since there will be no need for the internal reformers. In addition, since carbon can be firstly captured in the reformers of the system and then be further separated through the CLP process, the carbon capture rate of the system can be consequently very high and is definitely higher than that of the ZEC system. In fact, with the co-gasification process and the CLP technology, the net carbon discharge of this system can even be minus since biomass is carbon neutral. It can be seen that the biggest difference between this system and the ZEC system is the integration of the CLH process. The system developed in this work can then be named the CL-ZEC (chemical looping zero emission coal) system. The sketch of the CL-ZEC system is shown in Fig. 1.

In addition to the system proposed in this work, many similar systems have also been presented by the former researchers during the last few decades. Rokni once developed a power generation system integrating the biomass gasification, the SOFC and the Stirling engine [14]. The system thermal efficiency was about 42.4% and the effects of different operating conditions on the system properties were also studied. Mazzucco once set up an integrated biogas-fueled SOFC system for electric power generation [15]. The system was composed of a gasification plant, a SOFC and a retrofitted steam-injected gas turbine. It was reported that the system energy efficiency and exergy efficiency could be above 53% and 43%, respectively. Biomass was chosen as the feed stock in the above two systems. Since biomass is carbon neutral, carbon discharge in the two systems does not need capturing. However, as aforementioned, biomass cannot be thoroughly substituted for coal in large scale power generation system. Chen recently developed a power generation system which integrated the coal gasification, SOFC and the CLC (chemical looping combustion) technologies [16]. The system is very novel and promising. It used O₂ and CO₂ as the gasification agent and O₂ was obtained by an ASU (air separation unit). Thus, additional power was needed for oxygen generation. In addition, the syngas generated in the gasification unit was mainly CO, which would expose the SOFC to the risk of the carbon deposit. Prabu [17]

recently developed a clean power generation system with CO₂-oxy coal gasification and CLC. This system proposed another new concept and was also very promising. Since the system used CO₂-oxy coal gasification as the syngas generator, ASU was then a requirement. In addition, the system used steam turbine and gas turbine as the power generation unit, which was less efficient than SOFC [17]. From Fig. 1, it can be seen that the system proposed in this work mainly consists of a hydrogasifier, a series of cleaners, a reformer, a calciner, a reducer, an oxidizer, a combustor, a SOFC and a contracting and condensing steam turbine. The overall technological process of the system is as follows: 1) syngas is generated in the hydrogasifier unit and then is cleaned in the cleaners; 2) the cleaned syngas is reformed in the reformer to generate the gasification agent, H₂; 3) part of the reformed syngas is circulated to the hydrogasifier while the left is converted to pure H₂ in the chemical looping unit; 4) pure H₂ is consumed in SOFC to generate power; 5) the waste heat is recycled to generate additional power in the steam turbine. With the chosen technologies and the specific technological process, the system can reach high total energy and exergy efficiencies. The carbon deposit issue of the SOFC can be thoroughly avoided and the net carbon discharge can be very low and even negative. In addition, nitrogen can also be produced in this system as the byproduct.

2. Development of the CL-ZEC system

The CL-ZEC system proposed in this work mainly consists of a hydrogasifier, a reformer, a SOFC and a steam turbine. Detailed mathematical models for the main sub-models have been validated against experimental data in our former work [18] except the steam turbine whose calculated energy efficiency is about 35% and is also reasonable. The other parts of the system including the cleaners, the reducer, the oxidizer and the combustor are all simple Gibbs reactors and they are justified in the thermodynamic view. The dominant reactions in different parts of the system are listed in Table 1. The detailed flow sheet of the CL-ZEC system is shown in Fig. 2. Coal and biomass are dried and transported to the hydrogasifier where the solid fuels are decomposed and react with the recycled gasification agent. The flow rate of the feed stock is calculated using the design specific block in Aspen Plus to ensure the output power of the SOFC is 120 kW. Ash and the unreacted carbon are splitted and the gaseous product is cleaned sequentially by small amount of CaO, NaHCO₃ and ZnO to remove part of CO₂, HCl and H₂S, separately. The cleaned syngas then enters the reformer where CH₄ is reformed by H₂O to generate H₂. Reformer is a requirement for this system because it can generate additional hydrogen to balance the hydrogen consumption in the gasifier and the SOFC. CaO is added in the reformer since the carbonation process can release large amount of heat to maintain the reactor temperature and in the meanwhile promote the reformation process by absorbing the generated CO₂. CaCO₃ generated in the reformer is then circulated into the calciner to regenerate CaO. The heat required for the decarbonation process in the calciner can be obtained by burning part of biomass in the heater where additional biomass is burned with CuO in Comb1 using the CLOU (chemical looping with oxygen uncoupling) technology [19] so that the flue gas is rich in CO₂. Cu₂O generated in Comb1 is then circulated to Comb2, where it is oxidized by air to regenerate CuO. In addition, highly pure N₂ can also be produced in this step as byproduct. Part of the sensible heat contained in the flue gas from the heater unit can be used to heat the steam entering the reformer. It has been reported that the reactivity of CaO will decay with the circulation times. The reactivity of CaO with the number of cycles can be described with Eq. (1).

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