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Parameter analysis of a biomass based SOFC-Engine polygeneration system for cooling, heating and power production

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ABSTRACT

In order to meet the demand of clean and efficient energy conversion technology, a novel combined cooling, heating and power (CCHP) system fueled by biomass is proposed. This system is consists of biomass gasification unit, solid oxide fuel cell, IC engine unit and absorption refrigeration chiller. Thermodynamic model of the CCHP system are developed and then parameter analysis is adopted to optimize the performance of this system. The effect of air equivalent ratio (ER), steam biomass ratio (S/B) and the fuel utilization factor of SOFC (μ) on the performance of the entire system are studied. The results show that increase of S/B and μ will prompt the electrical efficiency, while the increase of ER has a negative effect on electrical efficiency. The exergy analysis shows that the exergy destruction of biomass gasification process and engine is larger, which is 454.5 kW and 207.2 kW respectively. On the contrary, exergy destruction of SOFC and absorption refrigeration chiller are 15.9 kW and 52.8 kW, respectively.

Keywords: Solid oxide fuel cell, Biomass gasification, Parameter analysis, Exergy analysis

1. INTRODUCTION

In order to alleviate the contradiction between increasing energy demand and social development in a sustainable and environmentally friendly way, clean and efficient energy conversion technologies have been promoted greatly in the past few years. In such framework, the utilization and development of renewable energy has gradually become one of the main research directions at present. Among all renewable energy sources, biomass energy is the fourth largest energy source in the world, accounting for nearly 14% of the world's primary energy demand [1]. Therefore, the efficient utilization of biomass energy has also become an important issue in the field of renewable energy.

On the other hand, fuel cell (FC) is known as the next power generation technology due to its excellent energy conversion performance. The FC can achieve high energy conversion efficiency because it is not limited by Carnot cycle [2]. As a kind of high-temperature fuel cell, solid oxide fuel cell (SOFC) usually operates at the temperature around 800 ℃, indicating that the inlet fuel of SOFC will be more flexible because the fuel can be pretreated by reforming and shifting reaction. Biomass gasification, as one of the main utilization methods of biomass, can produce syngas with hydrogen, oxygen and low carbon hydrocarbons under the action of gasification agent [3]. Moreover, the syngas can be adopted as SOFC fuel for power generation after high temperature reaction pretreatment. Therefore, the integration of biomass gasification and SOFC is expected to achieve the target of clean and efficient energy conversion. It should be noted that the off-gas of SOFC generally carrying a large amount of thermal energy and chemical energy due to its high operating temperature and not very complete electrochemical reaction. From this perspective, the full utilization of energy carried by SOFC off-gas will further improve the energy conversion efficiency of the whole fuel cell system. Combining the SOFC-based system with other cycles or equipment for energy recovery demands is one of the possible ways.

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In fact, there have been relevant studies on the utilization of SOFC off-gas energy, most of which focus on the use of gas turbine or Stirling engine as the downstream generation equipment to recover the energy. However, compared with the gas turbine, the power capacity of the IC (Internal combustion) engine is generally smaller, which is comparable to the SOFC power capacity. Meanwhile, IC engine operate more stably and have a nice dynamic performance in harsh environment. In our previous research, it was also confirmed that adopting engine as the SOFC downstream power generation equipment for secondary power generation greatly improves the performance of the system [4,5]. In addition, SOFC based biomass gasification systems are generally oriented towards distributed generation scenarios. As a distributed energy supply system, thermal energy and cold energy are also indispensable forms of energy output besides electricity. So far, to our knowledge, the biomass SOFC-Engine polygeneration system for cooling, heating and power production has not yet been reported. Based on the above analysis, in order to realize the cascade utilization of energy, improve the energy utilization efficiency and meet the requirements of users for distributed energy system, a novel biomass based SOFC-Engine system for cooling, heat and power supply was proposed in this work. Then the thermodynamic model of the system is established and the thermodynamic performance of the system is analyzed and optimized.

2. SYSTEM DESCRPTION

As shown in Fig 1, the novel combined cooling, heat and power supply system proposed in this work is mainly composed of biomass gasification unit, SOFC unit, HCCI (Homogeneous compression ignition) engine unit and absorption refrigeration cycle. The working principle of the whole system can be described as follows. The biomass (Stream 1) can be converted to syngas (Stream 4) under the action of the gasifying agent by the gasification process occurred in the gasifier. The syngas (Stream 4) is separated into impurities, hydrogen (Stream 6) and other mixed gases (Stream 6) by the separator. The mixed gas is fed into reformer to produce more hydrogen by reforming and shift reaction. Then, all the hydrogen fuel and preheated air are fed into SOFC to generate electricity through electrochemical reaction. The SOFC off-gas (Stream 10) is used as the inlet fuel of the engine for additional power generation through the Otto cycle. Generally, the off-gas of SOFC is lean fuel, which is difficult to be used as fuel for conventional engines. HCCI is a type of combustion mode that can make better use of the lean fuel for combustion. Therefore, this system adopts HCCI engine as the SOFC off-gas energy recovery equipment for secondary power generation. The heat of exhaust gas (Stream 20) from the engine is recycled to preheat the air and water. Afterwards the heat of stream 18 is further recovered by the absorption refrigerator and waste heat collector for heat and cooling energy supply.

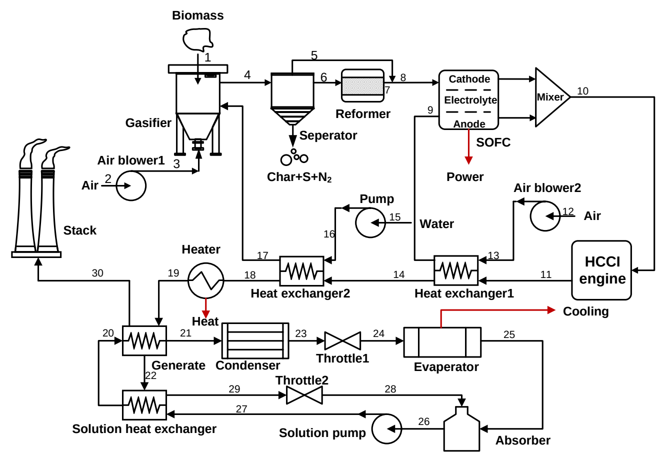

Fig 1 Schematic diagram of CCHP system based on SOFC-Engine and absorption chiller

3. SYSTEM MODELING

3.1 Biomass gasification model

Rice straw from Jiangsu province was adopted as the research object of biomass, and the proximate analysis and ultimate analysis results of biomass can be obtained from Ref [6]. The biomass decomposition process can be described by Eq. (1).

$$CH_xO_yN_zS_w \rightarrow C + \frac{x}{2}H_2 + \frac{y}{2}O_2 + \frac{z}{2}N_2 + wS \quad (1)$$

where $CH_xO_yN_zS_w$ is molecular formula of the biomass calculated according to the proximate analysis result.

The air equivalent ratio ER and steam to biomass ratio are two main parameters affecting the gasification process. The definition of these two parameters can refer to our previous work [5].

3.2 Reformer SOFC model

The heat released during the fuel cell operation can be calculated according to the Gibbs Helmholtz equation.

$$\Delta H = -nFE + nFT\left(\frac{\partial E}{\partial T}\right)_p \quad (5)$$

where *ΔH* is the enthalpy of electrochemical reaction; *n* is the number of transferred electrons; *E* is electrochemical reaction electromotive force; *F* is Faraday constant; *T* is the fuel cell temperature.

The relationship between the actual output voltage V of SOFC and the polarization voltage can be described by Eq. (6), where V_{re} is ideal reversible voltage, and can be calculated by Nernst equation [7].

$$V = V_{re} - V_{act} - V_{conc} - V_{ohm} \quad (6)$$

$$V_{re} = E_r^{\theta} - \frac{RT}{4F} \ln \frac{p_{H_2O}^2 p_0}{p_{H_2}^2 p_{O_2}} \quad (7)$$

where V_{act}, V_{conc} and V_{ohm} are activation, concentration overvoltage and ohm overvoltage, E_r^{θ} is standard voltage of SOFC, R is ideal gas constant, p is partial pressure of gas, p_0 is standard atmospheric pressure.

3.3 HCCI engine model

The thermodynamic process of the classical Otto cycle was used to approximately model the HCCI engine, which can be simplified into four sequential working strokes including polytropic compression, constant volume combustion, polytropic expansion, and constant volume exhaust. Due to the limited space of the article, the model of engine can refer to our previous work [5].

3.4 Absorption refrigeration chiller model

Each component should meet the NH_3 mass balance equation, that is, the mass of the import and export of NH_3 should be equal, as shown in Eq (13) [8].

$$\sum \dot{m}_{j,in} x_{j,in} = \sum \dot{m}_{k,out} x_{k,out} \quad (13)$$

where $\dot{m}_{in}$ and $\dot{m}_{out}$ are respectively the mass flow of NH_3 at the inlet and outlet of the component; x_{in} and x_{out} are respectively the concentration of ammonia solution at the inlet and outlet of the component.

The energy conservation equation of each component of NH_3-H_2O refrigeration cycle is shown in Eq (14) [8].

$$Q_k + \sum m_{j,in} h_{j,in} = \sum m_{k,out} h_{k,out} \quad (14)$$

4. RESULTS AND DISCUSSION

4.1 Parameter analysis

In order to optimize the performance of the design system, this section discusses the influence of the main parameters like ER, S/B, fuel utilization of the SOFC stack, etc., on the performance of the system. Fig. 2 describes the impact of S/B on the electrical power, heating power, cooling power and efficiencies of the system, respectively. With the increase of S/B ratio from 0.5 to 1.0, the electrical power output of the system gradually increases from 1076.9 kW to 1114.8 kW, and the gross electrical efficiency increases from 53.8% to 55.7%. The upward trend of the output electrical power can be explained as follows. The increase of steam flow is conducive to the forward movement of water gas shift reaction of carbon monoxide converting into hydrogen, so that the content of hydrogen and carbon dioxide increases, while the content of carbon monoxide decreases. The increase in hydrogen fuel leads to an increase in electrical power generated by SOFC. The SOFC is the main power generation device, so the electrical power and efficiency of the system increases gradually. Meanwhile, the output heat power decreases continuously and to a large extent, which decrease from 301.4 kW to 55.2 kW. The output cooling power increases slightly, from 98.5 kW to 109.6 kW. Correspondingly, the total output power and the CCHP efficiency also decrease gradually.

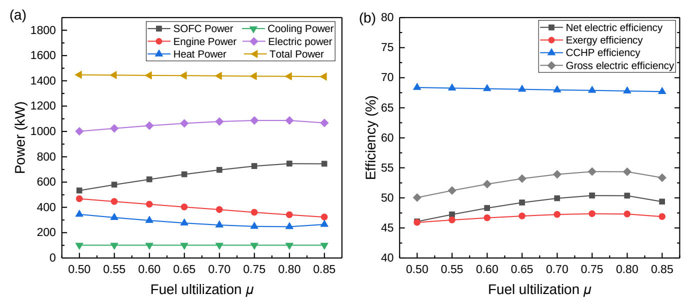

Fig 4 Effects of fuel utilization factor μ on system performance

Air equivalent ratio ER is another important parameter affecting biomass gasification process, so the influence of ER on system performance is also investigated. Fig. 3 depicts the effect of ER on out power and efficiency of the biomass based hybrid system. With the increase of ER from 0.05 to 0.20, the total output power of the system decreases from 1465.2 kW to 1402.0 kW, and the electrical power decreases from 1104 kW to 991 kW. The heat power first decreases and then increases, while the cooling power remained basically unchanged, at about 101 kW. When ER is less than 0.1, the SOFC output power is gradually increased while the engine output power and heat power decrease. However, when ER is greater than 0.1, the trend of the curve is opposite. SOFC output power gradually decreased while engine output power and heat power gradually increased. This trend is mainly due to the increase of ER, which leads to the increase of oxygen fed into the gasifier. Correspondingly, the temperature of the gasifier increases, and the water gas shift reaction of carbon monoxide and stream moves in the positive direction, which increases the hydrogen production. However, the hydrogen-oxygen reaction consumes a certain amount of hydrogen, resulting in a slight decrease in the concentration of hydrogen input to the

SOFC. As ER continues to increase, the reaction between hydrogen and oxygen will intensify, resulting in a significant drop in hydrogen content. Therefore, the output power of SOFC decreases slowly and then greatly decreases.

Fuel utilization factor μ is an important parameter of SOFC. Fig. 4 illustrates how the μ influences the system energy conversion performance. As fuel utilization increased, exergy efficiency and electrical efficiency of the system gradually increased. When the fuel utilization factor increased from 0.5 to 0.85, exergy efficiency and electrical efficiency increased from 50.1% to 54.4% and 45.9% to 47.3% respectively. The increase in fuel utilization factor means that more hydrogen participates in the electrochemical reaction, which increases the output power of the SOFC, but it will make the output power of engine decreased accordingly. Since the efficiency of SOFC is generally much higher than that of engines, lead to the increase of SOFC output power is greater than the decrease of engine power, which decides the increase of electrical power and electrical efficiency of the proposed hybrid system.

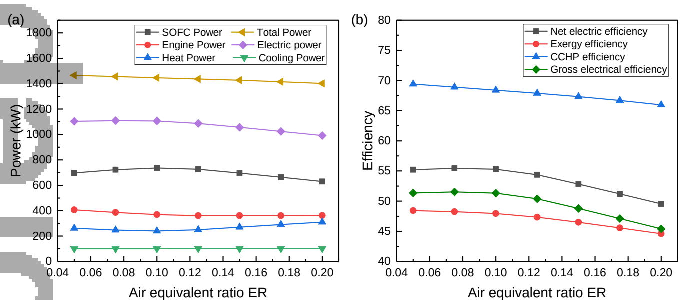

Fig 3 Effects of air equivalent ratio ER on system performance

5. CONCLUSION

This work proposes a novel biomass-based SOFC-Engine system for cooling, heating and power production. This CCHP system is modeled by Aspen Plus firstly and investigated from first and second law of thermodynamics. The main conclusions can be summarized as follows.

1) When the inlet biomass is set as 500 kg/h, the system can generate 1086.8 kW of electrical power, 249 kW of heating power, and 101 kW of cooling power. Correspondingly, CCHP efficiency, net electrical power efficiency, and exergy efficiency are 67.6%, 50.1%, and 47.4%, respectively.

2) Single-parameter sensitivity analysis have been conducted for the energy and exergy efficiency against several key parameters individually. The increase of S/B ratio and fuel utilization factor will prompt the electrical efficiency, while the increase of air equivalent ratio ER has a negative effect on electrical efficiency.

ACKNOWLEDGEMENT

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