



Performance analysis of the SOFC–CCHP system based on H₂O/Li–Br absorption refrigeration cycle fueled by coke oven gas



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ABSTRACT

The CCHP (combined cooling, heating, and power) system, especially combined with the SOFC (solid oxide fuel cell), has great potential for improving energy utilization efficiency. Therefore an integrated SOFC–CCHP system, fueled by COG (coke oven gas) which contains large amount of hydrogen, has been designed and proposed in this paper. The flue gas exhausted from the HRSG (heat recovery steam generator) is used for heating and the latent heat of water exhausted from the ST (steam turbine) is used for cooling achieved by a single-effect lithium bromide absorption chiller. Based on the corresponding models, the evaluations of the system performance are carried out aided by Aspen Plus process simulator. The calculation results indicate that the electrical efficiency of the SOFC can reach over 60% while the total power efficiency and the overall system efficiency of SOFC–CCHP system are about 70% and 90% respectively. Furthermore, the effect of several operating parameters including fuel flow rate, hydrogen content of COG, fuel utilization factor and operating pressure are investigated and analyzed on the proposed system performance. This research lays a good foundation for the designing of the proposed integrated SOFC–CCHP system, which would be an efficient utilization option of COG.

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1. Introduction

As is known to all, China has plenty of coal and thus derives many primary energy industries of coal consumption such as the iron steel industry and coking industry. Whereby coking industry consumes a great deal of heating, electricity and cooling energy and yields many byproducts, one of which is COG (coke oven gas) while COG contains large percentage of hydrogen which is an environmentally friendly fuel (see, e.g., Ref. [1]). However, traditional coking factories have not properly taken full advantage of COG, which is just stored, burned as a conventional fuel and ignored its characteristics. Therefore, considering of energy saving and emission reduction, an efficient distributed energy generation system is being proposed on coking industry to utilize COG directly to provide energy for coking or other related industrial links.

With economy development and growing environment problems like global warming, the use of a more efficient power system has become a critical challenge for power plant planners and

operators. CCHP (Combined cooling, heating, and power) system, which have great potential for increasing resource energy efficiency and reducing air pollutant emissions dramatically, can produce both electric and usable thermal energy on site or near site according to local conditions.

SOFC (Solid oxide fuel cell) not only has the main characteristic of high performance efficiency (more than 50%) but also the high exhaust temperature (see, e.g., Refs. [2–5]). Therefore it is generally considered to be composed with a Brayton cycle or an ORC (organic Rankine cycle) as bottoming cycle recovering waste heat to increase the overall system efficiency. Many researchers have studied the performance of the integrated SOFC–GT system or the combined SOFC–ORC power system over the past decades.

Brayton and Rankine cycles have been proved to be more applicable now as the bottoming cycle due to mature technology in this area. However, when operating temperature of SOFC decreases in the future, the use of GT as bottoming cycle will be less beneficial. Therefore, some studies have been carried out with a Stirling engine as the bottoming cycle when SOFC is used as topping cycle (see, e.g., Refs. [6–8]). Meanwhile, there are only a few studies which analyze the SOFC–CCHP system performance (see, e.g., Refs. [9–11]). A new combined CCHP (cooling, heating and power)

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system driven by SOFC is investigated in Ref. [12]. In this system, ammonia–water system is regarded as its bottoming cycle which conducts a new bottoming cycle of the SOFC–CCHP system.

In addition, because absorption chillers can utilize low temperature (less than 100 °C) heat, they are widely used for providing waste heat-powered cooling or refrigeration in CCHP system to improve energy efficiency. Water/lithium bromide ($\text{H}_2\text{O}/\text{Li}-\text{Br}$) and ammonia/water are the two most common combinations of absorption chillers working fluids (see, e.g., Refs. [13–15]). However, $\text{H}_2\text{O}/\text{Li}-\text{Br}$ chillers usually have higher COPs than those of ammonia/water chillers and do not have working fluid toxicity issues. Therefore, in present work, a $\text{H}_2\text{O}/\text{Li}-\text{Br}$ absorption chiller is chosen to recover the waste heat from the steam exhaust to produce cooling for cold users.

In this study, the integrated SOFC–CCHP system fueled by COG is systematically presented and thermodynamically analyzed with network capacity of 220 kW and it produces large amount of cooling and heating which is suitable for coking industry. Then the system is investigated on several performance characteristics including efficiencies (efficiency of SOFC, total power efficiency, and overall system efficiency), power, heating, cooling and so on under four variables, i.e. fuel flow rate, hydrogen content of COG, fuel utilization factor and operating pressure. The model of SOFC is verified with experimental data and the parameters of $\text{H}_2\text{O}/\text{Li}-\text{Br}$ absorption chillers are compared with Ref. [16].

The study is aimed to develop an efficient distributed energy system called the SOFC–CCHP system based on $\text{H}_2\text{O}/\text{Li}-\text{Br}$ absorption refrigeration cycle fueled by COG which can provide cooling, heating and power for coking industry simultaneously.

2. System description

Fig. 1 illustrates the schematic diagram of SOFC–CCHP system based on $\text{H}_2\text{O}/\text{Li}-\text{Br}$ absorption refrigeration cycle fueled by COG, which can produce power, heating and refrigeration simultaneously. This system includes a SOFC, a GT driven by an afterburner, a ST (steam turbine) driven by HRSG (heat recovery steam generator), a heating-process heat exchanger to supply heating and a single-effect $\text{H}_2\text{O}/\text{Li}-\text{Br}$ absorption chiller to produce cooling. The system is divided into a topping SOFC–GT system cycle and a bottoming chiller cooling cycle.

The flows in the SOFC–CCHP system according to Fig. 1 are described as follows. For the topping SOFC–GT system cycle, the ambient air (state 1) at 20 °C is compressed by an air compressor to the operating pressure (state 2). Next the compressed air is preheated by the preheater which uses the exhaust of the GT (state 11) and then fed to the cathode of the SOFC (state 3). For the anode side, the gas exited from the anode (state 7) is split into two strands by a splitter. One (state 9) enters the afterburner and the other (state 8) mixes with the COG (state 5). And the separation ratio of the splitter is decided by ratio of steam and carbon (S/C) which has a great importance of SOFC efficiency (see, e.g., Ref. [17]). The COG is clean enough to be fed directly into the SOFC just like Ref. [18]. The electrochemical reactions occurred in the SOFC stack produce DC (direct current) which can be converted into AC (alternating current) by an inverter. The steams exited from SOFC have high temperature for highly exothermic reactions in SOFC stacks. The afterburner is implemented to increase the system fuel utilization because the COG cannot react completely in the SOFC stacks. Therefore, in the afterburner, the excess air out of the cathode (state 4) and strand 9 are mixed up for chemical reaction, and the produced gas (state 10) will drive the GT to generate power output at high pressure and temperature.

After the exhaust heat of the low pressure exhaust gas from GT (state 11) is sequentially recovered by the compressed air (state 2),

the pumped water (state 14) and the circulating water (state 18) in preheater, HRSG (heat recovery steam generator) and the heat exchanger respectively, the gas (state 20) enters into the atmosphere. Meanwhile, the pumped water (state 14) becomes superheated steam (state 15) and then goes through the ST to generate power. And the circulating water exited from the heat exchanger (state 19) with an outgoing temperature of 60 °C which is proved to be sufficient to address bacterial problems and satisfy heat requirement for heat users (see, e.g., Ref. [17]).

In the bottoming cycle, a single effect $\text{H}_2\text{O}/\text{Li}-\text{Br}$ absorption chiller is implemented. The working fluids of the chiller cycle are water and a solution of $\text{Li}-\text{Br}$ and water. The temperature of steam exited from ST (state 16) is high enough to heat the desorber. Part of the water evaporates from the solution of the $\text{Li}-\text{Br}$ and water existing as steam condition (state d) and then enters the condenser. In the condenser, water is cooled down and exits from the condenser at saturated liquid (state h). After that, the saturated water goes through a throttle valve and then enters the evaporator at low temperature (state i). In evaporator, this part of water absorbs enough heat from the cooling water and gradually becomes saturated steam (state j), and then the cooling water supplies cooling for the cold users. Next, the steam enters the absorber and mixes with the higher $\text{Li}-\text{Br}$ concentration solution (state g) obtaining a lower $\text{Li}-\text{Br}$ concentration solution (state a). After that, the solution is pumped to the SHX (solution heat exchanger) and heated by a higher $\text{Li}-\text{Br}$ concentration solution (state e) exited from the desorber. Then, the solution (state c) enters the desorber and is heated by the exhaust of ST. Part of the water in the solution evaporates and then exits the desorber (state d). Next, the rest of solution (state e) with a higher $\text{Li}-\text{Br}$ concentration exits the desorber and enters SHX. After that, the solution exited from SHX (state f) goes through a solution throttle valve and then goes into absorber (state g) to finish the bottoming cycle.

3. Methodology

The thermodynamic results in this study are obtained by the ASPEN PLUS simulation software (see, e.g., Refs. [19,20]) which contains rigorous thermodynamic and physical property database and can provide diversiform models for system secondary development. Therefore, it has special advantages for process simulation and result analysis. However, there is a big challenge that ASPEN PLUS does not have an inner model for basic SOFC stack and yet the calculation of the system is more complicated. To overcome this problem, ASPEN PLUS is chosen to establish the primary system and calculate some basic data like temperature and pressure. Then FORTRAN programming is adopted to calculate thermodynamic data, such as the voltage of the SOFC and the overall efficiency of the system.

3.1. Mathematic models of the SOFC

The present research of SOFC in open literature can be concluded into two main trends with different mathematic models. One trend adopts direct kinetics calculation and is accomplished based on experiments in Ref. [21]. The other is inclined to indirect thermodynamics calculation and also chosen to calculate the SOFC stacks in this paper.

Because of the fast reaction rate of methane, H_2 is assumed as the only fuel component participating in electrochemical reaction (see, e.g., Ref. [22]). This model has been validated by experimental data in the range of 900 °C–1000 °C (operating temperatures) as described in Ref. [23]. There are reforming reactions and electrochemical reaction occurring in the anode of the SOFC, as follows.

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