

Study on Buildings CCHP System Based on SOFC

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Received: 02 December 2019; Accepted: 30 January 2020

Abstract: The relationship among the working temperature, pressure and current density of a Solid oxide fuel cell (SOFC) and its output power and efficiency are analyzed in the framework of a theoretical model able to provide, among other things, the volt ampere characteristic curve. In particular, following the principle of temperature matching and cascade utilization, we consider a gas turbine (GT) and a LiBr absorption chiller to recycle the high-grade exhaust heat produced by the considered SOFC. This distributed total energy system is set up with the intent to meet typical needs of buildings for cooling, heating and power (CCHP). The total power generated by the considered SOFC and gas turbine is about 222 kW and the total power generation efficiency by low heat value of fuel (LHV) is 63.7%. In the CCHP system, the high temperature exhaust of GT is further used to drive LiBr absorption unit, which can produce about 34.8 kW cooling capacity or 84.5 kW of heat (the total energy utilization 78.03%).

Keywords: SOFC; gas turbine; absorption chiller; CCHP; total energy system

1 Introduction

With the rapid development of China, the problems of energy utilization and environment become increasingly prominent, which has been an important restricting factor for the sustainable development of society. In the total amount of commercial energy consumption, building energy consumption is huge with the proportion close to one third. At the same time, environmental problems caused by building energy consumption cannot be ignored. For example, in winter, dust particles, sulfides, nitrogen oxides and other pollutants emitted by urban heating in northern China frequently cause serious smog which damage the ecological environment and threaten people's life and health. Therefore, building energy conservation has great energy saving potential and important environmental protection significance, and has become a key research field of energy saving [1].

In buildings, there is commonly a large demand for power, heating, cooling, gas and other energy, which make the application of building energy conservation technology complex. For this reason, combined cooling heating and power (CCHP) system developed rapidly. Usually, CCHP system is also a distributed total energy system with the advantages of energy saving, environmental protection, fast response and close to users. The so-called distributed energy system is relative to the centralized energy system. It refers to the power generation or multi generation system that is located in or near the load center and does not take large-scale and long-distance power transmission as the main purpose, and meets the requirements of environmental protection.



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In addition, the total energy system is based on the principle of temperature matching and cascade utilization. Energy utilization equipment should be selected according to the energy grade, so as to maximize the use of energy. Through combination of distributed and total energy system, distributed total energy system has both characteristics. At present, the common distributed total energy systems include: gas turbine/absorption chiller, internal combustion engine/absorption chiller, high temperature fuel cell/gas turbine, high temperature fuel cell/absorption chiller, etc. [2].

Fuel cell is a kind of electrochemical reaction device which convert the chemical energy stored in fuel and oxidant directly into power. Because it does not generate energy through the combustion of fuel, and does not utilize the heat energy contained in the working medium to do mechanical work, the energy conversion process of fuel cell is not limited by the Carnot cycle with almost no emission of pollutants. Actually, its efficiency can be more than 60%, much higher than ordinary heat engines. Solid oxide fuel cell (SOFC) is a typical high-temperature fuel cell, which working temperature is 800°C–1100°C. As the third generation fuel cell, SOFC has the characteristics of high efficiency, no pollution and high value of waste heat utilization, which make people realize the superiority of building distributed total energy systems based on it [3].

In this study, the SOFC is modeled, and the effects of temperature, pressure and current density on SOFC performance are analyzed. On this basis, a buildings CCHP system based on SOFC as prime mover is designed and integrated. The main energy conversion equipment in the system include SOFC stack, gas turbine, LiBr absorption unit, heat exchanger, etc. According to the principle of temperature matching and cascade utilization, the chemical energy stored in the fuel is successively released and utilized in SOFC, gas turbine and absorption unit, so as to significantly improve the energy utilization efficiency and reduce pollution while generating cooling, heating, and power. Then, the CCHP system is calculated and analyzed by using MATLAB according to the model, and the performance parameters such as power generation, cooling capacity, heating capacity, energy utilization efficiency are obtained.

2 Modeling of SOFC and Performance Analysis

2.1 Prototype and Simplification

The SOFC stack model in this paper is based on the high temperature tubular fuel cell produced by SWPC. The effective length of a single cell is 150 cm, the diameter is 2.2 cm, the activated area of electrochemical reaction is 834 cm², and the working temperature is 1000°C. The whole SOFC stack is made up of 1152 SOFC single cells. The fuel supplied to the cells is a mixture of methane, carbon dioxide and nitrogen, of which the mass fraction of CH₄ is 97%, CO₂ is 1.5% and N₂ is 1.5%. Before electrochemical reaction, the fuel is directly reformed in anode to generate H₂. In order to improve the reforming efficiency and save the fuel humidification process, the anode gas is recycled to utilize the water generated in the electrochemical reaction [4–6]. In this way, the direct internal reforming method eliminates the complex and expensive external reforming equipment as well as fuel humidification device, making the system simpler as shown in Fig. 1.

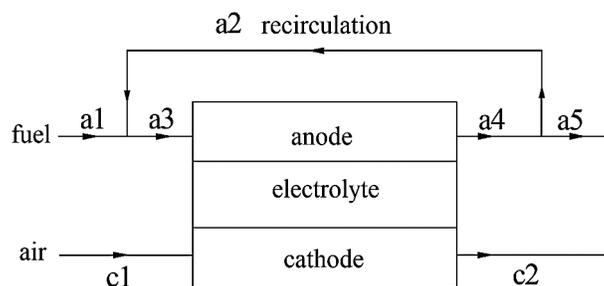


Figure 1: Schematic diagram of SOFC with fuel directly internal reformed

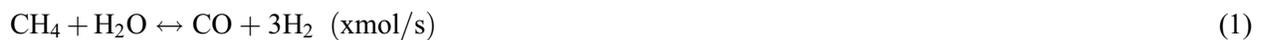
To simplify the SOFC stack model, the following assumptions can be made [6]:

- 1) The SOFC stack is simplified as a zero dimensional model, ignoring the temperature gradient and pressure gradient along the tube length.
- 2) The cathode is supplied with air, and the composition is calculated as 79% N₂ and 21% O₂ (mass fraction).
- 3) The SOFC operates in steady state and the reaction gas reaches chemical equilibrium at the outlet of the cells.
- 4) The SOFC is in an adiabatic state with no heat exchange with the environment.
- 5) Only H₂ is involved in the electrochemical reaction, and CO generates CO₂ and H₂ through water gas shifting.
- 6) The water gas shifting reaction inside the cells does not need external steam input, completely provided by water generated in the electrochemical reaction.

2.2 Modeling of SOFC

There are altogether three kinds of chemical reactions in the cells, which are steam reforming, water gas shifting and electrochemical reaction. Their reaction equations and reaction rates are as follows:

Reforming:



Shifting:



Electrochemical:



Assuming that the internal reforming reaction and water gas shifting reaction of SOFC are in chemical reaction equilibrium state, the chemical equilibrium constants can be expressed as functions of the mole fraction of each gas component:

$$K_{pr} = \frac{n_{\text{CO}}n_{\text{H}_2}^3p^2}{n_{\text{CH}_4}n_{\text{H}_2\text{O}}p_0^2} \quad (4)$$

$$K_{ps} = \frac{n_{\text{H}_2}n_{\text{CO}_2}}{n_{\text{CO}}n_{\text{H}_2\text{O}}} \quad (5)$$

K_{pr} and K_{ps} are the equilibrium constants of reforming reaction and water gas shifting reaction respectively, p is the working pressure of SOFC stack, p_0 is the atmospheric pressure under the standard condition. K_{pr} and K_{ps} are only related to temperature and they can be estimated by the following relationships and the values of A, B, C, D, E are shown in Tab. 1 [4]:

$$\log(K_p) = AT^4 + BT^3 + CT^2 + DT + E \quad (6)$$

According to Faraday's law, when there is an electron transfer of n moles, the charge of nF Coulomb passes through (where F is Faraday constant and its value is 96485 C/mol). The output current of SOFC can be calculated by the following formula:

Table 1: Values of A, B, C, D, E

	Reforming	Shifting
A	-2.63121×10^{-11}	5.47301×10^{-12}
B	1.24065×10^{-7}	-2.57479×10^{-8}
C	-2.25232×10^{-4}	4.63742×10^{-5}
D	0.195028	-3.91500×10^{-2}
E	-66.1395	13.2097

$$I = 2Fz \quad (7)$$

The ideal reversible voltage of SOFC can be calculated by Nernst equation:

$$E_N = E^0 - \frac{RT}{2F} \ln \left(\frac{p_{\text{H}_2\text{O}}/p_0}{p_{\text{H}_2}/p_0 (p_{\text{O}_2}/p_0)^{1/2}} \right) \quad (8)$$

where $E^0 = 1.2723 - 2.7645 \times 10^{-4}T$, it shows the relationship between the Nernst voltage and temperature of SOFC at atmospheric pressure with hydrogen and oxygen as fuel and oxidant.

2.3 SOFC Performance Analysis

In Fig. 2, the computed results of volt ampere characteristics of SOFC stack at 900°C are compared with the volt ampere characteristics of SWPC's 100 kW SOFC stack in Westervoort, the Netherlands. It can be seen that the simulation data is in good agreement with the experimental data. With the increase of current density, the output voltage of SOFC decreases gradually, for the reason that the voltage drop caused by the internal resistance of the cells increases.

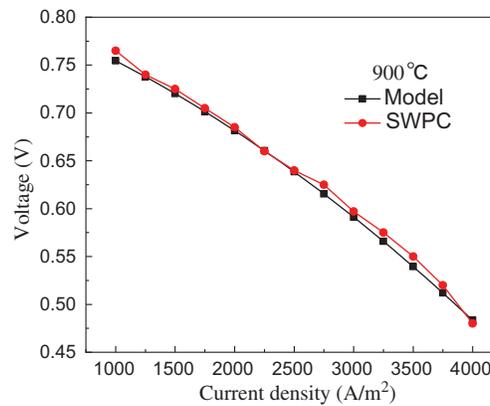


Figure 2: Comparison between model results and experimental data at 900°C

Fig. 3 depicts the effect of the operating temperature on the output power of SOFC (in terms of single cell). It can be seen that with the increase of temperature, the output power also increases. This is because the increase of temperature leads to the increase of chemical reaction rate and fuel consumption per unit time. On the other hand, the increase of temperature leads to the enhancement of ionic conductivity of solid oxide electrolyte in the molten state, which also promotes the electrochemical reaction.

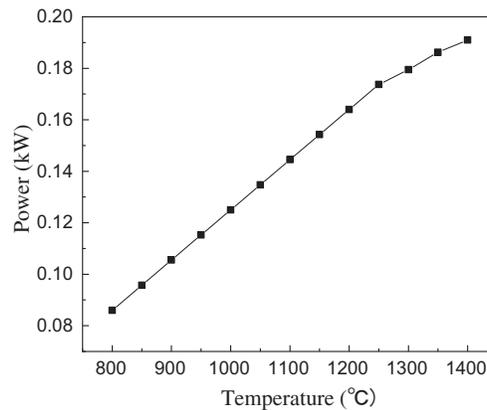


Figure 3: Effect of operating temperature on output power

Fig. 4 shows that the working efficiency of SOFC gradually decreases with the increase of temperature. When the temperature is over 1000°C, the efficiency of SOFC has no obvious advantage over the traditional heat engine, so the development of SOFC should be towards the low temperature direction. Although the efficiency of SOFC is not very high in high working temperature, the value of waste heat utilization increases. Through rational use of waste heat, the total efficiency may be higher.

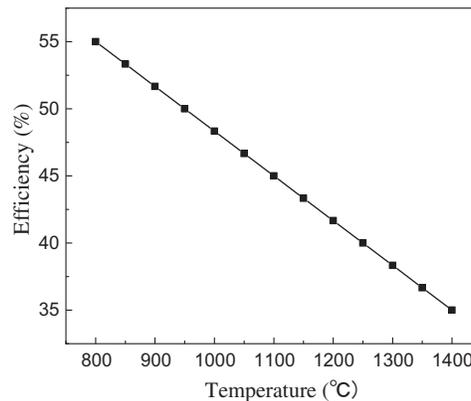


Figure 4: Effect of SOFC working temperature on efficiency

Pressure is also an important factor affecting the performance of SOFC. Fig. 5 describes the effect of pressure on SOFC voltage and output power. It can be seen that both the voltage and power increase with the increase of working pressure. This is because the concentration of reactants in the cells increases with the increase of pressure, which reduces the polarization loss of both activation and concentration in the electrochemical reaction, thus improving the performance of SOFC.

3 Establishment of Buildings CCHP System Based on SOFC

The exhaust temperature of SOFC can reach 800°C–1100°C, which contains abundant thermal energy. Through reasonable recycling, the energy utilization efficiency of fuel could be significantly improved so as to offset the reduction of SOFC power generation efficiency under high temperature conditions. By the principle of temperature matching and cascade utilization, the buildings CCHP system based on SOFC can be designed. In the system, each energy utilization equipment needs corresponding grade of energy, and they are selected according to temperature matching. Therefore, these equipment can reduce the

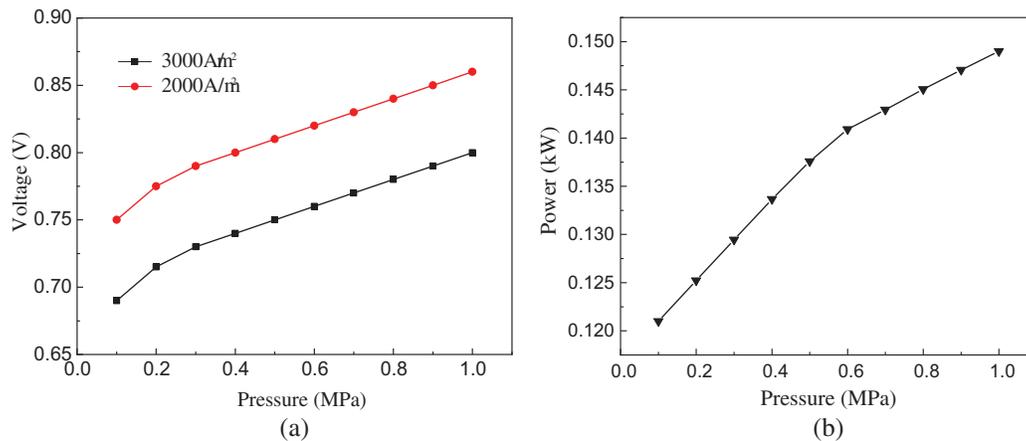


Figure 5: Effect of pressure on performance of SOFC (a) Effect of pressure on voltage (b) Effect of pressure on Power

exhaust temperature of SOFC step by step, so as to realize the cascade utilization of energy, and achieve the goal of using as much as possible. In addition, the system is close to the client with very small line loss which can simultaneously meet the cooling, heating and power load demand of buildings or an area [7].

3.1 SOFC/GT Hybrid System

The 800°C–1100°C exhaust of SOFC is consistent with the inlet temperature of gas turbine, which could form a SOFC/GT combined cycle power generation system, as shown in Fig. 6. In the hybrid system, the high temperature fuel cell replaces the combustion chamber of the gas turbine system to heat the working medium before it expands in the turbine. After compressed by the compressor and preheated, the air enters the cathode of the SOFC while the fuel enters the anode. Then, fuel and air undergoes electrochemical reactions on the anode and cathode electrodes respectively and converts the chemical energy into electric power directly [8]. This is the first stage of energy utilization, then the exhaust enters the gas turbine to expand and output expansion work, which is the second stage of energy utilization. After two stages of utilization, the exhaust of GT can be used to preheat the air or fuel before discharged to the atmosphere. By model calculation, the power generation efficiency of SOFC/GT hybrid system is more than 50% [9–11].

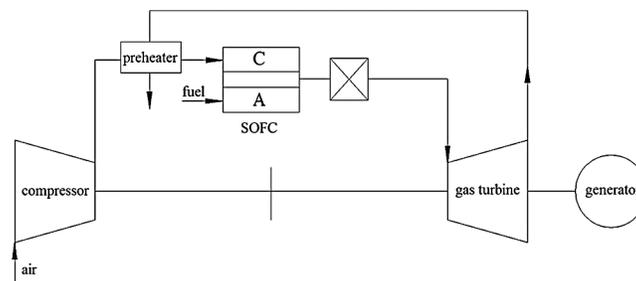


Figure 6: SOFC/GT hybrid system

The isentropic efficiency of gas turbine is:

$$\eta_G = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}} \quad (9)$$

The expansion work of gas turbine is:

$$W_G = m(h_{in} - h_{out}) \quad (10)$$

where $h_{out,s}$ is the enthalpy of gas turbine outlet under isentropic condition.

3.2 SOFC/GT/Absorption Chiller (Heat Pump) System

As the gas turbine belongs to the high temperature energy conversion equipment, in the SOFC/GT hybrid system, the gas turbine exhaust still has a certain use value because of its high temperature [12]. According to the principle of temperature matching and cascade utilization, some medium-low temperature energy conversion equipment can be used to further recover the residual heat at the outlet of gas turbine and lower the exhaust temperature. Thus, a three-stage energy utilization system can be built. In practical application, the thermal energy with lower grade is more suitable for heating or cooling. Therefore, it can be considered to use the exhaust of GT to drive a LiBr absorption unit to generate heat or cooling capacity, so as to form a CCHP system [13–15]. Driven by heat, LiBr absorption unit can effectively recover most kinds of industrial waste heat, and its refrigeration COP is usually 0.65–0.75 [16].

Fig. 7 shows the buildings CCHP system composed of SOFC, GT, and absorption chiller/heat pump. It can be seen that the energy contained in the fuel is first used in the way of electrochemical reaction in SOFC. Then the high-temperature exhaust of SOFC enters the gas turbine to expand and output work which is the second stage of total energy system. At last, as the third stage, the waste heat of gas turbine is used to drive LiBr absorption chiller/heat pump which can supply cooling in summer or heat in winter. In order to recover as much heat as possible, the compressed air enters SOFC after two stages of preheating, thus increasing the inlet oxidant temperature and reducing the internal temperature gradient of the cells. Through the three-stage utilization of energy, the final exhaust temperature is further lowered and the theoretical efficiency will be higher than SOFC/GT hybrid system.

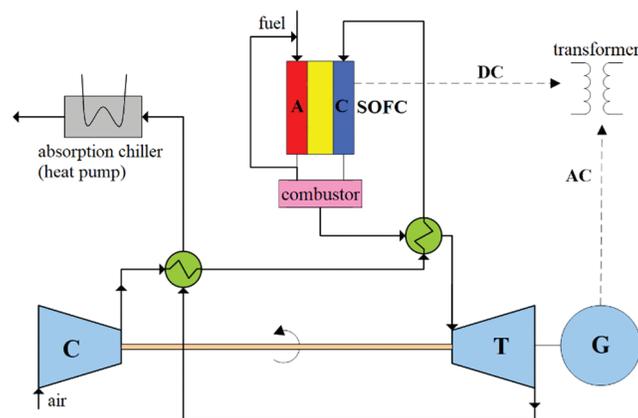


Figure 7: SOFC/GT/absorption chiller (heat pump) system

The model of SOFC/GT hybrid system has been given above, and the calculation method of absorption unit is still needed. As the driving heat source, the exhaust of GT enters the generator of absorption chiller to exchange heat, and then will be discharged into the atmospheric environment after the temperature is

reduced. Therefore, we can calculate the cooling capacity of absorption chiller as follows:

$$Q_c = m(h'_{in} - h'_{out}) \cdot COP \quad (11)$$

When the LiBr absorption unit is used as a heat pump, the heating capacity is:

$$Q_h = m(h'_{in} - h'_{out}) \cdot (1 + COP) \quad (12)$$

where COP is the refrigeration coefficient, generally 0.65–0.75; h'_{in} is the inlet enthalpy of the driving heat source, h'_{out} is the enthalpy of the exhaust, and they are determined by the inlet and exhaust temperatures. Generally, the generator working temperature of the LiBr absorption unit is about 120°C, and the heat transfer temperature difference of the generator is about 3–7°C, so that the exhaust temperature can be determined.

Then, the total energy utilization efficiency of CCHP system is:

$$\eta_t = \frac{W_{SOFC} + W_{GT} + Q_G}{Q_{LHV}} \quad (13)$$

where, W_{SOFC} is the output power of SOFC, W_{GT} is the output power of GT, and Q_G is the heat released in the generator per unit time by driving heat source, Q_{LHV} is the low heating value (LHV) of consumed fuel per unit time in the CCHP system.

4 Performance Computation of Buildings CCHP System Based on SOFC

The SOFC stack consists of 1152 SOFC single cells produced by SWPC. Based on the model, the SOFC/GT/LiBr absorption unit (CCHP) system designed in Fig. 7 is calculated by using MATLAB and the main input parameters are in Tab. 2.

Table 2: Input parameters of SOFC/GT/LiBr absorption unit (CCHP) system

Parameter	Value	Unit
Environmental pressure	101.3	kPa
Environmental temperature	298	K
Anode recycling rate	0.2	–
Air flow rate	13.6	mol/s
Fuel utilization	0.85	–
Air utilization	0.25	–
Current density	3000	A/m ²
Pressure ratio of compressor	3.8	–
Isentropic efficiency of compressor	0.8	–
Isentropic efficiency of turbine	0.8	–
AC/AC efficiency	0.95	–
DC/AC efficiency	0.9	–
Absorption chiller COP	0.7	–

Under the rated working conditions shown in Tab. 2, the SOFC stack generates about 190 kW DC power, while the work output by gas turbine is 53 kW which equals the expansion work minus the work consumed by compressor. The total AC power generation of fuel cell and gas turbine is 222 kW and the total generating efficiency calculated by low heat value of fuel (LHV) is 63.7%. At the turbine outlet, the residual heat is used to drive absorption chiller/heat pump which can generate about 34.8 kW cooling capacity in summer or 84.5 kW of heat in winter. Finally, the total energy utilization of the CCHP system is 78.03%. The output parameters are in Tab. 3.

Table 3: Output parameters of SOFC/GT/LiBr absorption unit (CCHP) system

Parameter	Value	Unit
SOFC voltage	0.662	V
SOFC power generation	190.8	kW
SOFC working temperature	1273	K
Fuel flow rate	0.445	mol/s
GT output work	53	kW
Total power generation	222.07	kW
Total power generation efficiency	63.7%	–
Cooling capacity	34.8	kW
Heating capacity	84.5	kW
Total energy utilization	78.03%	–

5 Conclusions

SOFC is a kind of fuel cell with the highest operating temperature, which is suitable for building distributed total energy system or CCHP system. According to the simulation results and analysis above, the conclusions are as follows:

(1) The simulation and experimental data of SOFC are in good agreement: as the current density increases, the output voltage decreases gradually; as the temperature increases, the output power increases, while the efficiency of SOFC decreases; as the working pressure increases, both the voltage and power increases.

(2) According to the principle of temperature matching and cascade utilization, a buildings CCHP system composed of SOFC, GT, LiBr absorption chiller/heat pump is designed as shown in Fig. 7, and its efficiency is higher than SOFC/GT hybrid system.

(3) In the CCHP system, the total power generated by SOFC and GT is 222.07 kW, and the total power generation efficiency calculated by LHV is 63.7%. The absorption chiller/heat pump driven by GT exhaust is able to supply about 34.8 kW of cooling or 84.5 kW of heat. The total energy utilization of the CCHP system reaches as high as 78.03%.

Acknowledgement: Thank to the Professor Jitian Han of ShanDong University for the help in this study.

Funding Statement: This work was supported by the doctoral research initiation fund of Linyi University (Grant No.: 204-40618051; Zhang, B.; <http://www.lyu.edu.cn/>).

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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