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EXPERIMENT BASED THERMOELECTRIC CHARACTERISTICS ANALYSIS OF SOLID OXIDE FUEL CELL SYSTEMS UNDER HYDROGEN AND METHANE

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ABSTRACT

Solid oxide fuel cell (SOFC) has attracted more and more attention due to its power generation characteristics of high efficiency, low emission, and strong fuel adaptability. In order to ensure the stable and efficient operation of the system, it is urgent to study the thermoelectric characteristics and control laws of SOFC systems under different fuels for different fuel types can result in different thermoelectric characteristics. Therefore, based on the 200-hour experimental data obtained from an external steam-reforming SOFC independent power generation system, the temperature distribution and electrical characteristics of the system at different power stages are studied. Moreover, the thermoelectric characteristics of the independent SOFC systems under pure hydrogen and methane fuel types with the same output power are further compared. The results show that, the stack voltage and the fuel utilization rate of the methane fed SOFC system is lower than that of the hydrogen fueled SOFC system. And the temperature gradient on the fuel side of the methane fed SOFC system is relatively large, while the temperature gradient on the air side of the hydrogen fueled SOFC is relatively large. The analysis process plays a significant role in system control strategy design, which improves the fuel adaptability of the system.

Keywords: solid oxide fuel cell, temperature distribution, electrical characteristics, temperature gradient

1. INTRODUCTION

Today, with the shortage of resources and the increasingly serious environmental pollution, the fuel cell has become one of the most promising green power generation methods in the future. In addition to being an efficient, clean, low-emission power generation [1], solid oxide fuel cells (SOFCs) have the unique-merits of fuel flexibility, no need for precious metal catalysts such as platinum, no need to worry about CO poisoning, and easy maintenance of all solid-state structures, so it has attracted more and more attention. Various types of fuel can be utilized for SOFC systems, such as hydrogen, methane, liquefied petroleum gas, biomass gas and other hydrocarbons [2]. Currently, SOFC power generation systems are mainly divided into two categories according to the fuel used, hydrogen fueled SOFC system and external steam-reforming SOFC system.

According to the actual experiment, it is urgent to study the thermoelectric characteristics and control laws of SOFC systems under different output powers and fuels for different types of fuels can cause different thermoelectric properties of systems. It not only can fully improve the fuel adaptability of the SOFC system [3], design the SOFC systems under different fuels, but also better grasp the control law and optimize the controller to extend the life span of the system. Moreover, the comparison of system performance under different types of fuel can take insight into system configuration optimization, which facilitates system design and control.

At present, the research on the distribution of thermoelectric characteristics of SOFC system mainly consists of two types, numerical simulation and experimental exploration. Due to the limitations of experimental cost and time cost, more numerical simulation work has been done to explore the thermoelectric characteristics distribution of SOFC system. Dolenc et al. [4] designed an online estimator for the maximum and minimum stack internal temperatures using an efficient data-driven approach. Fardadi et al. [5] developed a dynamic solid oxide fuel cell model to study the effects of different flow arrangements and uneven flow between channels on temperature distribution and thermal gradient under transient and steady-state responses. In addition, Amiri et al. [6] used a system-level model to study the performance of SOFC systems supplied by different fuels such as natural gas, biogas and syngas.

However, due to the high risk and cost of experimental test, the studies of SOFC system based on a real SOFC stack is relatively less [7]. Razbani et al. [8] established an experimental device consisting of a cross-flow stack of six cells, placing the stack in a constant temperature electric furnace and using five thermo-couples to measure the steady-state temperature distribution. Guan et al. [9] measured and studied the temperature distribution of the single cell in the stack by using a thin K-type thermocouple and a self-developed CAS-I sealing material.

From the research work above, many significant results about SOFC stack thermoelectric characteristics have been grasped. However, it is scarce to analyze the temperature distribution and electrical characteristics of SOFC systems under different fuels through SOFC independent power generation system. So the thermoelectric characteristics of SOFC systems under different output powers and fuels are studied in this paper. The remaining part of the paper is organized as follows. In Section II, the structure and working principle of the 1kW external steam-reforming SOFC system are introduced. In Section III, the thermoelectric characteristics of the system at different power stages under hydrogen and methane fuel types are obtained**.** In Section IV, the temperature distribution of the stack fed with methane in a constant temperature electric furnace is obtained. In Section V, the temperature field and electrical characteristics of the system at different power stages under hydrogen and methane fuel types are analyzed, and the differences of thermoelectric characteristics distribution between them under the same output power are compared. In Section VI, the main work of this paper is summarized and conclusions are drawn.

2. EXPERIMENTAL EQUIPMENT AND PRINCIPLE INTRODUCTION

The system experimental test is based on the 1kW external steam-reforming SOFC independent power generation system integrated by Center for Fuel Cell Innovation (CFCI) of Huazhong University of Science and Technology. As shown in Fig.1, the SOFC system is mainly composed of a blower, two bypass valves (air, fuel), a water pump, BOP Hotbox components (a heat exchanger, a reformer and a burner), a SOFC stack, and a power conversion device. When hydrogen is used as fuel, the water pump is off and no deionized water enters the reformer, and the reformer acts as a hydrogen heat exchanger; When methane is used as fuel, deionized water is transported to the system by the pump and then preheated and vaporized by the heat from the burner. Finally, the steam jointly enters the reformer with the hot methane to take part in steam reforming reactions.

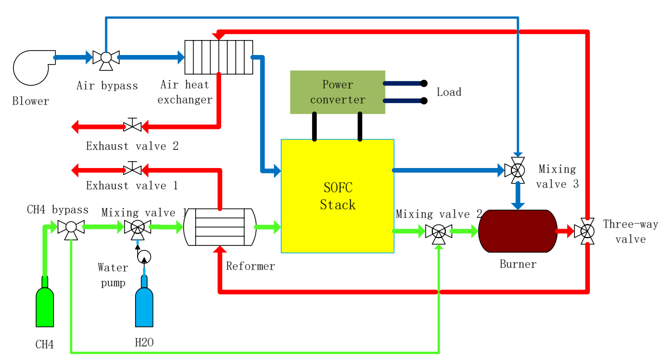
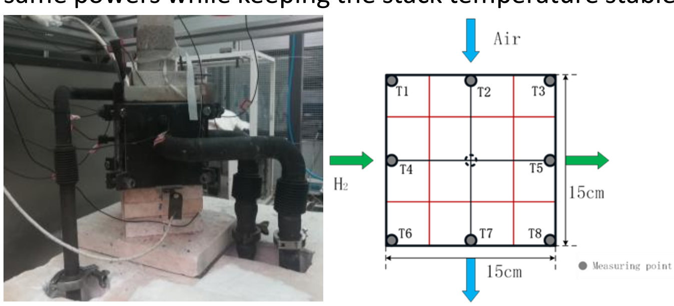


Fig. 1. SOFC system structure and composition

3. EXPERIMENTAL TEST PROCESS

The stack of the 1kW external steam-reforming SOFC system consists of 27 cells connected in series and the size of single cell is 15*15cm. In order to better understand the temperature status of the stack, the system has installed 8 thermocouples on the periphery of the stack. The integrated stack and the measuring positions are shown in Fig.2. At the same time, the system uses an electronic load to discharge, adjusting the electronic load current to change output power.

The main test processes of this experiment are that the system is first heated by pure hydrogen for the temperature of steam reformer is too low to generate hydrogen if methane is used directly in the beginning. The system begins to discharge under hydrogen when the temperatures of the stack and reformer reach around 620°C. Because at this time the key components of the system, especially steam reformer, have reached the appropriate temperature (above 600°C), therefore the fuel can be switched to methane for power generation, and then the thermoelectric characteristics of the two fuels (pure hydrogen and methane) under different power stages are obtained. Aiming at taking insight into the difference characteristics of SOFC systems under various fuels, we first start to generate electricity at different powers at about 620°C using hydrogen and then switch the fuel to methane to generate power at the same powers while keeping the stack temperature stable.



(a) (b)

Fig. 2. The thermocouple installation position around the stack. (a) the integrated stack; (b) Schematic diagram of installation position of thermocouple.

4. TEMPERATURE DISTRIBUTION OF THE STACK IN THE ELECTRIC FURNACE

In order to take insight into the temperature distribution inside the stack, a SOFC stack composed of a single cell fueled with methane is assembled and tested on the test bench. Eighteen thermocouples are symmetrically installed in the stack, as shown in Fig. 3(a) (b). Considering the fact that Razbani et al. [8] measured the temperature distribution inside the stack under hydrogen fuel in a constant temperature electric furnace, a single cell stack using hydrogen is not constructed in this paper. During this process, the temperature of electric furnace is maintained at 750°C and the voltage is maintained at 0.7V. The temperature distribution is shown in Fig. 4. The temperature gradient on the fuel side of the stack is relatively large, which is basically consistent with that measured by eight thermocouples installed around the stack under methane in Section V. Moreover, the temperature distribution of the stack fueled with hydrogen in Section V is basically the same as that obtained by Razbani et al. [8] in the constant temperature electric furnace, which reflects the relatively large temperature gradient of the stack air side.

(a) （b）

Fig. 3. The SOFC stack composed of a single cell assembled on the test bench. (a)the stack test electric furnace; (b) the thermocouples installed inside the stack.

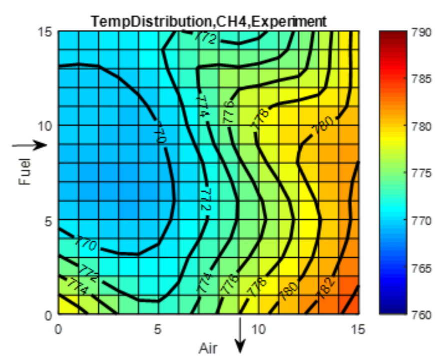


Fig. 4. The temperature distribution of the stack measured by thermocouples in the constant temperature electric furnace.

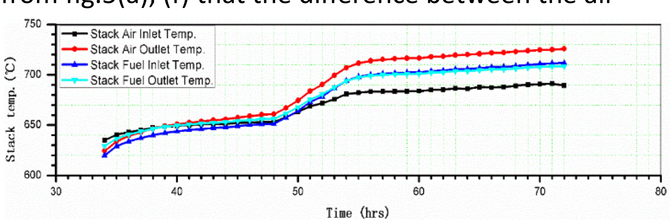
5. RESULTS AND DISCUSSION

5.1 Thermoelectric characteristics of the SOFC system under hydrogen

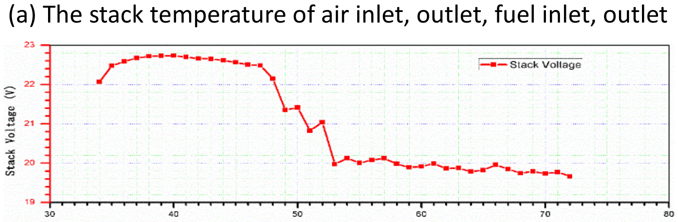
Fig.5 (a)~(f) show the thermoelectric characteristics of the SOFC independent power generation system at different power stages under hydrogen. The system runs for a longer time around 310W and 620W.

When the system is running at about 310W, that is, the period time range of 34~47h, it can be found from Fig. 5(a) that the average temperature of the stack is about 640°C, and it maintains a steady rising state, and the hydrogen flow rate of the system does not increase at this stage. It is because the stack has just entered the discharge state, and the heat production of the stack itself increases, which makes the overall temperature of the stack rise steadily. From Fig. 5 (f), it can be concluded that the temperature difference on the fuel side decreases gradually, and the temperature difference on the air side changes gradually from negative to positive. This is because the temperature of the air layer is the main factor determining the temperature of the stack. Before discharge, the temperature of the stack increases mainly by the heat brought by the air after the preheating of the flue gas. So the initial temperature difference of the air side is negative. After discharge, the temperature of the air outlet of the stack gradually increases due to the increase of the heat generated by the stack itself, so the temperature difference of the air side changes from negative to positive.

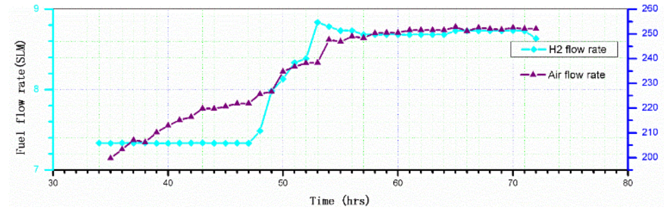
When the system is running at about 625W power point, i.e.53~72h, the power and current remain unchanged, and the voltage of the stack enters a state of natural degradation, and the voltage of this stage is reduced by about 0.2V. At the same time, it can be found from fig.5(a), (f) that the difference between the air



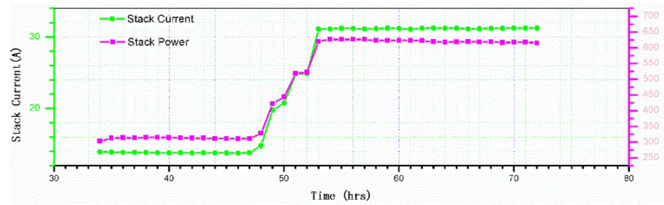
(a) The stack temperature of air inlet, outlet, fuel inlet, outlet



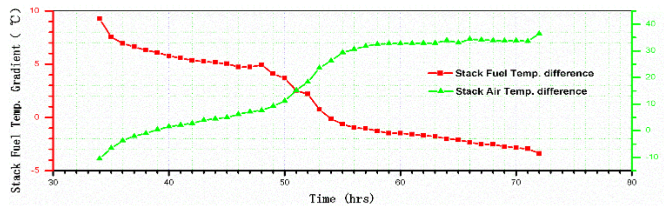
(b) Stack voltage



(c) The fuel flow rate, air flow rate of SOFC system



(d) Stack current, stack power



(e) The temperature difference of stack on the fuel and air side

Fig. 5. Inputs and outputs of the SOFC system under pure hydrogen.

outlet temperature and the air inlet temperature of the stack is further widened.

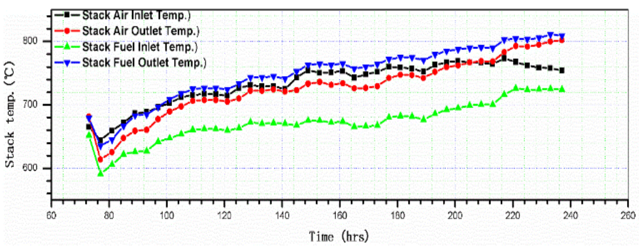
5.2 Thermoelectric characteristics of the SOFC system under methane

Fig. 6 shows the thermoelectric characteristics of the SOFC independent power generation system under methane at different power stages.

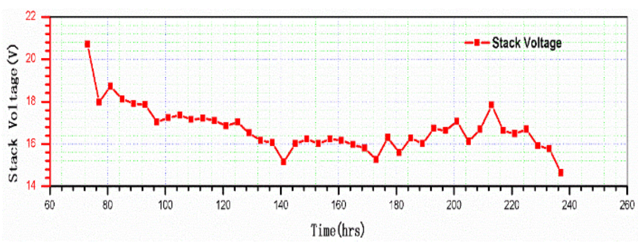
From Fig.6, it can be found that the temperature of the stack decreases significantly during 73~77h, and the temperature difference on the air side of the stack changes from positive to negative. The reason is that the SOFC system is performed the operation of switching the fuel gas during 72~73h. The stack current drops to zero when the gas is cut. After the system is switched to methane, the load current is gradually increased, the heat production of the stack itself relatively decreases.

From the voltage curve of Fig. 6(b), it can be found that the voltage of the stack under the methane has obvious fluctuations, especially after 169h, which is basically the same as the fluctuation trend of the fuel pressure in Fig. 6(e). In connection with the actual structure of SOFC power generation system, deionized water is added into the fuel channel at the inlet of the fuel reformer to participate in steam reforming reactions, and the pressure fluctuation in the fuel channel is caused by the evaporation of deionized water. When deionized water evaporates drop by drop, the pressure in the pipeline increases, which may accelerate the reforming reaction rate. At the same time, sufficient water vapor is provided for the reforming reaction, which promotes the reforming reaction to proceed in the direction of hydrogen generation, resulting in the increase of stack voltage, showing the same trend as the pressure.

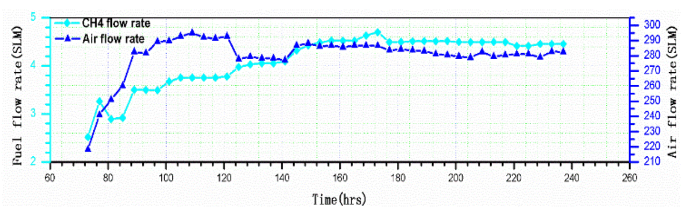
At the same time, it can be found that the temperature difference on the fuel side is much higher than that on the air side, up to 95°C in Fig.6 (f). The main reason is that the heat absorption of the reforming reaction of partial methane at the fuel inlet of the stack leads to the decrease of the fuel inlet temperature.



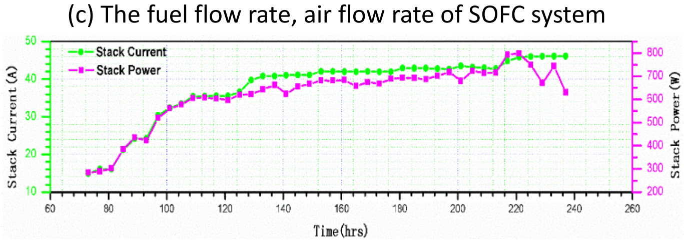
(a) The stack temperature of air inlet, outlet, fuel inlet, outlet



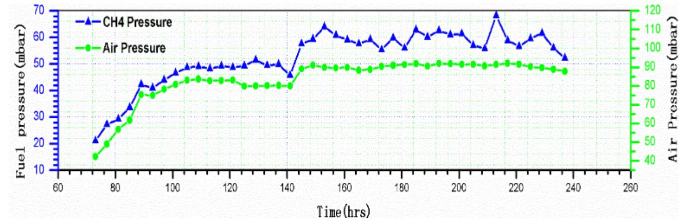
(b) Stack voltage



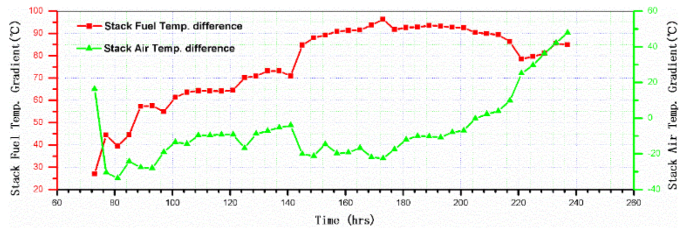
(c) The fuel flow rate, air flow rate of SOFC system



(d) Stack current, stack power



(e) The fuel inlet pressure, air inlet pressure of SOFC System



(f) The temperature difference of stack on the fuel and air side

Fig. 6. Inputs and outputs of the SOFC system under methane.

5.3 Comparison of thermoelectric characteristics of the SOFC systems under hydrogen and methane.

In order to better compare the thermoelectric characteristics of the SOFC systems under hydrogen and methane, this paper selects the 614W power point which maintains relatively stable in the hydrogen and methane stage. After using the thermocouples to measure the eight temperatures around the stack, the temperature of the central node is averaged using the stack air inlet and outlet temperatures, and fuel inlet and outlet temperatures. The temperature distribution of the stack shown in Fig. 7 is made by cubic interpolation.

5.3.1 Electrical characteristics of the stack

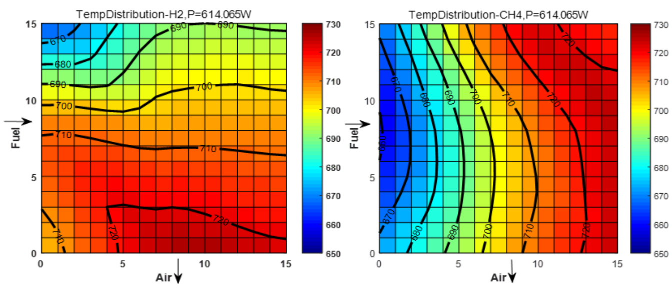
From Table 1, it can be found that under the same power, the stack voltage of the methane fueled system is lower than that of the hydrogen fueled system. The reason is that after the steam reforming of methane, the hydrogen concentration on the anode is much lower than that of the hydrogen fueled SOFC system, resulting in an increase in the activation overvoltage loss and concentration overvoltage loss. Moreover, it can be found that the stack fuel utilization rate of the methane fueled SOFC system is lower than that of the hydrogen fueled SOFC system at the same power.

5.3.2 Thermal characteristics of the stack

From the temperature distribution of the stack in

Table 1 Comparison of electrical characteristics of SOFC systems under hydrogen and methane fuel types at 614W.

	H_2	CH_4
Voltage (V)	19.63	16.79
Current (A)	31.27	36.57
Power (W)	614.065	614.065
Fuel utilization rate of stack	67.75%	43.31%



(a) The stack under hydrogen (b) The stack under methane

Fig. 7. Temperature distribution of stacks at 614 W power point.

Fig. 7, it can be found the temperature gradient on the fuel side of the methane fueled SOFC system is relatively large, while that on the air side of the hydrogen fueled SOFC system is relatively large. Therefore, the control of temperature gradient of the systems under hydrogen and methane should have different emphases.

6. CONCLUSION

In this paper, the thermoelectric characteristics of SOFC systems under different fuels at different output powers are studied. Moreover, the thermoelectric characteristics under different fuels with the same output power are compared. From the analysis, we draw the following conclusions. Firstly, the stack voltage and the fuel utilization of the methane fed SOFC system are lower than that of the hydrogen fueled system under the same power. Secondly, due to the evaporation of deionized water, the stack voltage of the methane fueled system has obvious fluctuations, which is basically the same as the fluctuation trend of the fuel pressure. Thirdly, the temperature gradient on the fuel side of the methane fueled system is relatively large, while that on the air side of the hydrogen fueled system is relatively large. The analysis process is of great significance for optimizing control strategies for different fuels and improving fuel adaptability of the system.

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