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Short communication

The voltage characteristics of proton exchange membrane fuel cell (PEMFC) under steady and transient states

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Abstract

In this paper, voltage sensors were developed to explore the voltage distribution characteristics inside the fuel cell under both steady and transient states. The effects of air stoichiometry and current density on the voltage distribution under steady state were discussed, and the dynamic voltage response due to the load change under transient state was also investigated. Results showed that under transient state, the fuel cell would experience a temporary voltage fluctuation due to the air starvation. Thus could probably lead to the degradation of materials, such as the catalyst, membrane, etc. To lessen the degree of air starvation, a method of pre-supplying certain amount of air before loading was adopted. The relationship between the voltage response at the loading transient and the amount of pre-supplied air was also studied, and a minimum value of the pre-supplied air was obtained. The experimental results of this paper could be applied to the optimization of vehicular fuel cell system.

Keywords: PEMFC; Voltage distribution; Dynamic operation; Air starvation

1. Introduction

The proton exchange membrane fuel cell (PEMFC) has received a lot of attentions in recent years due to its compact size, high efficiency, environmental benefits and mild operation conditions. It has been regarded to have a great potential to replace the internal combustion engine due to the shortage of fossil fuels [1,2]. Although it has made enormous developments and successfully been used in some demo electrical vehicles, there are still some critical issues that need to be solved to make PEMFC more competitive, so that it can be finally commercialized. One of the issues is the durability and reliability of fuel cell [3,4]. Until now, PEMFC has already achieved a relatively stable steady state performance. However, as a promising candidate to be used in automobiles, PEMFC must suffer from many dynamic operations, such as start-up, shut-down, acceleration, and deceleration, etc., and during which, since the air response rate lags the loading rate, the air starvation may occur inside the fuel cell, which will significantly affect the durability and reliability of the fuel cell [5]. In order to better understand the dynamic behaviors of fuel cell, researchers in the past resorted to elaborate mathematical models to simulate the dynamic behaviors of PEMFC, as the experimental diagnostic techniques were very complicated. However, with the fast development of mathematical models, there is an increasing need to verify these models and unveil the weaknesses with experimental data, but few experimental works about the dynamic behaviors have been reported [6–14], and among them, even fewer have been concentrated on the air starvation phenomena during dynamic loading.

The voltage distribution of PEMFC is conventionally assumed to be uniform, as the carbon paper is a good electric conductor with low resistivity. However, for the PEMFC with large surface area, there are slight differences among the local voltages of PEMFC on the fuel cell level, and they could be used to indicate the local oxygen concentration differences, which is a main focus of this study.

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In this paper, the voltage distribution under steady state and the voltage response of PEMFC under transient state were studied, and a method was developed to lessen the degree of voltage fluctuation due to air starvation during dynamic loading.

2. Experimental

2.1. Measurement system

The tested PEMFC was a 135-cell stack, each cell with 270 cm^2 active area. It was assembled by metal composite bipolar plates [15] and MEAs. The metal composite bipolar plates were made up of thin metal plates and parallel channel flow fields formed by expanded graphite plates. The MEAs consisted of Nafion® 212 membranes, catalyst layers with the total Pt loading of 0.8 mg cm^{-2} and Toray paper as diffusion layers. This experiment was conducted in auto mode with a 36 kW Fuel Cell Test Station (FCATS-H36000, Hydrogenics, Canada). The fuel cell stack was controlled and measured by a water-cooled electronic load system from TDI (WCL488400-1000-12000). The dynamic response of the electronic load system from 0 to 500 mA cm^{-2} was less than 0.1 s. The air flow rate was adjusted by a smart mass flow controller (Brooks), and the hydrogen was exhausted by the method of pulse purge to assure the sufficient supply of hydrogen during the dynamic operation. The operation temperature of the fuel cell stack is kept at 60 °C. Air and hydrogen were humidified by high-pressure steam, and the humidity was adjusted by changing the dew point temperatures.

2.2. Installation of voltage sensors

At the eleventh cell of the stack, three voltage sensors were placed on the surface of cathode diffusion layer, and two on the surface of anode diffusion layer, the detailed structure as described in Fig. 1. The voltage sensors used in this study were made of copper wires with insulating paint outside. The total diameter was 0.08 mm. For each voltage sensor, the insulating paint was removed for about 1 mm at the end of being placed on the diffusion layer, and then silver was plated there to avoid corrosion. Therefore, the voltage sensors were capable of indicating local voltages. Because the hydrogen was sufficient, the anode voltage was assumed to be stable. The mean value of the two local voltages on the anode side could be taken as a reference. In this experiment, three multi-meters were used to measure the local voltages of cathode inlet region, cathode middle region and cathode outlet region (hereinafter referred as inlet, middle and outlet) respectively against the reference.

3. Results and discussion

3.1. The voltage distribution under different current densities

Fig. 2 shows the voltage distributions inside PEMFC under different current densities at fixed air stoichiometry of 2.5 (with regard to the current densities 100, 200, 300, 400, 500, and 600 mA cm^{-2} respectively). It can be seen that with the increase of current density, the voltage distribution is more non-uniform. For the current densities from 100 to 300 mA cm^{-2}, the voltages of middle and outlet are only slightly lower than that of inlet, and almost the same. However, when the current density reaches above 400 mA cm^{-2}, the voltages of middle and outlet are obviously lower than that of inlet, and that of outlet is the lowest. This phenomenon is illustrated more clearly in Fig. 3, which is a plot of the voltage differences between inlet and outlet corresponding to Fig. 2. As shown, when the current density is 600 mA cm^{-2}, the voltage of outlet is about 6 mV lower than that of inlet. This may be attributed to the non-uniform oxygen concentration distribution, and the lower oxygen concentration at outlet under higher current density. As is well-known, the in-

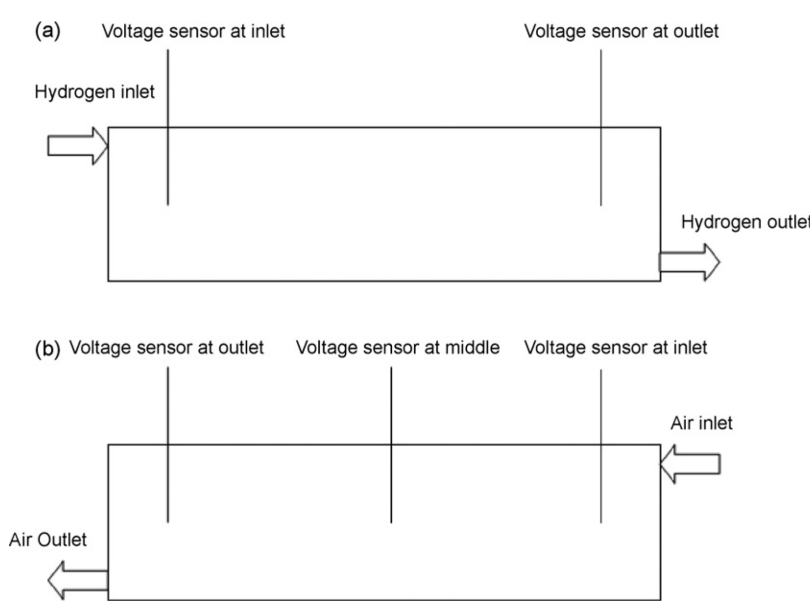

Fig. 1. Schematic of the detailed places of voltage sensors: (a) two voltage sensors on the surface of anode diffusion layer; (b) three voltage sensors on the surface of cathode diffusion layer.

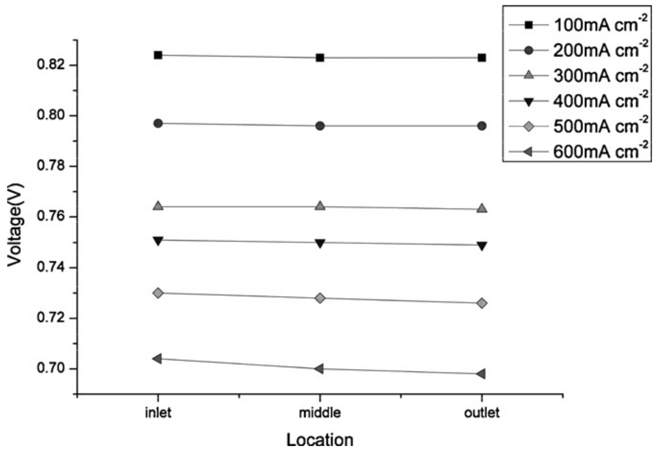

Fig. 2. The voltage distributions under different current densities at fixed air stoichiometry of 2.5 (with regard to the current densities 100, 200, 300, 400, 500 and 600 mA cm^{-2} respectively).

plane resistivity of Toray carbon paper used is about 5.8 mΩ cm, so when the voltage difference between inlet and outlet is 6 mV, the in-plane current could be calculated and is approximately 5 mA.

3.2. The voltage distribution under different air stoichiometries

Fig. 4 depicts the voltage distributions under different air stoichiometries (with regard to 500 mA cm^{-2}) at fixed current density of 500 mA cm^{-2}. As shown in this figure, at fixed current density, with decreasing air stoichiometry, the voltage decreases, and the voltage distribution becomes more non-uniform. Fig. 5 shows the voltage differences between inlet and outlet corresponding to Fig. 4, when the air stoichiometry is as low as 2.2, the voltage distribution is highly non-uniform, and the voltage difference between inlet and outlet reaches about 10 mV. With the increase of air stoichiometry, this difference lessens. The phenomena of these two figures might suggest that at low air stoichiometry, the air supply could not meet the demand in the

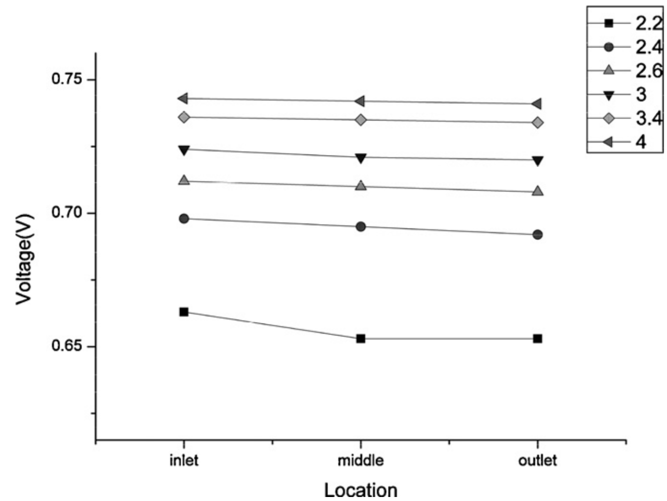

Fig. 4. The voltage distributions under different air stoichiometries (with regard to 500 mA cm^{-2}) at fixed current density of 500 mA cm^{-2}.

middle and outlet regions, and consequently the oxygen concentrations there are low, thus cause the decrease of voltages there. With the increase of air stoichiometry, the oxygen concentration becomes more uniform, so the voltage difference between inlet and outlet lessens. In short, low air stoichiometry could cause the voltage distribution to be more non-uniform.

3.3. Voltage changes under transient state

When loading dynamically, the load following mode is usually adopted with fixed air stoichiometry. However, if the fuel cell experiences a fast dynamic load change from idle state (corresponding to 50 mA cm^{-2} in this experiment) to a high current density (specified as 500 mA cm^{-2} in this experiment), the air response rate will lag the loading rate, which will make the fuel cell suffer a temporary air starvation, and the air starvation can cause many damages to fuel cell. A well-known method to prevent the occurrence of air starvation is to supply air with enough stoichiometry before loading, which however, will result in the

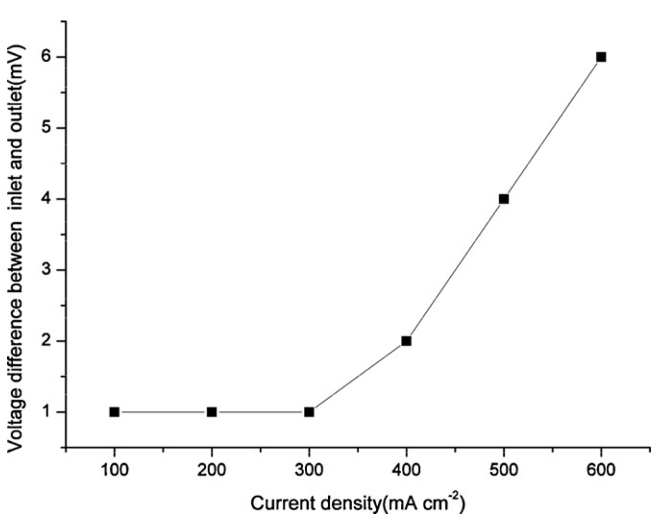

Fig. 3. The voltage difference between inlet and outlet relating to Fig. 2.

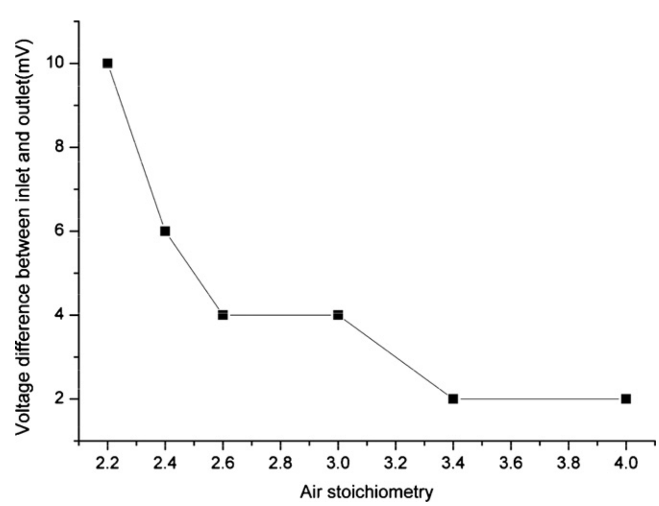

Fig. 5. The voltage difference between inlet and outlet relating to Fig. 4.

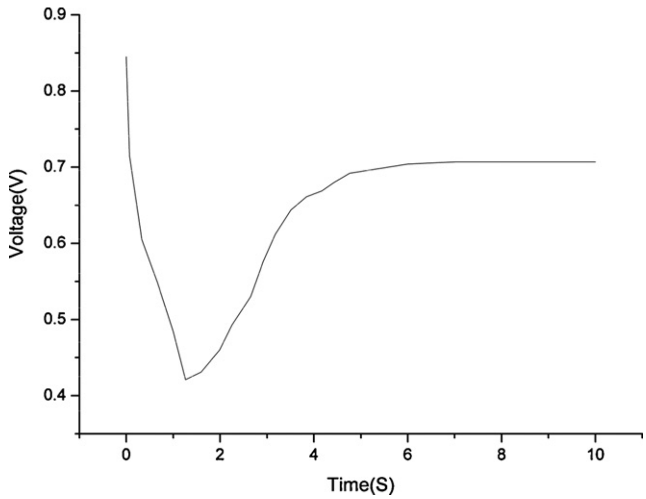

Fig. 6. Voltage change of PEMFC with time when loading dynamically from 50 to 500 mA cm^{-2}; the pre-supplied air stoichiometry is 1.1 with regard to 500 mA cm^{-2}, and the load following air stoichiometry is 2.5 with regard to 500 mA cm^{-2}.

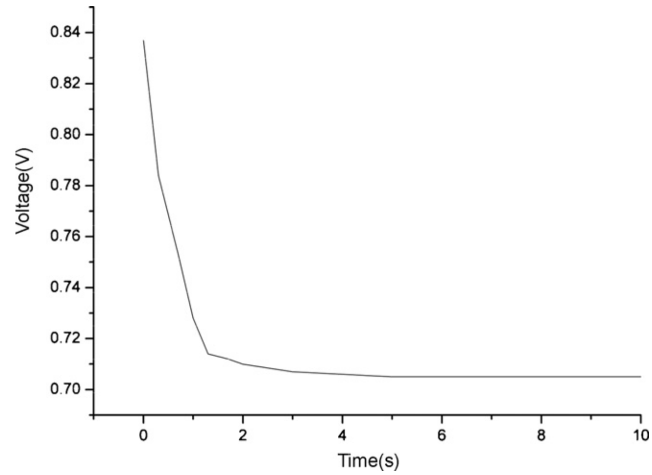

Fig. 8. Voltage change of PEMFC with time when loading dynamically from 50 to 500 mA cm^{-2}; the pre-supplied air stoichiometry is 1.5 with regard to 500 mA cm^{-2}, and the load following air stoichiometry is 2.5 with regard to 500 mA cm^{-2}.

parasitic power consumption and the system efficiency lowering. In our work, in order to find a minimum value of the pre-supplied air and mitigate the energy loss from the pre-supplying method, we investigate the relationship between the voltage response and the amount of pre-supplied air.

In this part, the mean value of the three local voltages is considered as the voltage of PEMFC. Fig. 6 provides the voltage change of PEMFC over time when loading dynamically from 50 to 500 mA cm^{-2}. The pre-supplied air stoichiometry is 1.1 with regard to 500 mA cm^{-2}, and the load following air stoichiometry is 2.5 with regard to 500 mA cm^{-2}.

As shown, the voltage of fuel cell firstly drops to a quite low value, which means that the pre-supplied air is not sufficient enough for the fuel cell to operate at 500 mA cm^{-2}, and the fuel cell suffers a temporary air starvation. When the load following air reaches the reaction site of the fuel cell, the voltage starts to increase, and finally arrives at the steady-state value.

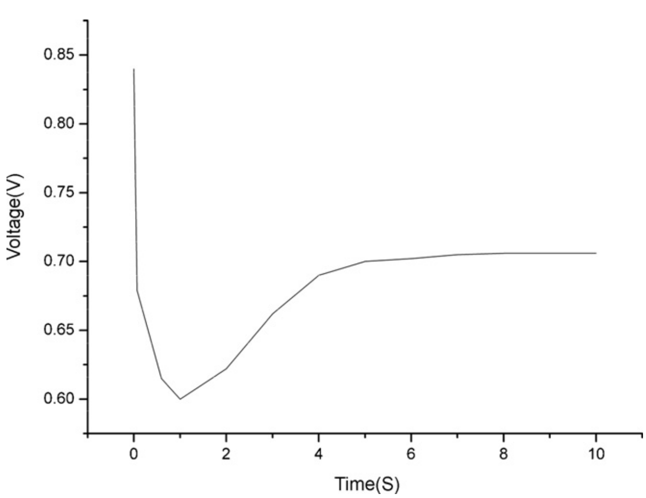

Fig. 7. Voltage change of PEMFC with time when loading dynamically from 50 to 500 mA cm^{-2}; the pre-supplied air stoichiometry is 1.3 with regard to 500 mA cm^{-2}, and the load following air stoichiometry is 2.5 with regard to 500 mA cm^{-2}.

Fig. 7 depicts the voltage change of PEMFC over time when loading dynamically from 50 to 500 mA cm^{-2}. The pre-supplied air stoichiometry is 1.3 with regard to 500 mA cm^{-2}, and the load following air stoichiometry is 2.5 with regard to 500 mA cm^{-2}.

As shown in Fig. 7, when the pre-supplied air increases, the voltage of fuel cell drops only a little during dynamic loading, and the degree of air starvation is lessened. When the stoichiometry of the pre-supplied air further increases to 1.5, it can be seen from Fig. 8 that no air starvation has occurred at the loading transient.

Above all, when the fuel cell is loaded in the load following mode, the degree of air starvation will be lessened with the increase of the pre-supplied air stoichiometry. In this study, when the pre-supplied air stoichiometry could reach 1.5, the fuel cell will not suffer from any air starvation at the loading transient.

4. Conclusions

Voltage sensors were successfully developed to investigate the voltage distribution characteristics of fuel cell. In this work, the voltage distribution of fuel cell under steady state was studied under a variety of operating conditions. It was found that the voltage distribution was non-uniform, and current density and air stoichiometry had significant effects on it. With the increase of current density and the decrease of air stoichiometry, the voltage difference between inlet and outlet increased. When loaded dynamically in the load following mode, since the air response rate lagged the loading rate, the fuel cell would suffer a temporary voltage fluctuation due to the air starvation. In this paper, the method of pre-supplying certain amount of air before loading was adopted to lessen the degree of air starvation. Experimental results demonstrated that with the increase of the pre-supplied air stoichiometry, the degree of air starvation during dynamically loading was lessened. When the pre-supplied air stoichiometry was 1.5, the fuel cell would not suffer from any air starvation at the loading transient. These results could be used to optimize vehicular fuel cell system.

Acknowledgments

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