Technical Note

In situ temperature measurement in a 5 kW-class Proton Exchange Membrane Fuel Cell stack with pure oxygen as the oxidant

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A B S T R A C T

In situ measurement of temperature distribution in a Proton Exchange Membrane Fuel Cell (PEMFC) stack is conducted by embed 36 T-type thermocouples on the MEA surface in four representative cells. Temperature increasing rate can get to 2.5 °C min^{-1} at 1000 mA cm^{-2}. The largest temperature difference is observed in the middle of the stack, and the temperature difference can reach 17 °C at the bottom of the stack. The non-uniformity of temperature distribution is found to be improved by increasing the operation pressure, and the largest temperature difference decreases by 2.5 °C when the absolute operation pressure is increasing from 100 kPa to 150 kPa.

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1. Introduction

Proton Exchange Membrane Fuel Cell (PEMFC) has been considered to be one of the promising power sources for portable devices, transportation and stationary applications due to its high energy conversion efficiency, high power density, and low environment pollution [1–8]. Temperature plays a significant role in achieving high performance of fuel cells because it deeply influences the activity of the catalyst, dehydration of solid polymer membrane, mass transfer and heat management in PEMFCs [9,10]. Compared with conventional hydrogen-air PEMFC, less convection heat is removed by the moisture in the outlet in a hydrogen–oxygen PEMFC. The non-uniform temperature distribution over the MEA surface may decrease the reliability and durability of the membrane applied in PEMFCs. The hot spot should be avoided for the membrane reliability and durability under the operating of PEMFCs [11,12].Therefore, the temperature distribution inside the stack is more important and crucial for safety operation in a hydrogen–oxygen PEMFC stack, and the main objective of this work is to find out the positions of the hot spots inside the stack, which is useful for the safety operation and optimization design.

2. Experiments

The same PEMFC stack and thermocouple array in our precious work [10] is used in this experiment. The length and diameter of thermocouples used in the experiments are 500 mm and 0.1 mm, respectively. Cooling channels are designed in both anode and cathode sides. The depth, width and ridge width are 0.75 mm, 1.5 mm and 1.5 mm, respectively. Prior to the performance evaluation of the stack, internal and external leakages of reaction gases are tested, and the fuel cell stack is pre-activated with fully humidified H_2/O_2 for about 3 h before the leakage result is found to be acceptable. Both hydrogen and oxygen are 80% humidified at 65 °C, with the fluxes are 40 LPM (Liter Per Minute) and 50 LPM, respectively. Unless otherwise stated, the flow rate of the coolant water is set at 45 LPM. The ambient temperature is 9 °C. The V-I curve of the stack is addressed in Fig. 1.

3. Results and discussion

3.1. Temperature distribution inside the single cell

Temperature distributions in different positions of the MEA inside the marked single cell are show in Fig. 2(a)–(d). As can be seen, compare with hydrogen-air stack, similar temperature distribution characteristic is observed in hydrogen–oxygen stack. However, the maximum temperature difference reaches 8 °C in cell

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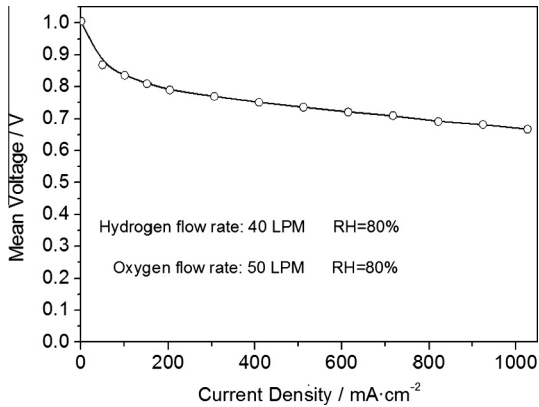 E-mail address: tzklq@whut.edu.cn (Z. Tu).

Fig. 1. V-I curve of the stack.

23 at 600 mA cm^{-2}, whereas it is 6 °C in the hydrogen-air stack with the air flow rate of 500 LPM in Fig. 2(e). Heat generated in the stack is close related with cell voltage [13]. As seen in Fig. 2(f), the average voltages in the hydrogen–oxygen stack and hydrogen-air stack are 0.72 V and 0.58 V, respectively. Accordingly, heat generated in the stack is less when oxygen is used as the oxidant in the cathode. However, more heat is removed by the coolant water in the hydrogen–oxygen stack due to the larger temperature difference as addressed in Fig. 2(f). As a consequence, part of the generated heat in the hydrogen-air stack is removed out of the stack by the air, which is helped to cool the single cell inside the stack as the form of convection heat transfer.

3.2. Effect of current density on temperature distribution

Fig. 3 shows the effect of the current density on stack temperature distribution. Temperatures increase faster at the increased current density, which leads to the increase of the maximum temperature difference inside every single cell as seen in Fig. 3(b). Up to a current density of 600 mA cm^{-2}, the maximum temperature is

below 70 °C, and the temperature difference between the coldest and warmest measuring point is 7.6 °C. The maximum temperature climbs to 82 °C in 1.5 min with a temperature increasing rate of 2.5 °C min^{-1} at 1000 mA cm^{-2}. The maximum temperature difference of 13 °C at 1000 mA cm^{-2} would be acceptable if the maximum temperature does not exceed 90 °C when Nafion® 211 membrane is used as the MEA material. However, the maximum temperature would easily increase to 90 °C without the temperature monitor and control, and hot spots would generate inside the single cell, which is not tolerable for safe operation. Additionally, the temperature difference between the coolant water and MEA surface is more than 13 °C. This means that the heat generated by reactions cannot be removed out of the stack quickly by the coolant water. Monitoring the temperature of the coolant water cannot supply an accurate reference to control the MEA's temperature. So, it is essential to explore the detailed heat transfer processes inside PEMFCs with more detail experiments and numerical simulations.

3.3. Temperature distribution of the stack

Fig. 4 shows the temperature and cell voltage distributions of the stack. As seen in Fig. 4(a), the downstream temperature is higher than that in the upstream, temperature on the top of the stack is the lowest along the flow channel, and temperature in the middle is nearly the same with that at the bottom of the stack. The main reason is that both the membrane hydration and water activity increased along the flow path during the electrochemical reaction. Proton is in higher conductivity at downstream, and the local current increases along the flow channel, which leads to higher temperature at the bottom of the stack [14]. In addition, temperature differences have the similar characteristic as the temperature evolution in the three layers. The temperature difference on the top of the stack is 8 °C, whereas it reaches 17 °C at the bottom of the stack. The temperature distribution affects the voltage distribution [15]. Fig. 4(b) shows the temperature distributions and the corresponding voltage distributions of the stack at 600 mA cm^{-2} and 1000 mA cm^{-2}, respectively. The highest
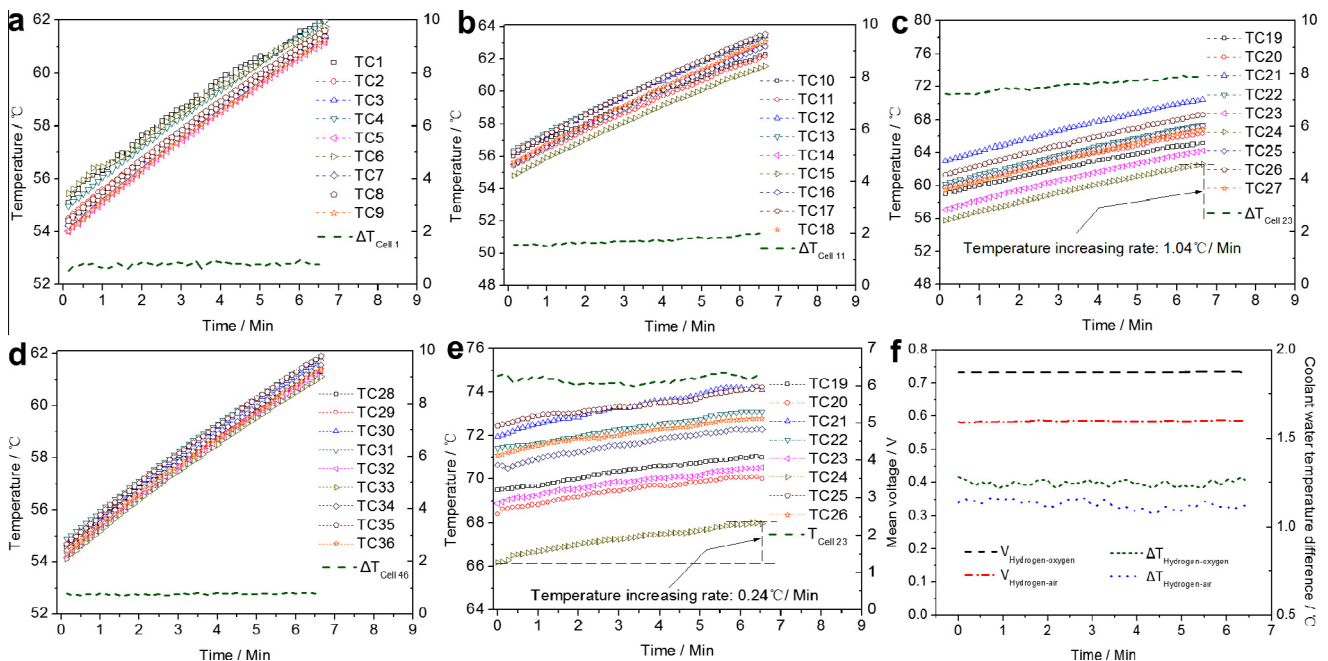

Fig. 2. Temperature distributions of different cells at 600 mA cm^{-2}. (a) Temperature distribution in Cell 1; (b) temperature distribution in Cell 11; (c) temperature distribution in Cell 23; (d) temperature distribution in Cell 46; (e) temperature distribution in Cell 23 in Hydrogen-Air stack; and (f) voltage and coolant water temperature difference evolutions.
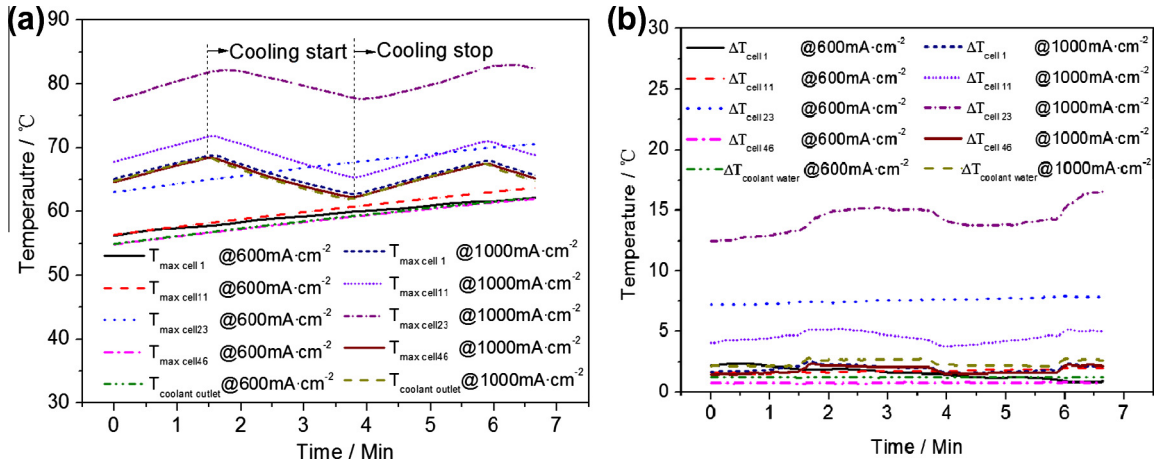
Fig. 3. Effect of the current density on stack temperature distribution. (a) Temperature distribution; and (b) temperature difference distribution.
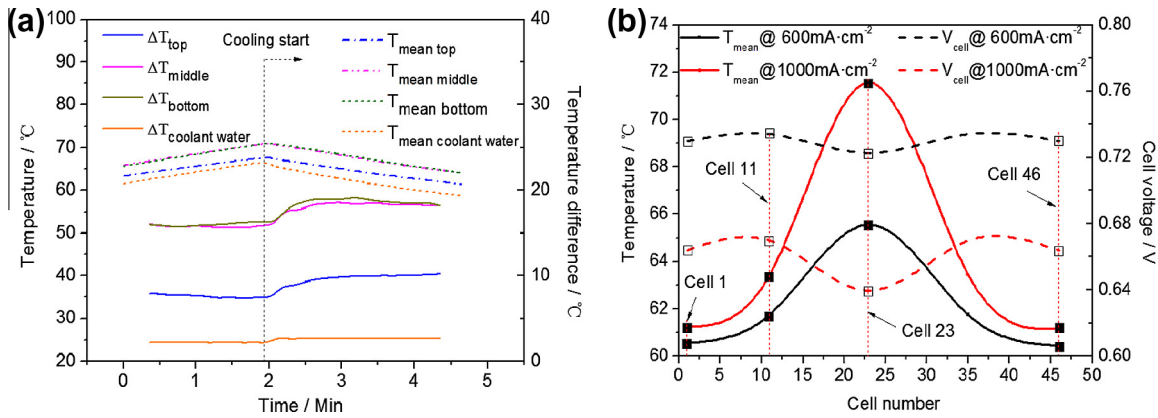

Fig. 4. Temperature distributions of the stack. (a) Temperature distributions in different layers at 1000 mA cm^{-2}; and (b) Comparison of temperature distribution and cell voltage distribution.

temperature appears in the 23th cell located in the middle of the stack during the operation. However, the voltage of the 23th cell is the worst in the whole stack, the peak value of the cell voltage is observed in the 11th single cell lied in the center of the end cell and middle cell. Temperature in the end cell is the lowest, but the corresponding voltage is still higher than that in the 23th cell. As mentioned previous, local temperature in PEMFC is intimately related to local performance because temperature has significant effects on electrochemical reaction kinetics. This behavior of voltage variation with temperature indicates that the catalyst activity is the dominant effect on the cell voltage at a lower temperature,

and the dominant effect on cell voltage at a higher temperature will be an increase in electrical resistance.

3.4. Effect of operation pressure on temperature distribution

Technically, the performance of a PEMFC in terms of voltage and power density can be greatly influenced by the operating pressure [16]. As mentioned previous, temperature is intimately related to the cell performance, and the temperature distribution in the stack will also greatly influenced by increasing the operating pressure. Fig. 5 shows the effect of back pressure on temperature distribution
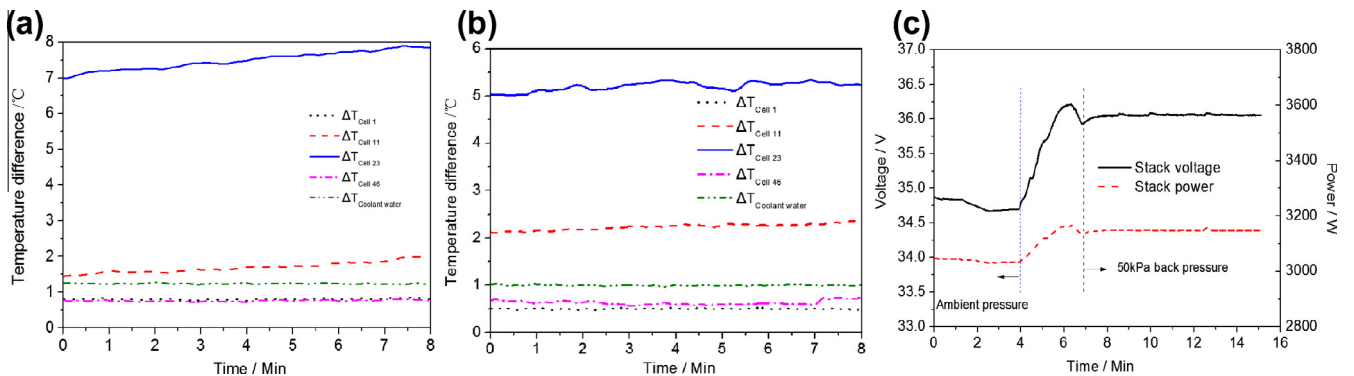

Fig. 5. Effect of back pressure on temperature distribution. (a) Temperature difference at ambient pressure; (b) temperature difference at 150 kPa; and (c) stack performance.

and stack performance. The maximal and minimum temperature differences inside the single cell are all decreased when the operation pressure increases to 150 kPa. Temperature difference in cell 23 can decrease by 2.5 °C, whereas it was about 0.25 °C in cell 1 lied in the end plate of the stack. The main reason is that the distribution of the reactants in the flow channel is more uniform with the increase of operation pressure, and the uniformity of the corresponding distribution of current density is greatly improved. Furthermore, as seen in Fig. 5(c), the output power is increasing by 500 W when the operation pressure increases to 150 kPa, and the amount of the waste heat is decreased as the coolant temperature difference is decreased by 0.25 as seen in Figs. 5(a) and (b). The reason is that the concentration of the reactants at the electrochemical processes is enhanced with the increased operation pressure, better performance is achieved and less waste heat is generated in the stack. Altogether, the uniformity of the temperature distribution can be enhanced by increasing the operation pressure.

4. Conclusions

With the in situ measurement technology, temperature distributions in the MEA surface in a hydrogen–oxygen PEMFC stack with straight channel flow bed are studied experimentally. The results are helpful for the better understanding of the temperature distribution characteristic and improving cell design and safety operation inside PEMFCs. The following conclusions can be drawn from this work:

(1) Temperature distribution would deteriorate at increased current density. Hot spots would generate in the middle cells of the stack, temperature management inside PEMFCs becomes more serious, and especially at higher current densities.
(2) Temperature difference between the cell and coolant increases with the increasing of current density, and the gap can reach 12 °C at 1000 mA cm^{-2}. Monitoring the temperature of coolant water cannot provide an accurate reference to the temperature control on the MEA surface inside the stack.
(3) Better voltage performance and less waste heat would generate by increasing the operation pressure of the stack, and temperature uniformity will be greatly improved inside the single cell and PEMFC stack.

Conflict of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled "In Situ Temperature Measurement in a 5 kW-class Proton Exchange Membrane Fuel Cell Stack with Pure Oxygen as the Oxidant".

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