TEMPERATURE MEASUREMENT TECHNOLOGIES AND THEIR APPLICATION IN THE RESEARCH OF FUEL CELLS

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ABSTRACT

Fuel cells have attracted extensive attention throughout the world in recent years for their high efficiency and high environmental compatibility. Temperature plays a key role in achieving high performance of fuel cells because it deeply influences the activity of catalyst, dehydration of solid polymer membrane, mass transfer and heat management of fuel cells. The temperature distribution has close relationship with current density distribution and lifetime of fuel cells because the uniformity of temperature distribution is a quite important problem for fuel cells. In this paper, a review of temperature measurement technologies that can be used to measure temperature distribution of fuel cells was presented. The measurement of cathode exterior surface temperature fields of a hydrogen proton exchange membrane fuel cell under various operational conditions was conducted by using the technology of infrared thermal imaging. The proton exchange membrane fuel cell structure was designed for uniformity of input heat. A NEC TH5102 thermo tracer was applied to measure the cathode exterior surface temperature distributions of the cell with 5cm^2 active area. The experimental results showed that the infrared thermal imaging is an effective method to measure the exterior temperature fields of the PEMFC. The cathode temperature distributions of the cell varied with cell temperatures and flow rates.

Keywords: Temperature measurement technologies; Hydrogen proton exchange membrane fuel cell; Infrared thermal imaging.

INTRODUCTION

Now, the fuel cell is the interest focus as the most promising power generation technology. Fuel cells have some advantages compared with existing energy supply systems, especially in environmental aspect. The visions for the future application of this technology encompass the wide span from power supply for small electronic equipment with only a few watts up to power stations in megawatt range for centralized power systems.

According to the operational temperature, fuel cells are classified as low-temperature and high-temperature fuel cells. Low-temperature fuel cells include the Alkaline Fuel Cell (AFC), the Proton Exchange Membrane Fuel Cell (PEMFC), the Direct Methanol Fuel Cell (DMFC) and the Phosphoric Acid Fuel Cell (PAFC). High-temperature fuel cells operate at temperatures approximate 600-1000℃. Two different types of high-temperature fuel cells, which are named the Molten Carbonate Fuel Cell (MCFC) and the Solid Oxide Fuel Cell (SOFC), have been developed. An overview of the fuel cell types and their features is given in table 1.

Temperature has a significant influence on the performance of fuel cells. For the DMFC, the maximum power density at 95℃ was approximately 50% greater than at 70℃. The performance at the higher temperature in general was more stable (John C et al., 2001). The limiting factors for performance of fuel cells are different under different operational temperatures (Noponen et al., 2002). The electrodes' kinetics, hydration of solid polymer membrane, mass transfer and heat management etc. are greatly affected by the operational temperature in fuel cells.

The electrodes' kinetics appears different in different temperatures (Beden et al., 1981; Kauranen et al., 1996),

Table 1, Different Fuel Cell Features

	AFC	PEMFC	DMFC	PAFC	MCFC	SOFC
Temperature (℃)	<100	60-120	60-120	160-200	600-800	700-1000
Anode reaction	$H_2+2OH^- \rightarrow 2H_2O+2e^-$	$H_2 \rightarrow 2H^+ + 2e^-$	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$
Cathode reaction	$1/2O_2 + H_2O + 2e^- \rightarrow 2OH^-$	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$3/2O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$1/2O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$	$1/2O_2 + 2e^- \rightarrow O^{2-}$
Anode catalyst	Pt/Ni	Pt/C or Pt-Ru/C	Pt-Ru/C	Pt/C	Ni/Al, Ni/Cr	Ni/YSZ
Cathode catalyst	Pt/Ag	Pt/C	Pt/C	Pt/C	Li/NiO	Sr/$LaMnO_3$
Intended applications	Vehicle, stationary, portable, spatial			Stationary	Vehicle, stationary	

which is responsible for the overvoltage occurred in electrodes. Hydration and proton conductivity of solid polymer membrane are closely related to the cell temperature. Most membranes are based on Nafion in which the proton conductivity depends on the rate of hydration (Noponen et al., 2002). Higher temperature leads to the increase of water vaporization in solid polymer membrane which causes the increase of the resistance of proton transportation. The proton conductivity of common membrane materials is normally improved with rising temperature as long as hydration of the membrane remains constant (Mennola et al., 2002).

Mass transfer is affected by the cell temperature in PEMFCs. The high temperatures lead to increased water vaporization at the cathode, which reduces the partial pressure of the oxygen. In addition, the amount of water permeation by electro-osmosis increases with rise of temperatures due to swelling effects of the membrane. The additional water is responsible for the decreasing transport properties of both the cathode catalyst and diffusion layer (Dohle and Divisek et al., 2002). The methanol crossover in DMFCs is deeply influenced by the cell temperature. Although increase of temperature results in decrease of the methanol permeation (Dohle and Divisek et al., 2002), the cell performance may be better at lower temperatures because current loss caused by the crossover methanol oxidation increases largely with the cell temperature rising (Qi and Kaufman, 2002).

The cell temperature greatly influences the heat management of fuel cells. The electrochemical reactions occurred in fuel cells produce heat. With increasing temperature within the fuel cell stack, an increasing vaporization of water occurs within the stack, which causes cooling of the fuel cell stack (Dohle and Mergel et al., 2002). So, proper temperature is very important to achieve the heat balance in fuel cell stack. The local overheating existing in the fuel cell deteriorates the performance of the overheating occurred locations of fuel cell stack and prevents from the formation of a uniform current distribution (Noponen et al., 2002). Locating the hot spots by temperature distribution will benefit heat management of fuel cells.

For the SOFC, inlet air temperature has a linear influence on voltage, fuel utilization, stoichiometric number and excessive preheating (Haynes and William, 2001). The cell temperature has a close relation to electrochemical reaction, thermal stress, vaporization of electrolytes and corrosion of the cell components in the MCFC (Fujimura, 1992). So, accurate "point" temperature and temperature distribution measurements in full field are very important in the research of fuel cells.

In this paper, the thermocouple, infrared thermal imaging and the thermochromatic liquid crystal technologies which could be used in the research of fuel cells were reviewed. The temperature distribution measurement in cathode exterior surface of a hydrogen PEMFC was conducted by the infrared thermal imaging technique.

TEMPERATURE MEASUREMENT TECHNIQUES IN THE RESEARCH OF FUEL CELLS

There are many ways to measure temperature (McGhee et al., 1999). In this section, the thermocouple, infrared thermal imaging and thermochromatic liquid crystal technologies were discussed.

Thermocouple

Thermocouple is the most common "point" temperature measurement technique for its high precision, simple configuration, fast dynamic response, remote measurement and broad measurement range. It is suitable for all types of fuel cells. According to the different operational conditions of different fuel cells, different types of thermocouples are adopted. Material compatibility and structure of thermocouple and its cannula and sheath must be adaptive to the actual operational conditions of fuel cells. For the high temperature fuel cell, the qualities of anti-oxidant and anti-high temperature must be considered when selecting or designing the thermocouples. In order to directly measure the temperature of electrode regions of PEMFC and diagnose the local overheating problem, thermocouple should be placed close to the electrodes. But applying the common size diameter (millimeter level) thermocouple will greatly destroy the seal, electrochemical reaction and mass transfer etc. in PEMFCs. Micro size thermocouple is a solution. The diameter of microthermocouples used in traditional heat transfer research is about 12-25 μm

(Lamaison et al., 2001; Auracher and Marquardt, 2002; Hohl et al., 2001). The size of microthermocouple applied in the research of electrodes need to be small enough that no disturbance of the PEMFC normal operation. The thin-film thermocouple is effective in measuring the transient temperature (Emi et al., 2002; Lei and Herbert, 1998). So, it could be used for transient temperature measurement in the research of the dynamical characteristics of fuel cells. The temperature distribution of the plates of fuel cells could be monitored by arranging thermocouples in multi-locations of the plates (Ali and Kalili, 1994). Adzic et al. (1997) designed a thin, flat-type thermocouple to measure the temperature distributions at the cathode side of a SOFC and located hot spots.

Thermochromatic Liquid Crystal

Thermochromatic liquid crystals （TLCs） is a "field" temperature measurement technique which can achieve quantitative temperature measurement. It utilizes the feature that TLCs change their reflex light colors with variation of temperature and apply an image capturing and processing system to calibrate the characteristic curve of TLCs' color-temperature, and then use it to measure the distribution of surface temperature. It is an advanced temperature measurement technique, which can not only measure temperature but also provide thermochromatic images. Therefore, it can solve some problems that can not be solved by traditional "point" temperature measuring methods in heat transfer field. The temperature and space sensitivity of liquid crystals can achieve 0.1℃ and 0.1mm respectively (Cheng, 2002). The measurable temperature range of the liquid crystals is about -30℃～115℃(Cheng, 2002). So, it is possible for the AFC, PEMFC and DMFC to use TLCs technique to measure external surface temperature distributions. The technique had been applied in analysis of heat transfer and flow fluid (Colucci and Viskanta, 1996; Maflat, 1990; Ishihara et al., 2002; Wozniak and Wozniak, 1991), nondestructive testing (Fergason, 1968) and medical diagnosis (Kim and Yoon, 1997).

Infrared Thermal Imaging

Infrared (IR) thermal imaging is a wave length converting technique. The technique converts infrared radiated from the objective body into visible light. Infrared thermal imaging has a relative long history, with the first demonstration of the existence of infrared radiation in 1800 by William Herschel. Thermal imaging cameras have been shown to give a key military advantage since the first demonstration of infrared photon detection during World War 1 (Tim, 2002). The difference of heat radiations from various parts of the objective body are captured to gain the two dimension image. The vision, analysis and measure of temperature distribution of object surface are achieved by computer image technology and demarcating technology of infrared temperature measurement. As an effective non-contacting temperature measurement method, the outstanding advantages of the technique are real time and ability of giving temperature distribution of whole surface. The technique can satisfy the measure of the surface temperature distribution of all types of fuel cells for its broad measurement range. The infrared wave of SOFC and MCFC are shorter than that of AFC, DMFC and PEMFC when they work normally. The infrared attenuation is relative with the background noise such as vapor and dust between object and lens (Ferdinandov et al., 1998). So, the environment reflection calibration must be done before measurements and the distance between object and lens should be as short as possible when measure. The emissivity of object must be calibrated before measurements in order to get the real temperature of object. The technique had been applied to detect the faulty in the electrochemical cells or battery (Russell and Benjami, 1996). The uniformity of wall temperature distribution in heat transfer also could be diagnosed by the technique (Abdulnour, 2000). In present paper, the authors utilized this technique to measure the surface temperature distributions of cathode end plate of a hydrogen PEMFC under various operational conditions.

EXPERIMENTAL

Our experimental system for PEMFC test is shown in Fig. 1. Special structure PEMFC (Fig. 2) with 5 cm^2 active area was designed. In the cell anode, the material of end plate and polar plate are copper and graphite, respectively. While in the cathode, the end plate was machined by organic glass and a gold plated copper slice with slots used as flow channels was taken as cathode current collector and reactant distributor. The channel is parallel type; the length and width of each channel are 21.6 mm and 0.8 mm, respectively. The membrane used in the cell is Nafion 112. Catalyst is platinum/carbon with loading of 0.4 mg/cm^2 in two sides. Carbon paper acts as diffusion layer. The anode was heated by embedding a heating stick in the end plate, while not in polar plate, which is useful to decrease the non-uniformity of the temperature distributions in the anode polar plate and reactive regions. There is no heating in the cathode to avoid that the measurements was interfered by cathode heating. The reactants in the anode and cathode are hydrogen and pure oxygen without preheating and hydration. The inlet temperature of oxygen maintained 13℃ during experiment.

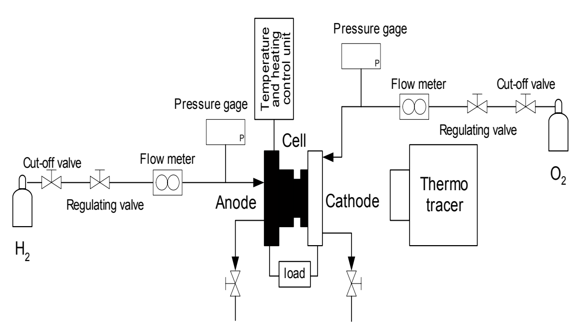

Fig. 1 Schematic of the test system

A NEC TH5102 thermo tracer was used to measure the cathode external surface temperature distribution of the cell. The measurable temperature range of the device is from -20 ℃ to 800℃. The environment reflection calibration was done through a black body in the work before measurements, which intended to reduce the affect of environmental reflection. The window protective cap of the thermo tracer was used as the black body. In order to achieve real temperature, the actual emissivity of the measured surface should be found. A point on the edge of the surface was located and the temperature of the point was measured by a thermocouple. The temperature of another point near the first point was measured by the thermo tracer. The two temperatures were compared under various emmissivities. The emmissivity, under which the temperatures of two points were equal, was considered as the approximate emmissivity of the surface. By the method presented above, the emmissivity of the surface was set as 0.93. The temperature distributions under various operational temperatures and flow rates were investigated.

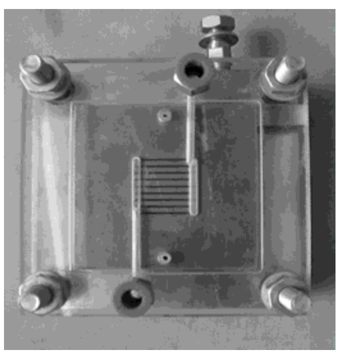

Fig. 2 Experimental hydrogen PEMFC

RESULTS AND DISCUSSION

The experimental results obtained refer to the cathode side end plate of the PEMFC. During the temperature measurement, the pressure in the anode and cathode were always 1.5×10^5 Pa gage and 1.7×10^5 Pa gage, respectively. The operating temperature and flow rate were changed for investigating their influence on the temperature distributions. Fig. 3, Fig. 4 and Fig. 5 are the cathode surface distributions of the PEMFC fuel cell under different operating temperatures and flow rates. In these figures, the dashed squares indicate the active area of the fuel cell and the arrow lines point out the inlet direction and outlet direction of oxygen. Oxygen in each channel flows horizontally from right to left. The right columns of these figures are the according relation between colors and temperatures in Celsius degree.

Fig. 3 shows the cathode temperature distribution when the temperature of anode was 41℃ and the flow rates of anode and cathode were both 50ml/min. The local low temperature region is clear in the inlet of oxygen. The reason is that the oxygen was not preheated before entering the fuel cell. The temperature of outlet section is higher. But it is not obvious because the cell temperature is not high enough and can not heat the flow temperature higher when it flows through the channels.

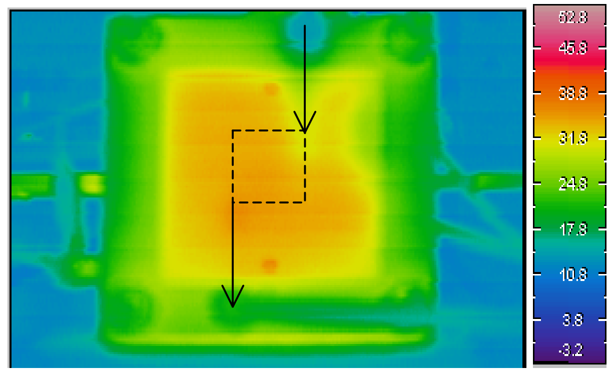

Fig. 3 Cathode surface temperature distribution (anode: temperature, 41℃; flow rate, 50ml/min; cathode: flow rate, 50ml/min)

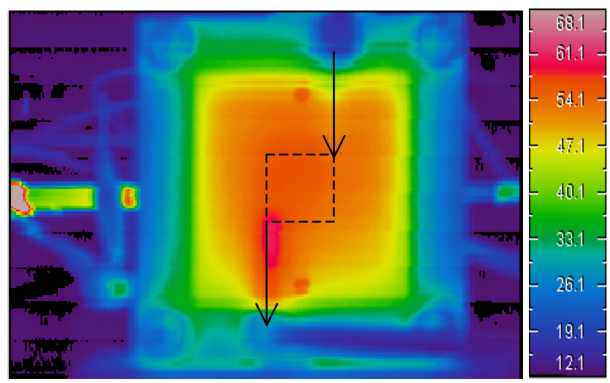

Fig. 4 Cathode surface temperature distribution (anode: temperature, 74.1℃; flow rate, 50ml/min; cathode: flow rate, 50ml/min)

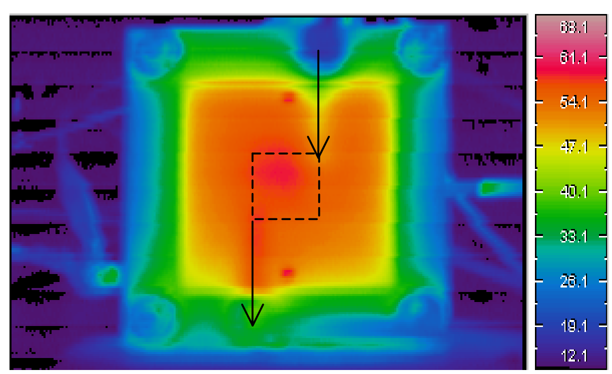

Fig. 5 Cathode surface temperature distribution after removing heating stick (anode: temperature, 74.1℃; flow rate, 50ml/min; cathode: flow rate, 250ml/min)

Fig. 4 shows the cathode temperature distribution as the anode temperature reached 74.1℃ and the flow rates of cathode and anode were both 50ml/min. Seen from the figure, the cathode surface temperature was clearly higher than that in Fig. 3, but, like Fig. 3, non-uniformity of temperature distribution was not observed. The area of the low temperature section in the oxygen inlet is smaller than that in Fig. 3 because the temperature of the fuel cell is higher enough to quickly heat flowing oxygen of 50ml/min. The temperature of outlet region is obvious higher because the flow temperature becomes higher after heated along channels.

Fig. 5 shows the cathode temperature distribution when the anode temperature was 74.1℃ and the flow rates of cathode and anode were 250ml/min and 50ml/min, respectively. At the same time, the heating stick was removed. Compared with Fig.4, the area of the low temperature region in the inlet is bigger. The reason is that the oxygen flow rate was increased greatly and the cell can not timely heat oxygen with 250ml/min rate. The temperature in the outlet section is higher than other positions because the oxygen reaching outlet was heated along the channels. Another point seen from Fig.5 is that the temperature distribution uniformity in active area (dashed square) is not as good as that in Fig.4. The temperature of the top left section is higher than other sections in the active area region. Maybe the non-uniformity of flow distribution in channels is the reason. The oxygen enters into manifold from inlet, and then turns left and goes into the channels. Because oxygen in inlet manifold flows from top to bottom with quite high flow rate, more fresh oxygen will flow through the bottom channels. Flow velocity in bottom channels likely higher than that in top channels. The little oxygen in the top channels will easily be heated to higher temperature.

The infrared thermal imaging is an effective way to measure cathode surface temperature distributions of the PEMFC. It is simple to measure the temperature distribution of the whole exterior surface of the cell by the technique. The temperature distributions varied with the cell temperatures and the flow rates of reactants. The non-uniformity of flow distribution will cause the non-uniform distribution of the temperature. The heating method was designed for uniformity of input heat in our experiment. It will be better to replace the heating stick with heating pad to obtain more uniform distribution of input heat. The active area of the cell is only 5cm^2. The non-uniformity of temperature distribution caused by non-uniformity of flow distribution would be clearer if fuel cell with bigger active area was adopted.

CONCLUSIONS

Temperature plays a key role in achieving high performance of fuel cells. The electrodes' kinetics, performance of electrolytes, mass transfer, heat management and fuel utilization etc. all associate with fuel cell operating temperature.

The thermocouple is the basis technique used to measure the temperature and temperature distribution of fuel cells and cell stacks. Microthermocouple is a tool by which the temperature of the reactive regions in the electrodes of fuel cells could be measured. The Infrared thermal imaging is a good and simple way to scale the external surface temperature field of fuel cells and cell stacks. The thermochromatic liquid crystals（TLCs）can be applied to measure the exterior surface temperature distributions of the low temperature fuel cell (AFC, PEMFC, DMFC) and stack.

The experimental results indicated that the temperature field of the single PEMFC could be effectively achieved by the infrared thermal imaging technique. When the anode temperature was 74.1℃, the temperature of the cell cathode was higher than that when the anode temperature was 41℃. There was a obvious high temperature section in the outlet of oxygen when the anode temperature was 74.1℃ and the flow rate of oxygen was 50ml/min. When the flow rate of oxygen was 250ml/min, the uniformity of temperature distribution was not as good as that when the flow rate was 50/ml/min. at anode temperature of 74.1℃. The temperature of top left portion of the flow field was higher than that of the bottom right portion when the flow rate of oxygen was 250ml/min.

Future work will investigate the surface temperature distributions of fuel cell with bigger active area under various conditions. The heating stick will be replaced with heating pad. The application of thermochromatic liquid crystals techniques in the temperature measurement of fuel cells is underway and the results from those three techniques will be compared.

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