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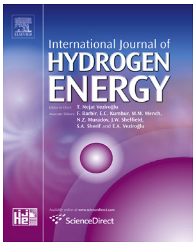

Flexible five-in-one micro sensor for in-situ diagnosis of high-temperature proton exchange membrane fuel cell stack

Chi-Yuan Lee[*], *Fang-Bor Weng*, *Sheng-Ming Chuang*, *Shuo-Jen Lee*, *Yen-Pu Huang*, *Yen-Ting Cheng*, *Chih-Kai Cheng*

Department of Mechanical Engineering, Yuan Ze Fuel Cell Center, Yuan Ze University, Taoyuan, Taiwan, ROC

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During the chemical reaction process of high-temperature proton exchange membrane fuel cell (HT-PEMFC) stack, the non-uniformity of internal local temperature, voltage, pressure, flow rate and current would result in poor membrane durability, fuel distribution non-uniformity and adverse impact on the fuel cell stack performance and service life. This study applies the micro-electromechanical systems (MEMS) technology to develop a flexible five-in-one micro sensor resistant to the high-temperature electrochemical environment. Six integrated micro sensors are embedded in the cathode field plate of HT-PEMFC stack. At the operational temperature of 160 °C, current (5, 13, 20 A) and long term testing results suggest that the trends of the curves of the internal local temperature, voltage, pressure, flow rate and current density of the fuel cell stack are considerably consistent, and the embedded flexible five-in-one micro sensors for in-situ diagnosis of fuel cell stack have impact of about 1.3% on fuel cell stack performance. The upstream temperature is higher than the downstream. The test result also shows that the heat distribution in the fuel cell stack is nonuniform.

Introduction

Intergovernmental Panel on Climate Change (IPCC) published the climate change assessment report, revealing the Earth's climate changes over the past century and the possible impact of various kinds in the next century under the warming effects. Faced with the challenge of global climate change and greenhouse gas reduction, people start thinking about the importance of sustainable development and green technology. Therefore, many countries around the world have actively promoted green energy industry. The high-temperature proton exchange membrane fuel cell stack (HT-PEMFC stack) is characterized by portable application, high energy conversion efficiency, no electrolyte loss, easy assembly and production and long operation life [1]. The operating condition of high temperature, which is expected to over 120 °C and low humidity [2].

The problems facing high-temperature proton exchange membrane fuel cell (HT-PEMFC), including membrane

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[*] *Corresponding author*. Department of Mechanical Engineering, Yuan Ze University, 135 Yuan-Tung Road, Chung-Li, 32003 Taoyuan, Taiwan, ROC. Tel.: +886 3 4638800x2478; fax: +886 3 4558013.

E-mail address: cylee@saturn.yzu.edu.tw (C.-Y. Lee).

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durability, corrosion of the catalyst, the non-uniformity of local flow rate, pressure, temperature, voltage and current inside the fuel cell stack, are yet to be solved for the commercialization of the fuel cell [3]. The issue of thermal management of HT-PEMFCs has been receiving attention [4]. Reddy [5] studied while a number of possibilities of thermal management exist for small stacks, the problem becomes more complicated for larger stacks. Salomov [6] studied that one of the reasons for performance degradation of high-temperature proton exchange membrane fuel cells originates from the gas dynamic action at the interface between the catalyst layer and membrane. Technically, the performance of a proton exchange membrane fuel cell in terms of voltage and power density can be greatly influenced by the operating pressure. Key parameters that contribute to the performance, such as temperature and air stoichiometry, can also be strongly affected by the operating pressure [7]. Hence, the in-situ monitoring of the internal local flow rate, pressure, temperature, voltage and current of the fuel cell stack is the topic of this study.

For the commercialization of fuel cell, the R&D of fuel cell stack is the key. HT-PEMFC stack capable of integrating the reorganizer is widely applied in transportation vehicles, auxiliary power unit (APU), and uninterruptible power sources (UPS). The integrated power generation system is considerably important to future green energy. However, for HT-PEMFC stack, the membrane electrode assembly ageing and fuel cell stack failure can seriously affect fuel cell stack performance. Moreover, the thermal management is a key impact on fuel cell stack performance and stability. When the internal temperature is too high, it will affect the catalyst activity, dry membrane, mass transfer and thermal management [8]; if the temperature is too low, the membrane electrode assembly may not react completely. By monitoring the pressure drop both in the cathode and anode of an operating fuel cell, water transport between the two electrodes can also be identified [9]. The voltage and current values are important basis to determine the fuel cell good or bad of the local performance [10].

Inman [11] presented the phosphor temperature measurement method to produce an optical temperature sensor, process on the bipolar plate and place the sensor inside the fuel cell to capture the temperature of cell reaction in real time. Shen [12] embedded 80 μm copper wire in the inlet and outlet of the cathode, and anode end flow channel plate. They found that the voltage distribution inside the fuel cell is different under the operating conditions of different current densities and gas equivalents. Regarding the fuel cell stack performance and discussion of internal information, there are methods including external measurement, intrusive measurement, theoretical simulation and measurement of single temperature, voltage, flow rate, pressure and current. However, as the sensors are too big in volume, the measurement accuracy is not high, effect fuel cell stack performance and failure to learn the real internal reaction. In the past, our research team has successfully embedded the micro temperature and voltage sensors inside the HT-PEMFC stack [13–15]. Andreasen [16] studied that the current, temperature for the fuel cell performance change. Dai [17] studied that the review for water balance in the membrane electrode assembly of proton exchange membrane fuel cells. Therefore, this study aims to develop flexible five-in-one (temperature, voltage, pressure, flow rate and current) micro sensor resistant to the electro-chemical environment of high temperature for the real-time monitoring of internal local conditions of HT-PEMFC stack. The non-uniformity distribution of the temperature, voltage, pressure, flow rate and current of different cells in the fuel cell stack are analysed, in order to promote the fuel cell stack performance and lengthen its service life.

Theory and design of micro sensors

Sensing principles of the five-in one micro sensors

Micro temperature sensor

The micro temperature sensor used in this study is RTD (Resistance temperature detector). Its electrode type is of the snake-like structure and the sensing area is 400 μm × 400 μm, the minimum wire width is 10 μm, its temperature sensing resistant material is gold (Au). As its chemical properties are stable, the process is simple and of high linear degree. For general metallic conductors, the resistance can be described as Eq. (1).

$$R = \rho \frac{L}{A} \tag{1}$$

where ρ is the resistivity; L is the wire length (m); A is the wire sectional area (m^2).

The sensing principle of micro temperature sensor is: when ambient temperature increases, as gold has the characteristic of PTC (Positive temperature coefficient), the resistance of RTD will increase due to TCR (Temperature coefficient of resistance) of the conductor, defined as Eq. (2).

$$\alpha = \frac{1}{\rho_0} \frac{d\rho}{dT} \tag{2}$$

where α is TCR; ρ_0 is resistivity at 0 °C.

Therefore, the relationship between conductor's resistance and temperature can be described as Eq. (3).

$$R_t = R_0\left(1 + \alpha_1 \Delta T + \alpha_2 \Delta T^2 + \alpha_3 \Delta T^3 + \cdots\right) \tag{3}$$

$$\Delta T = t - t_0 \tag{4}$$

where R_t is the resistance at t°C (Ω); R_0 is the resistance at 0 °C (Ω); α_1, α_2, α_3 is TCR (%/°C); ΔT is the gap of temperature with the reference temperature of 0 °C (°C); t is temperature at t°C (°C); t_0 is temperature at 0 °C (°C).

In Eq. (3), the relationship between the conductor temperature and resistance is non-linear. If RTD resistance is in the linear range, Eq. (3) can be simplified into Eq. (5).

$$R_t = R_0(1 + \alpha_1 \Delta T) \tag{5}$$

where the physical meaning of α_1 is micro temperature sensor's sensitivity (1/°C).

Design and sensing principle of the voltage sensors

The micro voltage sensors used in this study are the micro voltmeter probe, which is an extended wire. At the foremost end of the micro voltage sensor, there is a protruding sensing area of

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