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集成在微型直接甲醇燃料电池中加热器的设计

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摘要: 根据各种传热机理建立了微型直接甲醇燃料电池的热传导模型, 借助有限元分析工具, 设计模拟了集成在微型直接甲醇燃料电池中 3 种不同结构的加热器。仿真结果表明, 不同的加热器结构在极板表面将引起不同的温度分布, 这将对燃料电池产生不同的加热效果, 从而对电池的性能造成影响。其中一种比较理想的加热结构仅引起 1.4 °C 的温度偏差, 显示了良好的温度均匀性, 故在实验中被用来控制工作温度。而另外两种加热结构引起的温度偏差分别是 2.1 °C 和 3.0 °C。实验结果表明, 当电流 53.9 mA 时, 微型直接甲醇燃料电池工作温度为 58.2 °C, 产生的最大功率密度为 5.55 mW/cm²。集成后的微型加热器可以通过调整微型直接甲醇燃料电池的工作温度提高其性能, 并能在极端环境下工作。

关键词: 直接甲醇燃料电池; 热传导模型; 加热器

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Design of heater integrated into micro direct methanol fuel cell

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Abstract: The heat transfer model of a micro Direct Methanol Fuel Cell (μ DMFC) based on heat transfer mechanisms is presented. Three kinds of patterns of the heater integrated into a μ DMFC are designed and simulated using the Finite Element Analysis (FEA). The simulation results illustrate that the different patterns of the heater cause different temperature distributions on the surface of the plate, which would induce different heating effects on a fuel cell and great influence on its performance. According to the results, an ideal heater resistance which causes a maximum temperature contrasts of 1.4 °C is applied to control the operating temperature in experiments, for it shows an improvement on the temperature uniformity. Moreover, the heaters with other two patterns produce the maximum temperature contrast of 2.1 °C and 3.0 °C, respectively. Experimental results show that the μ DMFC can generate a maximum power density of 5.55 mW/cm² at a temperature of 58.2 °C when a current of 53.9 mA is applied to the heater. This work would make it possible for a μ DMFC to

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enhance the performance by adjusting to the temperature and to employ it in extreme environments.

Key words: Direct Methanol Fuel Cell(DMFC); heat transfer model; heater

1 Introduction

Micro fuel cells are considered as the dominant power provider to replace the current battery for portable application. The striking feature of micro fuel cells is their higher inherent potential of higher energy densities compared to batteries. Micro direct methanol fuel cells (μ DMFCs) are inevitably considered as the most promising candidate due to some factors such as the high energy density and the simpler and safer handling^[1].

Temperature is one of the most important factors that affect the performance of a μ DMFC^[2]. The conductivity of proton exchange membrane (PEM) and the catalytic activity of a μ DMFC can be improved significantly with temperature increasing^[3]. Especially, the catalytic activity of a μ DMFC is low due to the low kinetic activity of methanol oxidation and CO poisoning^[4]. Therefore, analysis of temperature characteristic is of great importance to improve the performance of a μ DMFC. A heat transfer model of a μ DMFC is built based on heat transfer mechanisms in this paper. Three kinds of patterns of the heater integrated into a μ DMFC are designed and simulated to find the best heater pattern that provides the best heating effect.

2 Theoretical research of temperature influence on μ DMFC performance

Equation Butler-Volmer is the basic equation describing electrochemical reaction current and overvoltage.

$$i = i_0^* \frac{C_R^*}{C_R^{0*}} \left[\exp \frac{-\alpha F \eta}{RT} - \exp \frac{(1-\alpha) F \eta}{RT} \right], \quad (1)$$

where i_0^* is the exchange current; C_R^* is the con-

centration at reaction surface; C_R^{0*} is the reference concentration of reactant; α is the exchange coefficient; $F = 96\,485$ C/mol is the Faraday constant; $R = 8.314$ J/(K · mol) is the ideal gas constant; η is the activation overvoltage; and T is the operating temperature. Exchange current i_0^* is expressed as

$$i_0^* = n F C_R^{0*} A \frac{k T}{h} \exp \left(\frac{-\Delta G_1^+}{RT} \right), \quad (2)$$

where n is the number of electrons transferred in the reaction; A is the active area of chemical reaction; $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann's constant; $h = 6.626 \times 10^{-34}$ J · s is the Planck's constant; and ΔG_1^+ is the activation energy barrier.

Considering anode activation overvoltage, cathode activation overvoltage and ohmic loss, the output voltage is expressed as

$$V = E - \eta_c - \eta_a - i \times r, \quad (3)$$

where E is the ideal open circuit voltage; η_c is the cathode activation overvoltage; η_a is the anode activation overvoltage; and r is the internal resistance of a μ DMFC. Fig. 1 shows the simulation results of the temperature influence on the μ DMFC performance. It is demonstrated theoretically that the cell performance can be improved with the increase of temperature in a certain range.

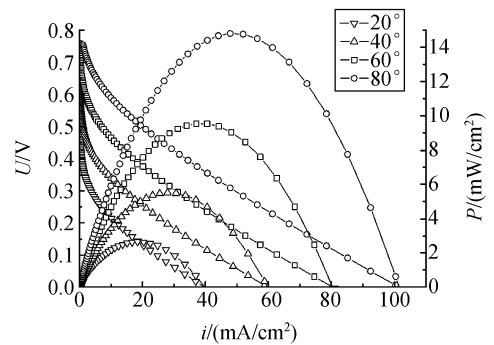


Fig. 1 Simulation results of the temperature influence on the μ DMFC performance

3 Analysis and modeling

Heat dissipates in several ways in a μ DMFC such as taken away by the methanol solution, thermal convection and radiation on the surface of the packaging material, and heat conduction through metal wires. Fig. 2 shows the schematic of a μ DMFC with the heater and dominant heat loss mechanisms.

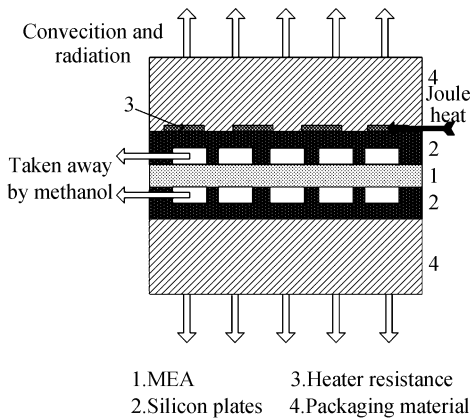


Fig. 2 Schematic of μ DMFC structure and heat dissipation

3.1 Thermal convection and radiation

Heat dissipates through convection and radiation on the surface of a μ DMFC. For the convection, the heat flow is expressed as:

$$q = hA(T_w - T_\infty), \quad (4)$$

where h is the heat transfer coefficient; T_w is the surface temperature of a μ DMFC; T_∞ is the environment temperature; and A is the surface area of the μ DMFC plates.

For thermal radiation, the heat flow is expressed as:

$$q = \varepsilon\sigma A(T_w^4 - T_\infty^4), \quad (5)$$

where ε is the emissivity; and $\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$ is the Stefan-Boltzmann constant.

Heat generated inside a μ DMFC is transmitted to the surface by the silicon plate and packaging material. On the surface, heat dissipates through convection and radiation. When the

temperature is steady, the heat system keeps dynamic equilibrium. h , ε , and σ are constants in (4) and (5). The heat flow of convection and radiation is primarily determined by T_w .

3.2 Heat conduction through metal wires

Metal wires also transmit part of the heat. Since the length of metal wire is much larger than the width and thickness, the metal wire is similar to infinite long rectangular rib. The temperature at the end of rib is equal to room temperature. The heat flow of conduction through metal wires is expressed as:

$$q = \sqrt{hPkA_s}(T - T_\infty), \quad (6)$$

where P is the cross-sectional perimeter; A_s is the cross-sectional area; and k is the thermal conductivity coefficient of metal wires. It can be seen obviously from Eq. (6) that the heat flow of conduction through metal wires is related to P , A_s and k , which are determined by the material and structure of metal wires.

3.3 Heat taken away by methanol solution

The methanol solution feeds back to the inlet of a μ DMFC, transfers heat inside the μ DMFC, and takes it away from the outlet. According to the calculated Reynolds number, the methanol solution flow in the channels is laminar. Heat flow taken away by the methanol solution is written as:

$$q = \dot{m}C_p(T - T_w) = \rho v C_p(T - T_w), \quad (7)$$

where \dot{m} is the mass flow; C_p is the heat capacity; ρ is the density of the methanol solution; and v is the flow velocity of the methanol solution. ρ and C_p are constants here. Heat flow taken away by the methanol solution is determined by the flow velocity v . The smaller v is, the less heat flow is.

4 Design and simulation of heater

A μ DMFC doesn't have optimal performance at lower temperatures, even does not work below 0 $^\circ\text{C}$, but it has a significant advantage that it can work at room temperature. This is a particular

problem in the application of portable devices because such devices may be used in cold environments. In our work the heater resistance is integrated into a μ DMFC to heat the fuel cell, actually the reacting region, so that the electrochemical reaction in the μ DMFC occurs at a higher temperature. The temperature is steady when the balance of heat dissipation and generation is achieved. Three patterns of the heater resistance are designed to compare their heating effort in Fig. 3.

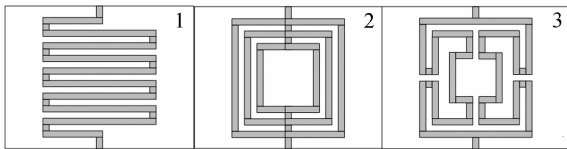


Fig. 3 Designed patterns of heater resistances

The heater structure, which tends to suffer from an uneven thermal distribution, could lead to an uneven catalytic reaction and reduce the heating effort for the μ DMFC. These heaters are simulated by Finite Element Analysis (FEA) and compared to optimize the structure. The thermal-electric coupled analysis mode is applied to the simulation during the FEA procedure. The voltage and thermal convection loads are defined as boundary conditions. The values of voltage loads are fixed according to the different resistances so that every heater generates the same heat. The thermal convection loads are applied on the surface of the model to indicate the heat dissipation through convection and radiation between the fuel cell and external environment. The heat taken away by the methanol solution is equivalent to thermal convection, only with different coefficients of thermal convection. The resistance of each heater can be measured by simulation so a proper voltage can be set corresponding to the resistance. The simulation results of the different heater resistances, including the gradient of temperature distribution and the maximal temperature contrast, are shown in

Fig. 4 to Fig. 6. The resistance and average temperature of each heated area are listed in Tab. 1.

Tab. 1 Parameters of simulation results

Pattern	Simulation results		
	Resistance (Ω)	Average Temp ($^{\circ}\text{C}$)	Max Temp Contrast ($^{\circ}\text{C}$)
1	85.46	67.36	2.141
2	3.082	68.04	3.011
3	19.23	67.84	1.40

The simulation results show that different patterns of the heater cause different temperature distributions on the plate of a fuel cell. The serpentine resistance produces a central hot spot as shown in Fig. 4. The heater resistance with more branches causes hot spots at the connections, as shown in Fig. 5. The heater in Fig. 6 which has two branches of resistance and leaves

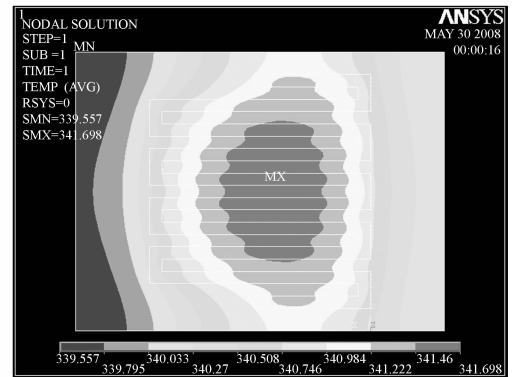


Fig. 4 Simulation result of pattern 1

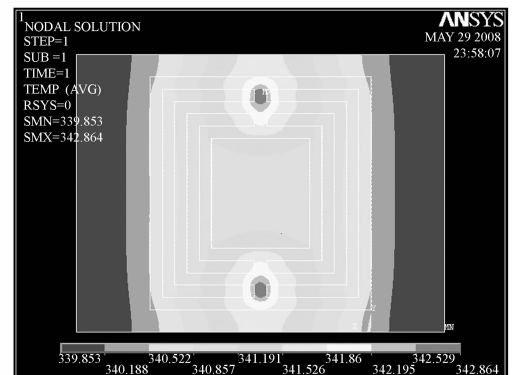


Fig. 5 Simulation result plot of pattern 2

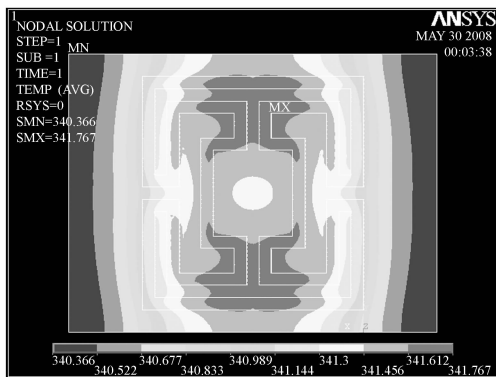


Fig. 6 Simulation result of pattern 3

space in the middle provides the most equilibrium temperature distribution without obvious hot spots.

The packaging of the fuel cell is ignored in the simulations above to observe the temperature distribution on the plate. To achieve more actual temperature distributions, the model used organic glass as the packaging material is simulated again. Fig. 7 shows the temperature distribution with packaging added. It is indicated that the organic glass is of great benefit to heating effort due to its lower thermal conductivity.

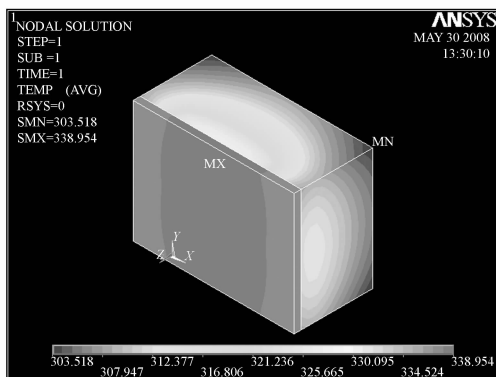


Fig. 7 Simulation with packaging added

5 Performance measurement

A silicon-based μ DMFC integrated with a heater and a temperature sensor is characterized. The details about the fabrication and assembly are

mentioned in our previous work^[5]. The heater pattern 3 is adopted and the μ DMFC we developed is shown in Fig. 8.

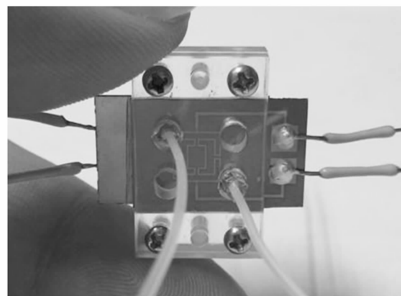


Fig. 8 Assembled μ DMFC integrated with temperature control devices

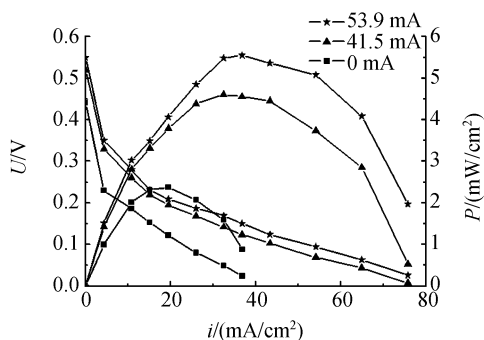


Fig. 9 Performance of the μ DMFC with 2 M methanol solution under 0.1 mL/min methanol flow rate, when different currents are applied to the heater

The performance of the μ DMFC integrated with the temperature control system is measured on an electrochemical interface, Solartron SI1287. Fig. 9 depicts the performance of the μ DMFC when the currents applied to the heater are 53.9, 41.5, and 0 mA, respectively. Obviously, the cell temperature is raised with the increasing current applied to the heater for more heat released from the heater. The experimental results show that the prototype has the maximum power density of 5.55 mW/cm² at 58.2°C, which is twice higher than that of the μ DMFC at the value of 2.37 mW/cm² at room temperature, using 2 M methanol solution under 0.1 mL/min methanol flow rate.

6 Conclusions

This paper presents several designs based on the heat transfer model of a μ DMFC and the simulations of the heater resistance integrated into a μ DMFC. The simulation results show that different patterns of the heater cause different temperature distributions on the plate of a fuel cell. Central hot spot or other spots at the connec-

tions must be avoided. Considering heating efficiency and equilibrium temperature distribution, the heater, which has two branches of resistance and leaves space in the middle and causes the maximum temperature contrast of 1.4 °C, is recommended. A μ DMFC with temperature control system is characterized. This work would make it possible for a μ DMFC to improve the performance by increasing the temperature and employ in extreme environments.

References:

- [1] KAMARUDIN S K, DAUD W R W, HO S L, *et al.*. Overview on the challenges and developments of micro-direct methanol fuel cells (DMFC) [J]. *Journal of Power Sources*, 2007,163:743-754.
- [2] LUA G Q, WANG C Y, YEN T J, *et al.*. Development and characterization of a silicon-based micro direct methanol fuel cell [J]. *Electrochimica Acta*, 2004, 49: 821-828.
- [3] OTOSHI S, SASAKI H, OHNISHI H, *et al.*.

Changes in the phases and electrical conduction properties of (La_{1-x}Sr_x)_{1-y}MnO₃ [J]. *J. Electrochem. Soc.*, 1991, 138:1519-1523.

- [4] LI Q F, HE R H. Approaches and recent development of polymer electrolyte membranes for fuel cells operating above 100 °C [J]. *Chem. Mater.*, 2003,15:4896-4915.
- [5] ZHANG Q, WANG X H, ZHU Y M, *et al.*. A micro direct methanol fuel cell integrated with a temperature control system for extreme environments [C]. *IEEE-MEMS2009, Sorrento, Italy,2009:25-29.*

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