

A laser-micromachined polymeric membraneless fuel cell

Aidan Li, Siew Hwa Chan and Nam-Trung Nguyen

Fuel Cell Strategic Research Programme, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

E-mail: mntnguyen@ntu.edu.sg

Received 28 February 2007, in final form 1 March 2007

Published 26 April 2007

Online at stacks.iop.org/JMM/17/1107

Abstract

This paper presents a laser-micromachined polymeric membraneless fuel cell. The membraneless fuel cell, constructed with three polymethyl methacrylate (PMMA) layers, takes advantage of two laminar flows in a single micro channel to keep the fuel and oxidant streams separated yet in diffusional contact. Laser micromachining was employed to make the flow channel and electrode substrate based on PMMA. The anode and cathode electrodes were fabricated by wet-spraying catalyst inks onto the gold-coated PMMA substrate. The packed fuel cell has been electrochemically characterized by an electrochemical analyser. The membraneless fuel cell works stably with Reynolds numbers ranging from 7.65 to 30.6. At room temperature, the laminar-flow-based micro membraneless fuel cell can reach a maximum power density of 0.58 mW cm^{-2} with 0.5 M HCOOH in 0.1 M H_2SO_4 solution as fuel and O_2 saturated 0.1 M H_2SO_4 solution as oxidant. When 0.01 M H_2O_2 in 0.1 M H_2SO_4 solution is used as oxidant, a maximum power density of 1.98 mW cm^{-2} is obtained. The paper reports for the first time the use of hydrogen peroxide in sulfuric acid as the oxidant. The new oxidant composition allows a simple recycling process and better fuel utilization.

1. Introduction

The widespread use of portable electronic devices stimulates the rapid development of miniature power sources. Among them, micro fuel cells have become more and more attractive due to their advantages of high energy-conversion efficiency, and capability of producing electricity as long as fuel and oxidant are supplied to the electrodes [1]. Miniaturization technology and fuel storage are the two critical issues for the successful development of micro fuel cells. Silicon-based microtechnologies previously used for the fabrication of microelectromechanical systems (MEMS) and advanced integrated circuits (IC) have been widely employed to make micro fuel cells [2–5]. However, compared to MEMS and IC, the relative large size of fuel cells makes the cost per device very high. Mass fabrication of micro fuel cells based on polymeric materials is a more economic solution. In the past, we have successfully developed fully polymeric microfluidic components such as microvalves [6] and micropumps [7]. Together with a fully polymeric micro fuel cell [8], we have

proved that complex polymeric micro fuel cells can be built at low costs.

Although hydrogen is one of the best fuels for polymer electrolyte membrane fuel cells (PEMFCs), especially for macroscale systems, the dimension, weight and safety concerns of the high-pressure hydrogen tank prevent their successful miniaturization. Ideal fuels for micro fuel cells should be in liquid form at ambient temperature. Methanol and formic acid are the two typical examples of liquid fuels.

Extensive studies have been reported on the development of micro direct methanol fuel cells (μDMFC) and formic acid fuel cells (μFAFC) due to the convenient storage of the liquid fuels [4, 5]. Most of the previous studies were based on the conventional Nafion membrane as the electrolyte to separate the fuel and oxidant and to conduct protons between the anode and the cathode. Performance deterioration and fuel crossover, especially when running methanol, are the intrinsic problems associated with the Nafion membrane [9]. Although some works have focused on developing methanol-tolerant cathode materials or/and innovative membrane materials less permeable to methanol,

their intrinsic activity is currently too low to make a significant difference to the overall cell performance [10]. Recently, some novel designs, such as bio-fuel cell and laminar-flow-based membraneless fuel cell, have been proposed to avoid the membrane-associated problems by removing the conventional polymer electrolyte membrane (PEM). Employing the selective catalysts, generally enzymes, to restrict the reaction of oxidant and reductant to the appropriate electrode, bio-fuel cells can operate with both oxidant and fuel present in a mixture [11, 12]. Bio-fuel cells have received increasing interest because they use biological enzymes instead of precious metals as catalysts. This fact may allow bio-fuel cells to be implanted in living organisms. The drawback of bio-fuel cells is the relatively low output power due to the low electrocatalytic activity of the enzyme electrodes, which is in the range from several $\mu\text{W cm}^{-2}$ to several hundred $\mu\text{W cm}^{-2}$ [11, 12].

The concept of the membraneless micro fuel cell based on laminar flow was first demonstrated by Ferrigno *et al* [13] using vanadium redox couples as fuel and oxidant. Because pressure-driven flow in microchannels is generally laminar, the flow has low Reynolds numbers and reasonably high Peclet number [14]. Two streams containing oxidant and fuel can be separated because of the dominant convective transport. Thus, ions can diffuse through the liquid–liquid interface similar to the case of a membrane interface. Currently, two designs exist for laminar flow based membraneless microchannel fuel cells. The first design is a Y-shaped microchannel with oxidant and fuel flowing side by side [15–17]. With this design, the fabrication of the electrode on the side wall is challenging. The second design lets the fuel and oxidant on the top and bottom of the micro channels [18, 19]. With this design, electrodes can be fabricated using conventional coating techniques on a substrate surface. In most cases, polydimethylsiloxane (PDMS) or silicon was used as the substrate for these membraneless micro fuel cells. Microtechnologies such as soft lithography [15] or standard photolithography [18] were employed for microchannel fabrication. The fabrication requires specialized clean-room facilities. Furthermore, the small dimension of the microchannels makes the integration of electrodes challenging. Chohan *et al* [15] fabricated the electrodes using electron-beam evaporation of platinum. Cohen *et al* [18] used electrodeposition of platinum black to form the electrodes. In general, both designs require complicated fabrication processes for the microchannels and electrodes. Due to the low saturation concentration of oxygen in the acid or alkaline media, the performance of laminar flow-based membraneless fuel cells was primarily limited by mass-transfer of oxygen at the cathode side. This situation could be improved by using an air-breathing cathode [20, 21] or high concentration oxidants, such as potassium permanganate [15]. In order to improve the fuel utilization in membraneless micro-fuel cells, it is desirable to recycle the unused fuel. The use of potassium permanganate as the oxidant makes fuel recycling very difficult.

As mentioned above, cost is a major factor for the commercial success of micro fuel cells. The cost factor will become critical, when widespread commercial use of the new broadband devices is established [22]. This paper reports a simple, fast and cost-effective way to fabricate laminar flow-based membraneless fuel cell by combining the rapid

prototyping characteristics of laser micromachining and the simple implementation of the membraneless fuel cell concept. The geometry of microstructures on the PMMA substrate can be controlled precisely by adjusting the power and the scanning speed of the laser beam. The technology allows the fabrication of functioning PMMA-based membraneless fuel cells with a gold layer as the current collector and wet-sprayed catalysts on the gold layer as the anode and cathode. The electrochemical performance of the fuel cell was evaluated with formic acid as fuel and hydrogen peroxide as oxidant. To the best knowledge of the authors, the use of hydrogen peroxide in sulfuric acid as oxidant in a membraneless fuel cell is reported for the first time. The use of hydrogen peroxide as oxidant significantly improves the mass-transfer at the cathode side, thus obviously enhancing the fuel cell performance. Furthermore, the use of hydrogen peroxide in sulfuric acid as the oxidant allows simple fuel recycling and better fuel utilization.

2. Experimental procedure

2.1. Fabrication of the membraneless fuel cell based on PMMA

Polymethylmethacrylate (PMMA) was chosen as the substrate for many microreaction platforms, because this material offers excellent properties such as low frictional coefficient, high chemical resistance and good electrical insulation [23]. An infrared CO_2 laser (Universal M-300 Laser Platform, Universal Laser Systems Inc., Arizona, USA) was used to engrave microstructures directly on the PMMA substrate. This technique has been proven to be rapid and effective for fabricating microfluidic devices, especially for lab-scale prototyping and small-scale production. The geometry of these structures can be controlled precisely by adjusting the laser power the scanning speed of the laser beam. The ease of varying machining parameters, and thus of the optimization process leads to a relatively short prototyping cycle.

Figure 1(a) shows the different layers of our membraneless fuel cell. This lamination technique was successfully used for making a variety of microfluidic components such as membrane-based micro fuel cells [8], micromixers [14], microvalves [6] and micropumps [7, 23]. The fuel cell is constructed based on three PMMA layers. The top PMMA layer contains two inlets and one outlet. This top layer serves as the electrode support structure as well as the fluidic access for the fuel and the oxidant. The bottom layer works as the electrode support and liquid sealing plate. A 100 nm gold layer was sputtered on the surface of the PMMA sheet (SC7640 sputter coater, Quorum Technologies Ltd) to reduce the contact resistance. This gold layer acts as the current collector on which catalyst inks were wet-sprayed to form the electrode. Before the sputtering process, the surfaces of the PMMA sheets were mechanically treated with fine sandpaper (1200 grit) to improve its surface roughness, and consequently to enhance the adhesion of the gold layer to the substrate. The intermediate layer is a 1 mm thick PMMA sheet for the channel structure. A separation wall was designed in the middle PMMA piece (figure 1(a)) to keep the fuel and oxidant apart at the entrance. Both drilling and shaping of the separation

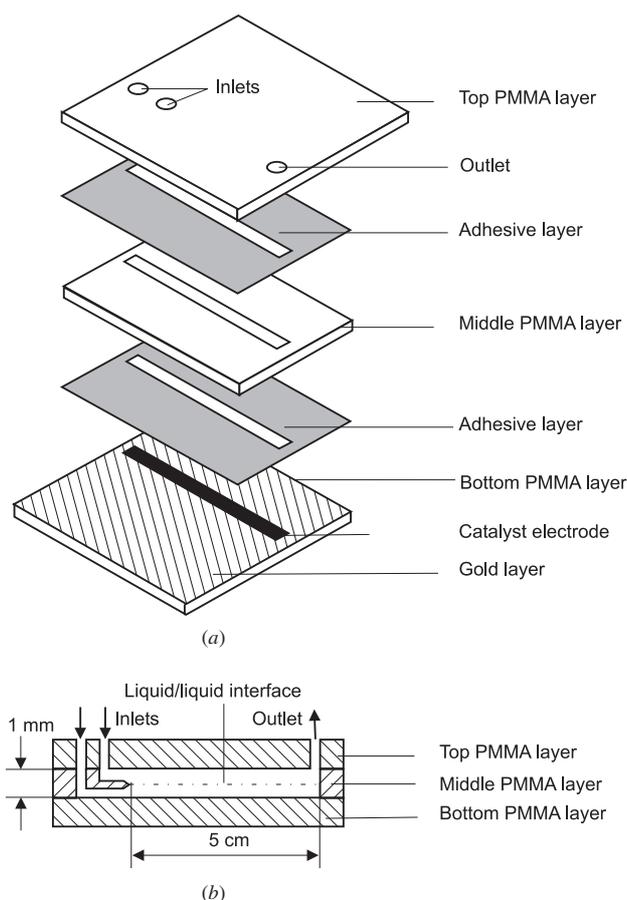


Figure 1. Schematic diagram of the membraneless fuel cell: (a) the different layers, (b) the reaction channel.

wall can be easily realized by CO₂ laser micromachining by adjusting the speed and power of the laser beam. The resulting reaction channel (figure 1(b)) has a width, depth and length of 1 mm, 1 mm and 5 cm, respectively.

Two different catalyst inks were prepared for the anode and the cathode. In brief, the platinum/ruthenium (Pt/Ru) catalyst (supported on carbon black with metal content of 60% and Pt:Ru = 1:1, from E-Tek) was mixed with Nafion solution (5 wt% Nafion 5112, from DuPont) in isopropanol with a final catalyst concentration of 5 mg mL⁻¹ and catalyst/Nafion ratio of 7:3. A homogeneous suspension was obtained by ultrasonically mixing the ink at room temperature for 25 min. The same procedure was applied to prepare the Pt catalyst ink. The inks were wet-sprayed onto the surface of the Au-coated PMMA substrate using a spray gun (Model 20106, Rich, Japan). Subsequently, the wet-sprayed electrode was heat-treated at 80 °C for 1 h in an atmospheric air oven to form a smooth electrode film. The final catalyst loading on the electrodes is 4.5 mg cm⁻².

The three PMMA layers were bonded together using an adhesive gasket (Adhesives Research, Inc., Arclad 8102 transfer adhesive), which can also be easily cut by the CO₂ laser system. Alignment holes were drilled in all three PMMA layers and the adhesive to allow a fast and accurate assembly of the membraneless micro fuel cell. The fabrication steps are shown in figure 2. The top and bottom PMMA plates have

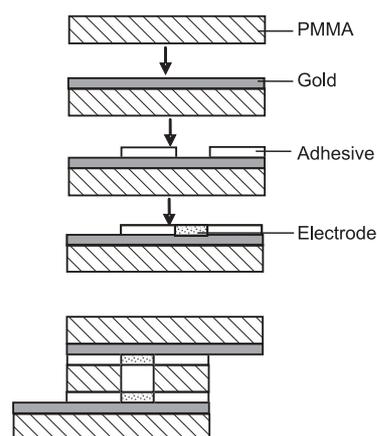
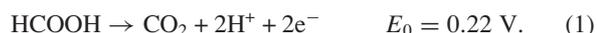


Figure 2. Fabrication steps for the PMMA-based membraneless fuel cell.

gold coating protruded so that the electrical contact to the electrode can be achieved. Polyethylene tubing was glued by epoxy to the inlets and outlet.

2.2. Electrochemical performance evaluation

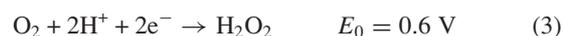
The power generation process in a membraneless fuel cell follows the electrochemical reactions at anode and cathode. At the anode, formic acid decomposes and creates electrons and protons:



In the case of saturated oxygen in a H₂SO₄ solution, oxygen reacts with electrons from the cathode and protons from the liquid/liquid interface to form water:



In the case of H₂O₂ in a H₂SO₄ solution, the reactions at the cathode are:



Since the diffusion process at the liquid/liquid interface determines the performance of the membraneless fuel cell, the two key parameters are the Reynolds number:

$$Re = \frac{UH}{\nu} \quad (5)$$

and the Peclet number:

$$Pe = \frac{UH}{D_{\text{H}^+}} \quad (6)$$

where U is the mean flow velocity in the reaction channel, H is the channel height, ν is the kinematic viscosity of the fuel/oxidant liquids. For simplification, we assume for an operation temperature of 25 °C a kinematic viscosity of water $\nu = 0.871 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ for both fuel and oxidant liquids and a diffusion coefficient of proton $D_{\text{H}^+} = 9.31 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$. With the known volumetric flow rate and channel cross section of 1 mm², the Reynolds numbers and the Peclet numbers can be estimated with the above properties.

First, the electrochemical performance of the laminar-flow-based membraneless fuel cell was evaluated. The open circuit potential (OCP) and current-potential curves as a

function of the volumetric flow rate of the fuel and the oxidant streams were measured by Solartron Electrochemical Analyser (Model 1287, UK). The flow rates of fuel and oxidant are kept at a fixed ratio of 1:1. The fuel consists of 0.5 M formic acid in 0.1 M H₂SO₄. Two types of oxidant compositions are used to study the effect of mass transfer on the fuel cell performance. The first oxidant includes O₂ saturated 0.1 M H₂SO₄. The second oxidant is 0.01 M H₂O₂ in 0.1 M H₂SO₄. A syringe pump (KD Scientific, Model 200) was employed to precisely supply the fuel and oxidant streams into the fuel cell channel. The flow rates in our experiments range from 0.2 to 1.6 ml min⁻¹. The fuel cell was operated at the room temperature of 25 °C. Before the testing process, the formic acid solution was degassed with N₂ for 30 min and oxygen was bubbled into sulfuric acid for more than 2 h to saturate oxygen in the sulfuric acid solution.

3. Results and discussions

The PMMA based membraneless fuel cell was first tested with 0.5 M HCOOH in 0.1 M H₂SO₄ as fuel and O₂ saturated in 0.01 M H₂SO₄ as oxidant to understand its functionality. Figure 3(a) shows the effect of the volumetric flow rate of the fuel and oxidant streams on the fuel cell polarization. The cell polarization curves were measured over a broad range of volumetric flow rate from 0.4 to 1.6 ml min⁻¹. The current densities and power densities were evaluated based on the real geometric area of the electrodes. When the volumetric flow rate was lower than 0.4 ml min⁻¹ ($Re = 7.65$, $Pe = 716$), the open circuit potential was close to zero so that no power was generated. At this low flow rate, molecular diffusion dominates over convection. Thus, severe fuel crossover phenomenon occurred at the liquid–liquid interface. Our experimental results agree well with the numerical prediction reported by Chen *et al* [25]. The upper limit of 1.6 ml min⁻¹ ($Re = 30.6$, $Pe = 2860$) is determined by the transition to instability. Above this critical point, the flow is not stable due to the dominant convective flow at high Reynolds number. The solubility of oxygen in the water-based electrolyte at room temperature is as low as around 0.5 mM [15]. Thus, obvious limiting current densities were observed from the polarization curves due to the insufficient supply of oxygen from the oxidant stream to the cathode. The limiting current density increased with the increase of the volumetric flow rate. An increment in limiting current density of 0.2 mA cm⁻² was achieved, when the volumetric flow rate increased from 0.4 to 0.6 ml min⁻¹. The increment was significantly reduced to 0.05 mA cm⁻² when volumetric flow rate increased from 1.4 to 1.6 ml min⁻¹.

From the polarization curves, the output power densities of the membraneless fuel cell at various volumetric flow rates are depicted in figure 3(b). The higher the volumetric flow rate, the faster the cathode depletion zone is filled with fresh oxygen contained liquid so that higher current can be drawn from the fuel cell. As a result, in the volumetric flow rate range of 0.4–0.6 ml min⁻¹ or the Reynolds number range of 7.65–30.6, the maximum power densities are obviously improved with increasing the flow rate. Once the supply of the oxygen into the cathode electrode cannot maintain the reaction, a limiting current would be observed. Thus, as shown in figure 3(c), the

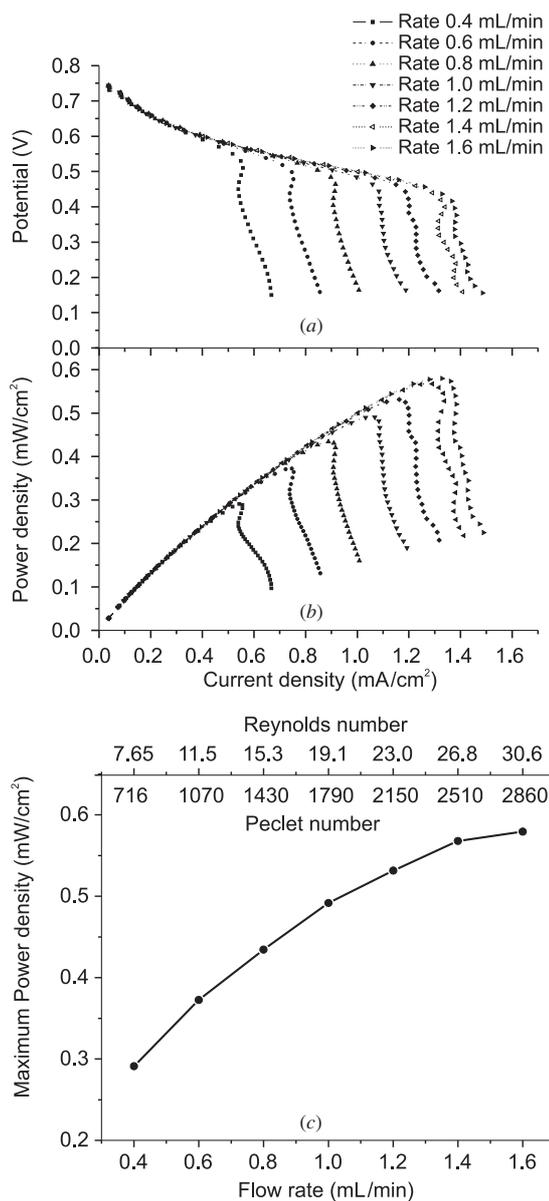


Figure 3. The performance of the PMMA-based membraneless fuel cell with different flow rates: (a) I - V curves; (b) power density curves; (c) the maximum power density versus the flow rate. The fuel stream is 0.5 M formic acid in 0.1 M H₂SO₄ and the oxidant stream is 0.01 M H₂SO₄ saturated with oxygen.

maximum power density increment of 81.2 $\mu\text{W cm}^{-2}$ with an increase of flow rate from 0.4 ml min⁻¹ to 0.6 ml min⁻¹ reduces to 11.5 $\mu\text{W cm}^{-2}$ with an increase of flow rate from 1.4 ml min⁻¹ to 1.6 ml min⁻¹. The periodic fluctuation observed on the polarization curves at high volumetric flow rate of 1.4 ml min⁻¹ and 1.6 ml min⁻¹ could be caused by the stepping motion of the syringe pump.

Under the current cell geometry and operating conditions, there are two challenges in the development of a high-performance membraneless fuel cell. The first challenge is the low performance of the fuel cell due to the mass transport limitation of saturated oxygen on the cathode side. The second challenge is the very low fuel utilization. For the first time, hydrogen peroxide in sulfuric acid was used as the oxidant in

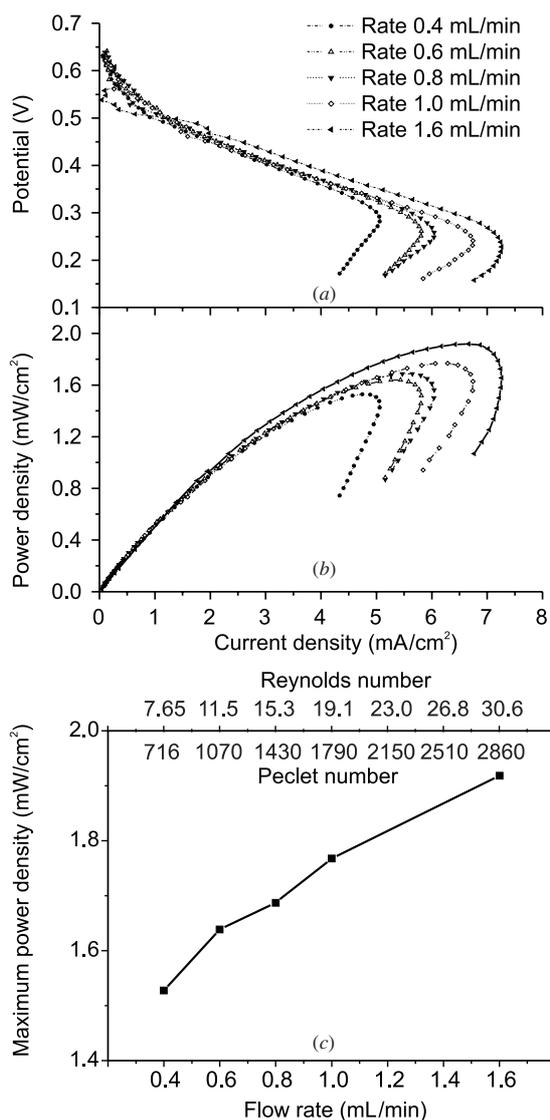


Figure 4. The performance of the PMMA-based membraneless fuel cell with different flow rates: (a) I - V curves; (b) power density curves; (c) the maximum power density versus the flow rate. 0.5 M formic acid in 0.01 M H_2SO_4 is fuel and 0.01 M H_2O_2 in 0.01 M H_2SO_4 is oxidant.

the membraneless fuel cell. The use of the hydrogen peroxide provides much higher oxidant content than oxygen saturated sulfuric acid and makes it possible to recycle the fuel. Figure 5 illustrates the performance of the fuel cell with different volumetric flow rate using 0.01 M H_2O_2 in 0.01 M H_2SO_4 as the oxidant. The fuel cell can operate stably in the volumetric flow rate range of 0.4 ml min^{-1} to 1.6 ml min^{-1} . Similar to the results presented in figure 3(a), the current density is enhanced gradually with the increase of the volumetric flow rate as shown in figure 4(a). Compared with oxygen saturated sulfuric acid, it is obvious that the fuel cell with hydrogen peroxide as oxidant could deliver a much higher power density. When the flow rate was 1.6 mL min^{-1} , the maximum power density was as high as 1.92 $mW\ cm^{-2}$, which is comparable with the Y-shaped membraneless fuel cell using 0.144 M potassium permanganate as oxidant and 2.1 M formic acid as fuel [15]. However, as can be seen in polarization curves shown in

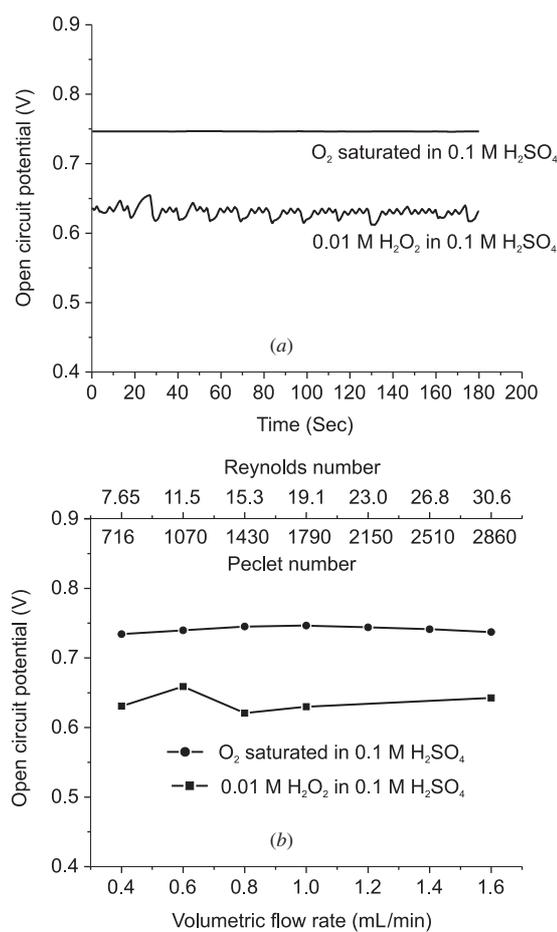


Figure 5. (a) The open circuit potential with volumetric flow rate 1.0 ml min^{-1} ; (b) open circuit potential as a function of the volumetric flow rate.

figure 4(a), the fluctuation at low current density becomes obvious at high volumetric flow rates. This phenomenon could be caused by the generation of oxygen bubbles during the decomposing process of H_2O_2 at the cathode surface, which disturb the laminar streams under the high flow rate condition. Output power densities of the membraneless fuel cell with H_2O_2 -based oxidant are summarized in figures 4(b) and (c).

Figure 5(a) shows the stability of the open circuit potential (OCP) in $HCOOH/O_2$ and $HCOOH/H_2O_2$ membraneless fuel cell systems. The data were evaluated at a total volumetric flow rate of 1.0 ml min^{-1} of both fuel and oxidant streams. While the OCP of the $HCOOH/O_2$ system is very stable during the testing experiments, the OCP of $HCOOH/H_2O_2$ system fluctuates. This phenomenon may be caused by the chemical decomposition of H_2O_2 to gaseous O_2 on the cathode catalyst surface. The oxygen bubbles disturb the laminar flow and subsequently lead to the fluctuation of OCP. Furthermore, it is apparent that the OCPs of both $HCOOH/O_2$ and $HCOOH/H_2O_2$ systems are much lower than their thermodynamic values. That means, the reaction kinetics of $HCOOH$ on the anode catalyst surface is a slow process. Under the open circuit condition, the equilibrium state of the $HCOOH$ reaction is not established on the catalyst surface. Figure 5(b) shows the mean OCP values of $HCOOH/O_2$ -based and $HCOOH/H_2O_2$ -based membraneless fuel cell systems as

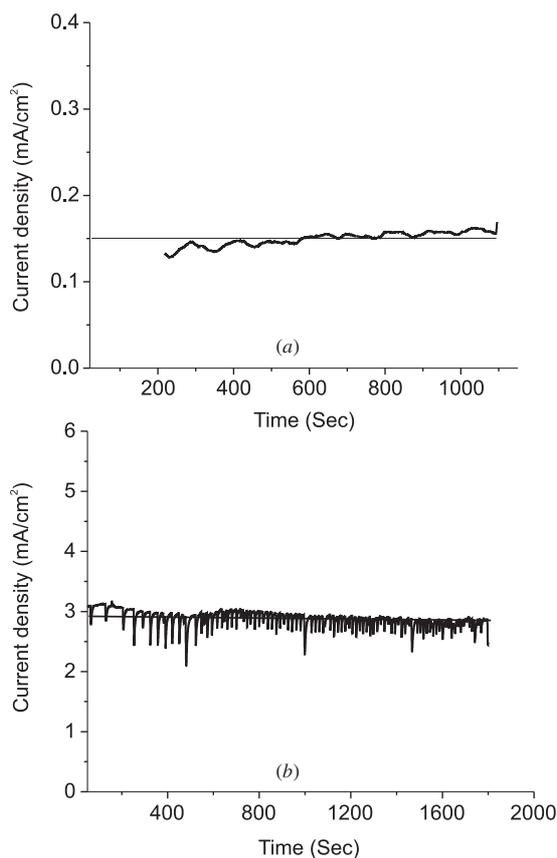


Figure 6. Stability of the membraneless fuel cell operating at a voltage of 0.4 V with flow rate 1.0 mL min^{-1} using (a) O_2 saturated in sulfuric acid as oxidant; (b) H_2O_2 in sulfuric acid as oxidant.

a function of volumetric flow rates. The OCP values are almost independent of the volumetric flow rate. The fluctuation of the OCP values at various volumetric flow rates is more obvious in the $\text{HCOOH}/\text{H}_2\text{O}_2$ system than that in the HCOOH/O_2 system. This phenomenon can be explained by the disturbance of oxygen bubbles on the cathode's catalyst surface. Figure 6 shows the stability of the PMMA based membraneless fuel cell under polarization condition. With the exception of some fluctuations of the output current, the fuel cell can operate stably in both HCOOH/O_2 and $\text{HCOOH}/\text{H}_2\text{O}_2$ systems during the testing period.

4. Conclusions

In this paper, we designed, fabricated and tested a novel membraneless fuel cell based on polymeric micromachining. A fully PMMA-based membraneless fuel cell was fabricated using CO_2 laser micromachining. The fuel cell electrodes were fabricated by wet-spraying the catalyst inks onto the top and bottom gold-coated PMMA substrates. The middle PMMA layer forms the reaction microchannel. The two laminar streams containing fuel and oxidant are kept separated in this microchannel but remain in diffusional contact. The electrochemical performance of the membraneless fuel cell was characterized using formic acid (HCOOH) as fuel and saturated O_2 as well as H_2O_2 as oxidant. The results demonstrated that the developed membraneless fuel cell can

stably operate in a wide range of volumetric flow rates of fuel and oxidant. In the Reynolds number range of 7.65–30.6, the higher the volumetric flow rate, the higher the maximum power density. Beyond this range, the fuel cell cannot operate stably due to fuel cross-over at low flow rates ($Re < 7.65$) and instability at high flow rates ($Re > 30.6$) of the fuel and oxidant streams. The optimal operation flow rate should be a trade-off between dominant convection and stable flow. The poor solubility of O_2 in the water-based electrolyte at room temperature limits the power output. H_2O_2 dissolved in H_2SO_4 was employed to improve the mass-transfer of the oxidant on the cathode side, thus significantly enhancing the electrochemical performance of the membraneless fuel cell. The maximum power density can reach 1.98 mW cm^{-2} in $0.5 \text{ M HCOOH}+0.1 \text{ M H}_2\text{SO}_4/0.01 \text{ M H}_2\text{O}_2+0.1 \text{ M H}_2\text{SO}_4$ system, which is more than three times of 0.58 mW cm^{-2} in $0.5 \text{ M HCOOH}+0.1 \text{ M H}_2\text{SO}_4/\text{saturated O}_2+0.1 \text{ M H}_2\text{SO}_4$ system at a volumetric flow rate of 1.6 mL min^{-1} .

References

- [1] Nguyen N T and Chan S H 2006 Micromachined polymer electrolyte membrane and direct methanol fuel cells—a review *J. Micromech. Microeng.* **16** R1–R12
- [2] Yu J *et al* 2003 Fabrication of miniature silicon wafer fuel cells with improved performance *J. Power Sources* **124** 40–6
- [3] Lee S J *et al* 2002 Design and fabrication of a micro fuel cell array with 'flip-flop' interconnection *J. Power Sources* **112** 410–8
- [4] Motokawa S *et al* 2004 MEMS-based design and fabrication of a new concept micro direct methanol fuel cell (μ -DMFC) *Electrochem. Commun.* **6** 562–5
- [5] Yeom J *et al* 2006 Passive direct formic acid microfabricated fuel cells *J. Power Sources* **160** 1058–64
- [6] Nguyen N T *et al* 2004 Micro check valves for integration into polymeric microfluidic devices *J. Micromech. Microeng.* **14** 69–75
- [7] Truong T Q and Nguyen N T 2004 A polymeric piezoelectric micropump based on lamination technology *J. Micromech. Microeng.* **14** 632–8
- [8] Chan S H *et al* 2005 Development of a polymeric micro fuel cell containing laser-micromachined flow channels *J. Micromech. Microeng.* **15** 231–6
- [9] Scott K *et al* 1999 The impact of mass transport and methanol crossover on the direct methanol fuel cell *J. Power Sources* **83** 204–16
- [10] Ren X M *et al* 2000 Recent advances in direct methanol fuel cells at Los Alamos National Laboratory *J. Power Sources* **86** 111–6
- [11] Mano N, Mao F and Heller A 2003 Characteristics of a miniature compartment-less glucose- O_2 biofuel cell and its operation in a living plant *J. Am. Chem. Soc.* **125** 6588–94
- [12] Mano N, Mao F and Heller A 2002 A miniature biofuel cell operating in a physiological buffer *J. Am. Chem. Soc.* **124** 12962–63
- [13] Ferrigno R *et al* 2002 Membraneless vanadium redox fuel cell using laminar flow *J. Am. Chem. Soc.* **124** 12930–31
- [14] Wu Z G and Nguyen N T 2004 Convective-diffusive transport in parallel lamination micromixers *Microfluidics Nanofluidics* **1** 208–17
- [15] Chohan E R *et al* 2004 Microfluidic fuel cell based on laminar flow *J. Power Sources* **128** 54–60
- [16] Chohan E R *et al* 2005 Membraneless laminar flow-based micro fuel cells operating in alkaline, acidic, and acidic/alkaline media *Electrochim. Acta* **50** 5390–8
- [17] Chohan E R *et al* 2005 Characterization of limiting factor in laminar flow-based membraneless microfuel cells *Electrochem. Solid-State Lett.* **8** A348–52

- [18] Cohen J L *et al* 2005 Fabrication and preliminary testing of a planar membraneless microchannel fuel cell *J. Power Sources* **139** 96–105
- [19] Cohen J L *et al* 2005 A dual electrolyte H₂/O₂ planar membraneless microchannel fuel cell system with open circuit potentials in excess of 1.4 V *Langmuir* **21** 3544–50
- [20] Jayashree R S *et al* 2005 Air-breathing laminar flow-based microfluidic fuel cell *J. Am. Chem. Soc.* **127** 16758–9
- [21] Jayashree R S *et al* 2006 Air-breathing laminar flow-based direct methanol fuel cell with alkaline electrolyte *Electrochem. Solid-State Lett.* **9** A252–56
- [22] Dyer C K 2002 Fuel cells for portable application *J. Power Sources* **106** 31–4
- [23] Nguyen N T and Truong T Q 2004 A fully polymeric micropump with piezoelectric actuator *Sensors Actuators B* **97** 137–43
- [24] Yang W 2006 Nanostructured silver catalyzed nickel foam cathode for an aluminum-hydrogen peroxide fuel cell *J. Power Sources* **160** 1420–4
- [25] Chen F *et al* 2007 Analysis of membraneless formic acid microfuel cell using a planar microchannel *Electrochim. Acta* **52** 2506–14