

Article

A Numerical Study of Bubble Blockage in Microfluidic Fuel Cells

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Abstract: Based on fuel crossover behavior and bubble nucleation in the microfluidic fuel cell's channel, this research numerically presents the performance of air-breathing direct formic acid microfluidic fuel cells. In the simulation, a three-dimensional microfluidic fuel cell model was used. The continuity, momentum, species transport, and charge equations were used to develop the model transport behavior, whereas the Brinkman equation represented the porous medium flow in the gas diffusion layer. The I–V and power density curves are generated using the Butler–Volmer equation. The simulation and current experimental data were compared under identical operating conditions to validate the I–V curve of the microfluidic fuel cell model. The model was used to investigate the current density distribution in the microchannel due to bubble obstruction and the reactant concentration on both electrodes. Fuel crossover resulted in a large decrease in open-circuit voltage and a reduction in fuel concentration above the anode electrode. The findings also showed that a low-flow rate air-breathing direct formic acid microfluidic fuel cell is more prone to CO₂ bubble formation.

Keywords: air-breathing microfluidic fuel cells; formic acid; fuel crossover; bubble blockage



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1. Introduction

Over the past decade, the miniaturization of fuel cell architecture to minimize over-voltage losses has been studied by many researchers. The concept of microfluidic fuel cells (MFC) is thus proposed, which can be characterized by four major components [1]: aqueous fuel; oxidant; catalyst/electrode materials; and supporting electrolyte flow. In other studies, the MFC configuration is classified into three generations (Jayashree et al., [2], and Ho et al., [3]). The first-generation cells named MFCs-G1 comprise Y-shaped MFCs, which have an aqueous fuel stream and oxidant stream at the anode and cathode channel inlets, respectively, that flow in parallel along the microchannel, with the anode and cathode electrodes running along the opposite side of the wall. Second-generation cells [4–7] called MFCs-G2 have two parallel streams of fuel and oxidants flow horizontally side by side in a Y- or T-shaped channel, interfacing the cathode and porous anode electrode placed on the bottom side of the microchannel. Third-generation cells [8–12] are called MFCs-G3, which are similar to the second-generation cells. These cells utilize a T- or F-shaped microchannel, but with the additional air-breathing mechanism at the cathode electrode inlet that drives the movement of the oxidant.

The evaluation of fuel crossover and internal current loss through the electrolyte of the microfluidic fuel cell is very important to assess the performance of the direct formic acid microfluidic fuel cell due to their potential effects in reducing the performance of the fuel cell. Schoemaker et al. [13] and Rejal et al. [14] reported that the design of the microchannel of the direct formic acid fuel cells could be optimized by including electrodes of the catalyst to decrease losses in the fuel cells such as fuel crossover, internal current loss, and ohmic losses across the electrolyte within the microchannel.

The assessment of bubble formation, and its influence on the performance of microfluidic fuel cells, was proposed by Shyu et al. [15]. The study showed the major disadvantages of bubble formation, including a high concentration of fuels caused by the removal of reaction products and CO₂ bubbles, which becomes difficult as the flow rate decreases. The generation of gas bubbles in a microfluidic fuel cell enhances the mixing of the parallel liquid streams along the upstream to the downstream in the microchannel, affecting the exchanging current and leading to a decrease in the open-circuit voltage [16–18]. To prevent the growth of CO₂ gas bubbles in the microfluidic fuel cells, the accuracy in the fabrication of electrode conditions with appropriate selection of the aqueous reactants and the various architecture configurations of microfluidic fuel cells should be considered [19,20].

Although the gas bubble generation, growth, and detachment on the surface of one of the electrodes in the MFCs have been confirmed and the resulting effects on the electricity generation of the MFCs have also been discussed in a related experimental study, very few numerical studies to analyze the influence of gas/liquid two-phase flow on the MFC characteristics have been reported. This is due to the fact that two-phase computational model coupling hydrodynamics, mass transport, and electrochemical reaction kinetics are so complex that the transient, three-dimensional, two-phase numerical investigation on the characteristics of the MFCs could either hardly be achieved or take a long computation time. Peng et al. [21] and Wei et al. [22] formulated the flow and mass transport in the catalyst layer in two-phase, and discussed the effect of gas volume fraction on the cell performances. However, the fluid flow along the microchannel was still assumed to be single-phase in both studies, deviated from the physical reality. Wang et al. [23] developed a mixture of two-phase computational modelling of MFCs with a flow-through porous anode to investigate the effect of CO₂ volume fraction on cell performance. Due to the complex nature of the numerical model, a two-phase numerical simulation of an air-breathing MFC with a flow-over anode was performed in a steady, two-dimensional flow by Ouyang et al. [24]. Based on the above-mentioned experiments and simulations, bubble formation has an impact on cell performance.

Therefore, in order to examine the gas bubble effect on the fuel crossover and the performance of the air-breathing direct formic acid microfluidic fuel cells with flow-over electrodes using a steady, three-dimensional computational model, static, blunt objects of different dimensions stayed in the microchannel of the MFCs will be used to imitate the bubble formation at different moments in time. Both fuel crossover and fuel cell performance of the MFCs with a different bubble position and dimensions will be numerically investigated in this study.

2. Numerical Method

2.1. Computational Domain

The air-breathing direct formic acid microfluidic fuel cell (DFAMFC) with a 1.5-mm-wide and 0.05-mm-deep T-shape microchannel was numerically studied at volumetric flow rates ranging from 0.05 to 0.5 mL/min. The structural model of the miniaturized DFAMFC with a T-shaped microchannel and an air-breathing cathode is depicted in Figure 1. All the boundaries of the model in Figure 1 are solid walls except the inlets and outlet. The fuel and supporting electrolyte are fed through two individual inlets and both are discharged through a single outlet as shown in Figure 1a, while the oxygen is supplied from the bottom face of the CGDL at a given concentration indicated in Figure 1b. The spacing between two 20-mm-long, 0.6-mm-wide, and 0.9-mm-thick GDEs in a fuel cell was 0.3 mm. The mixture

of formic acid and 0.5-M H_2SO_4 was used as the fuel, during a 0.5-M H_2SO_4 stream as a liquid electrolyte. The concentration of formic acid was 0.3 M, 0.5 M and 1.0 M.

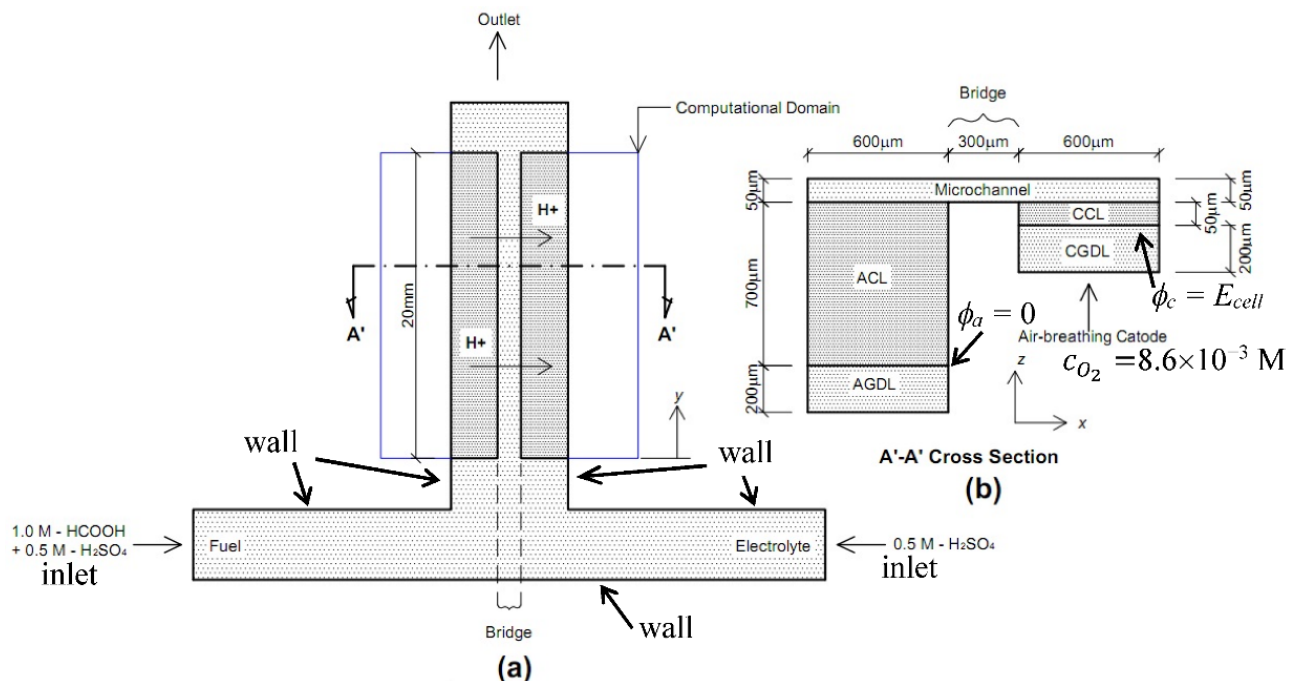


Figure 1. Schematic illustration of the computational domain and geometrical structure of the T-shaped air-breathing DFAMFC model: (a) the top view; (b) the sectional view.

While sufficient oxygen supply from the air is chosen as an oxidant, the electrolyte solution was added to both fuel and cathode electrolyte to allow better proton conductivity during the electrochemical kinetic reactions. The anode and cathode porous electrodes are placed on the bottom of the microchannel. The interface between the anolyte (fuel solution) and catholyte (electrolyte solution) allow the produced protons at the anode side to transfer from the anolyte to the cathode electrode. For breathing air as the oxidant, the bottom surface of the cathode gas diffusion layer (CGDL) is exposed to the ambient air, and oxygen penetrates into the porous electrode from that surface, making the reduction reaction happen within the cathode catalyst layer (CCL), as illustrated in Figure 1b. The bottom surfaces of the anode and cathode electrodes are electrical ground and electrical potential, respectively.

2.2. Assumptions

Numerical simulations of the microfluidic fuel cells performed with the computational domain, as presented in Figure 1 were based on a 3-dimensional model implemented by the commercially available software, COMSOL Multiphysics 5.1. The three-dimensional numerical simulation model was performed based on the following assumptions:

- (1) The fluid flow in the microfluidic fuel cells is steady, isothermal, laminar and incompressible with negligible body forces;
- (2) The physical properties of the electrodes (catalyst layers and GDLs) are considered isotropic and homogeneous;
- (3) The solutions are dilute and uniformly mixed;
- (4) Proton transport from the anode to the cathode is by electro-migration only;
- (5) Oxygen transport in the porous air-breathing cathode is by diffusion only;
- (6) Electromigration of formate ions is neglected due to the high concentration of supporting electrolyte;
- (7) Electrochemical reaction takes place at 300 K, 1 atm, which is governed by Butler–Volmer kinetics to get the V - I and P - I curves.

2.3. Governing Equations

Three-dimensional, single-phase numerical simulations have been regarded as effective ways to explore the cell characteristics [25–30], while a few numerical studies have been proposed to investigate the performance of fuel cells without a polymer membrane [9,31,32]. In order to predict the effect of polarization behaviors of the transport phenomena on MFC performance, the numerical model and the governing equations are constructed in three-dimensional Cartesian coordinates according to the formulation similar to those indicated in [31,32]. A set of steady-state conservation equations is used to govern the continuity, momentum, and species transport equations, as well as the electrochemical reaction kinetics, in the free channel and porous media of the MFCs, as follows:

Continuity equation:

$$(\nabla \cdot \vec{u}) = 0 \quad (1)$$

Momentum equation:

$$\rho(\vec{u} \cdot \nabla \vec{u}) = -\nabla p + \mu \nabla^2 \vec{u} \quad (2)$$

Porous media flow equation:

$$\frac{\rho}{\varepsilon^2}(\vec{u} \cdot \nabla \vec{u}) = -\nabla p + \frac{\mu}{\varepsilon} \nabla^2 \vec{u} - \frac{2}{3} \frac{\mu}{\varepsilon} \nabla^2 \vec{u} - \frac{\mu}{k} \vec{u} \quad (3)$$

Species transport equation:

$$\nabla \cdot (-D \nabla c + c \vec{u}) = 0 \quad (4)$$

Charge equation in the electrode:

$$\nabla \cdot \nabla \varphi_s = 0 \quad (5)$$

Charge equation in the electrolyte:

$$\nabla \cdot \nabla \varphi_l = 0 \quad (6)$$

where $\vec{u}$ is the velocity vector, ρ is the fluid density, μ is the fluid viscosity, p is the static pressure, ε is the porosity of the media, k is the permeability of the electrodes (catalyst layers and gas diffusion layers/porous electrodes), c is the local concentration of the species in the anode and cathode, D is the diffusion coefficient of the species, which refers to the formic acid diffusivity in aqueous media (water and electrolyte) in the anode and the oxygen diffusivity through the porous electrodes in the cathode, φ_s is the overpotential in the catalyst layer, and φ_l is the electrolyte over potential. Please refer to the publication [32] for more detailed information regarding the governing equations of the air-breathing DFAMFCs.

2.4. Boundary Conditions

In this study, there are two types of boundary conditions used in microfluidic fuel cells, i.e., hydrodynamic boundary conditions and species transport boundary conditions [32]. The three-dimensional numerical simulation was performed based on the following boundary conditions for hydrodynamic, species, and charge transport in the present model:

- Both the velocity and concentration of the fluid at both fuel and electrolyte inlets are given as shown in Figure 1a;
- No-slip boundary condition is set for all the walls of the MFCs as indicated in Figure 1a;

- c. All the walls of the MFCs are impermeable and insulating, except the bottom face of the CGDL in Figure 1b where the oxygen can diffuse into the porous face with a given concentration of 8.6×10^{-3} M;
- d. For the transport of the dilute species domain, the diffusion and convection flux conditions are applied through the outflow boundary conditions. Hence, this boundary condition vanishes the velocity and concentration gradients in the fluid flow direction at the outlet, as indicated in Figure 1;
- e. To calculate the electric field, the ground potential is set for the anode. The cathodic voltage is set as a variable, cell voltage E . Therefore, the anode voltage is set as $\phi_a = 0$ on the bottom surface of the ACL in Figure 1b, and the cathode voltage is set as $\phi_c = E_{cell}$ on the bottom surface of the CCL in Figure 1b

2.5. Parameter Constants

The performance of MFCs can be predicted by solving Equations (1)–(4) applied in both free channel and porous medium regions. The transport properties and simulation parameter conditions used in the three-dimensional computational model for the microfluidic fuel cells are adopted from [31] and listed in Table 1.

Table 1. The physical/transport properties used in the model for numerical simulation.

Parameters	Symbol	Values
Electrode properties:		
Porosity and permeability of catalyst layer	ε, κ	0.3 and $2.36 \times 10^{-14} \text{ m}^2$
Porosity and permeability of gas diffusion layer	ε, κ	0.4 and $1.18 \times 10^{-12} \text{ m}^2$
The conductivity of the electrode, S/m	σ_s	222
The conductivity of the electrolyte, S/m	σ_l	16.7
Fluid properties:		
The density of anolyte and catholyte stream, kg/m ³	ρ	1000
Dynamic viscosity, Pa·s	μ	0.001
Volumetric flow rate (Q_1, Q_2, Q_3), mL/min	v	0.05, 0.1, 0.5
Reference concentration of formic acid, mol/m ³	c_0, HCOOH	300, 500, 1000
Reference concentration of oxygen, mol/m ³	c_0, O_2	85
Diffusivity of formic acid as anolyte, m ² /s	D_{HCOOH}	2.546×10^{-9}
Diffusivity of oxygen in water, m ² /s	$D_{\text{O}_2(\text{H}_2\text{O})}$	2.1×10^{-9}
Diffusivity of oxygen in the air, m ² /s	$D_{\text{O}_2(\text{air})}$	2.1×10^{-5}
Anodic and cathodic kinetic reactions:		
Exchange current density at the anode, A/m ²	i_{0a}	2250
Exchange current density at the cathode, A/m ²	i_{0c}	6×10^{-4}
Anodic and cathodic charge transfer coefficient	α	0.5
Number of transferred electrons at the anode and cathode	n	2

2.6. Mesh of the Microfluidic Fuel Cell Model

The mesh in the microfluidic fuel cell model was built with a fine mesh size to ensure that the solution is proper, accurate, and independent of the mesh size, as shown in Figure 2. The maximum element size in the subdomains outside the electrodes was set to be 0.421 mm and the maximum element growth rate was set to be 1.25. A total of 78,551 unstructured, tetrahedral elements were established to discretize the entire computational domain of the air-breathing direct formic acid microfluidic fuel cells (DFAMFCs). Those partial differential equations listed in Section 2.3 were solved using a finite element method.

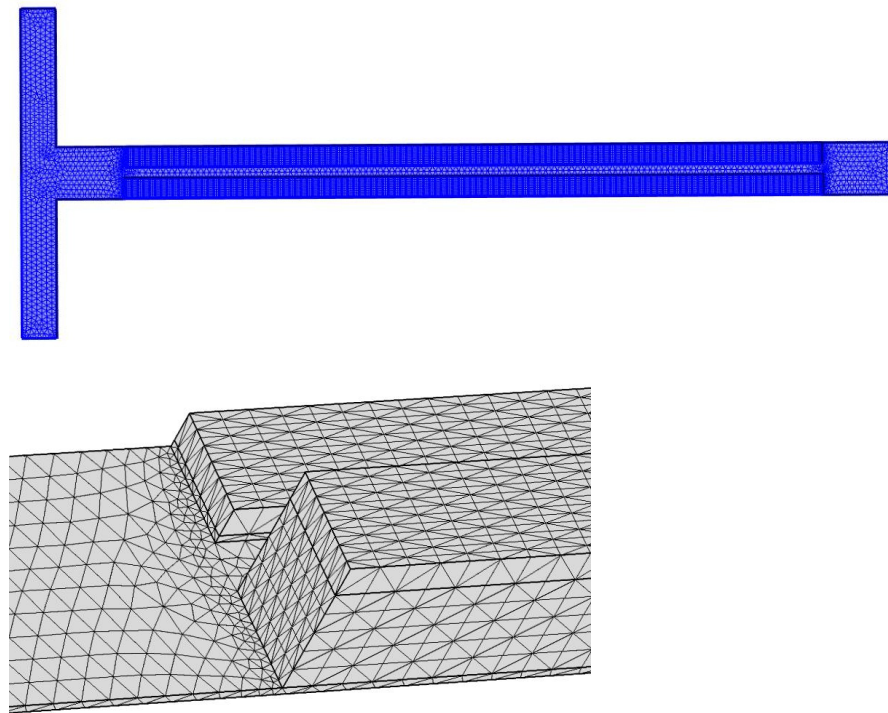


Figure 2. The mesh of the microfluidic fuel cell model.

In general, a greater number of grids in the computational domain generates more accurate simulation results at the expense of longer computation time. The number of grids in the present air-breathing DFAMFCs was determined to be 78,551 as the simulated *I-V* curve based on such element numbers was in good agreement with the *I-V* curve measured by Shyu et al. [15]. The comparison will be discussed later. The model was solved on a 64-bit Windows 7 Enterprise Service Pack 1, with an Intel (R) Core TM i7-4790 CPU @ 3.60 GHz, 20 GB RAM. Peak memory usage when running on the computation was observed to be approximately 6 GB and it took approximately 2 h to plot an entire polarization curve with 29 cell voltages for one case.

A parametric sweep and a direct solution procedure with a stationary segregated Parallel Sparse Direct Solver (PARDISO) were used to solve the velocity field and pressure in the air-breathing DFAMFCs, while a Multifrontal Massively Parallel Solver (MUMPS) was used to solve the concentration field and electric potential of the air-breathing DFAMFCs. Once those parameters were solved, the current densities at different cell voltages can be determined with the convergence criteria of the residual of 10^{-4} .

3. Results and Discussion

3.1. COMSOL Model Validation

Numerical models of T-shape air-breathing DFAMFCs were built with the same dimensions and operating conditions as the one used by Shyu et al. [15]. The polarization curve obtained by the numerical simulation of the present model was in good agreement with the measured polarization curve, with 1.0-M HCOOH at 0.5 mL/min [15], as shown in Figure 3. However, slight deviations between both curves in Figure 3 were observed at cell voltages of approximately 0.7 V and 0.05 V. The slight deviation at high cell voltage can be reduced by fine-tuning the electrode properties listed in Table 1, while the deviation occurring at a low cell voltage is likely as in reality the impact of the growing gas bubbles in the DFAMFCs on the cell performance cannot be properly presented in the single-phase numerical simulation in the present study. This confirms the reliability and effectiveness of the model. Several parameters for the studies such as proton conductivity, exchange current density, and the oxygen concentration on the CGDL face was maintained as constants, while the volumetric flow rate and the fuel concentration are conditional parameters whose

values are changeable. Furthermore, the model was being used to analyze polarization behavior on the electrode and the cell performance under various conditions.

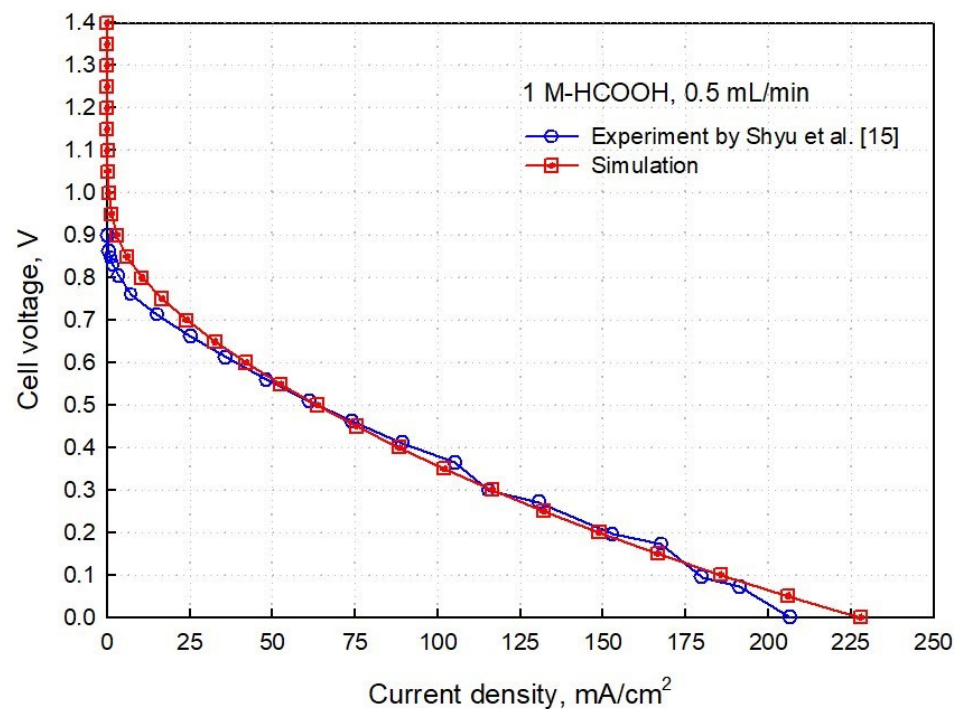


Figure 3. Performance of I - V curve comparison between the experimental data (Shyu et al., 2015) [15] vs. simulation (1.0 M-HCOOH, 0.5 mL/min).

This case indicates that even though a stronger volumetric flow rate can enhance the transport of fuel to the anode electrode, this influence alleviates gradually, and the concentration loss occurs lastly as a result of the inadequate transport of oxygen from the ambient air into the gas diffusion layer to the cathode electrode surface. In general, a stronger volumetric flow rate and concentration will increase the cell performance, including the cell current density and the cell power density.

3.2. Effect of Bubble Blockage

The CO₂ bubble evolution and development on the anode surface was recorded on the flow in the microfluidic fuel cell experiment [15] operated with 1.0 M-HCOOH at a volumetric flow rate of 0.5 mL/min. The bubble formation process [15] indicated that the nucleus gas bubble was firstly generated on the anode surface, and then it moved from the channel sidewall to the center of the anode surface before becoming large and elongated due to the coalescence. Subsequently, the elongated CO₂ bubble grew larger again to become a blockage that occupies the middle of the channel.

However, gas bubbles generated from the oxidation reaction of formic acid at the anode will result in the stagnation of the flow in the microchannel, and are considered unfavorable to the air-breathing DFAMFC performance. Bubble formation within the microchannel can disturb the diffusion process at the interface channel, further causing uncontrolled diffusive mixing of fuel and oxidant streams and cell performance degradation.

Figure 4 illustrates three static, blunt objects of the same size to simulate stationary bubbles presented in the microchannel. The bubble width of 0.2, 0.4, 0.6, and 0.8 mm, as illustrated in Figure 4b–e, will be numerically investigated in the following sections to realize the bubble blockage effect on the cell performance.

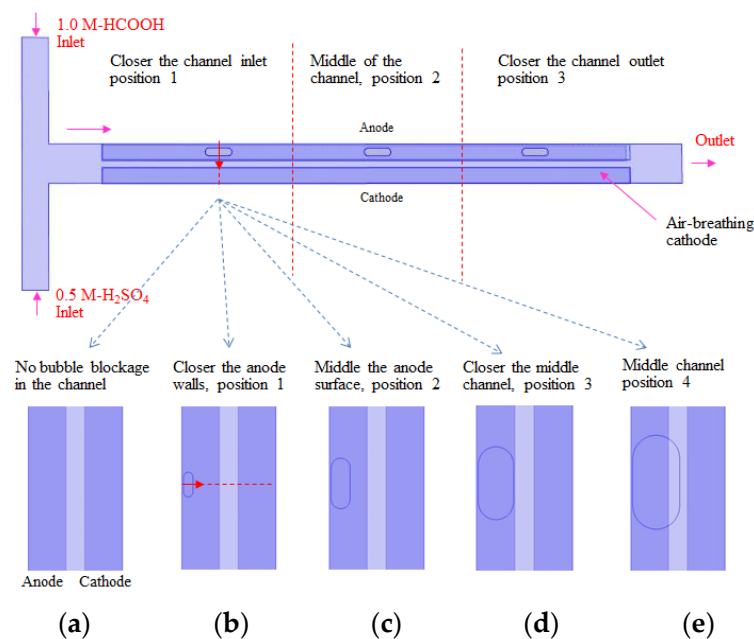


Figure 4. Distribution of bubble blockage starting from the anode walls to the middle of the channel at four specific positions of width coordinates of the channel: (a) no bubble; and bubble width of (b) 0.2 mm; (c) 0.4 mm; (d) 0.6 mm and; (e) 0.8 mm.

3.3. Effect of Fuel Crossover

The occurrence when fuel passes through the electrolyte to the cathode electrode without reacting on the anode, producing no current from the cell, is known as fuel crossover. Each formic acid molecule that diffuses and reacts with oxygen on the cathode of the fuel cell results in two fewer electrons in the generated current of electrons that travels through an external circuit. In this study, the fuel can diffuse through the fuel–electrolyte interface, reach the cathode, and then decrease the cell performance.

Figure 5 shows that the total crossover current on the cathode, defined as the integral value of the local crossover current over the entire width of the cathode, increases as the static, blunt object (bubble) width increases from 0.2 mm to 0.8 mm at a volumetric flow rate of 0.5 mL/min with inlet $[\text{HCOOH}] = 1.0 \text{ M}$. Note that the channel width aligns with the x -axis and the origin is set at the left sidewall of the microchannel in Figure 1b. Besides, Figure 5 also shows that the bigger the static blunt object is, the farther the wider area the crossover current generates over the cathode surface. The electro-oxidation of HCOOH over the cathode reduces the open-circuit voltage and results in a mixed voltage. The present simulation results reveal that the major reason for the drop of the open-circuit voltage from 0.95 V at 0.5 mL/min to 0.75 V at 0.05 mL/min at 1.0 M- HCOOH is due to the mixed voltage and fuel crossover at the cathode.

There are three reasons related to losses in the fuel crossover microfluidic fuel system, i.e.,: (1) the fuel crossover often occurs at low volumetric flow rates and with the reduction in the fuel concentration. Such reduction occurs over the anode where the formic acid fuel diffuses from the anode through the electrolyte to the cathode and then reacts with the oxygen directly due to the catalyst, producing no current from the cell; (2) the concentration of fuel decreases in the anolyte stream resulting in a decrease in the current density along the side surface of the electrode; (3) the electrochemical oxidation reaction at the fuel over the cathode catalyst can produce a mixed potential and reduce the open-circuit voltage. The numerical simulation shows that the major reason for low open-circuit voltage from 0.95 V- Q_1 to 0.75 V- Q_3 is due to the loss of fuel crossover, internal current, and the mixed voltage at the cathode in the microfluidic fuel cells. One method to alleviate fuel crossover is by reducing mass transport using a lower concentration of fuel, which will decrease the driving force for fuel diffusion.

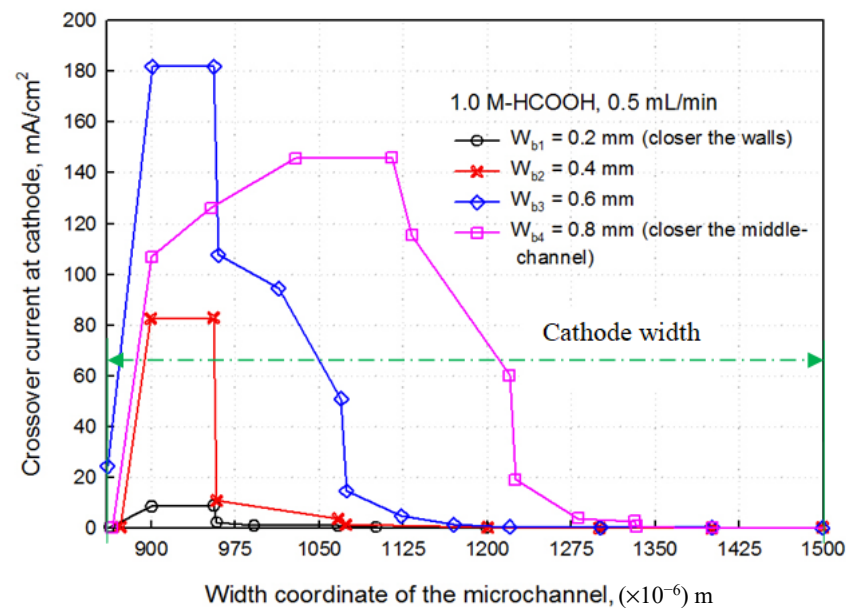


Figure 5. The effect of bubble size on the crossover current at the cathode along the microchannel at four specific positions of width coordinate of the channel using a volumetric flow rate of 0.5 mL/min with inlet [HCOOH] = 1.0 M on the electrode surface along the microchannel.

As previously described, the fuel crossover is considered in the MFCs to obtain the proper electrochemical reaction in the cathode. The results indicate that the effect of fuel crossover at the cathode has a more significant impact on cell performance than fuel crossover at the anode, since the local crossover current in Figure 5 is much higher than that in Figure 6. Furthermore, Figure 6 also shows that the bubble width has an insignificant effect on the anode crossover current. Therefore, the fuel crossover at the anode can be ignored.

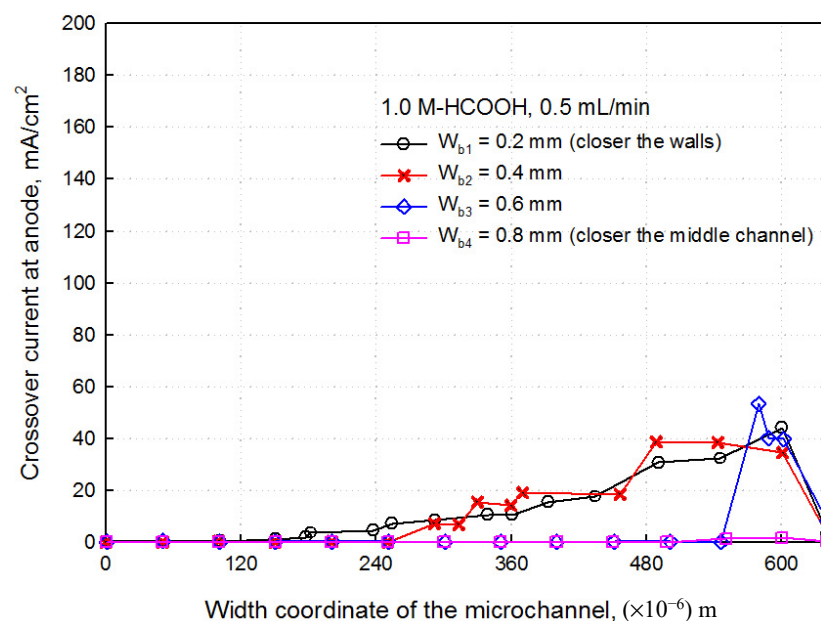


Figure 6. The effect of bubble growth on the crossover current at the anode along the microchannel at four specific positions of width coordinate of the channel using a volumetric flow rate of 0.5 mL/min with inlet [HCOOH] = 1.0 M.

Figure 7 shows the local current density distribution on the anode surface with the different sizes of the blunt object in the channel at a volumetric flow rate of 0.5 mL/min at $[\text{HCOOH}] = 1.0 \text{ M}$. It can be seen that the local current density distribution on the anode is obviously affected by the bubble size. As the blunt object used to simulate the static gas bubble in the microchannel occupies a partial anode surface, it prevents the fuel from reaching the catalyst layer from the top surface of the anode. Therefore, no current is produced on the anode as a 0.8-mm-wide blunt object stays on the 0.6-mm-wide anode. However, even though a 0.6-mm-wide bubble statically stays on the 0.6-mm-wide anode, it generates current over the anode edge between $x = 550 \mu\text{m}$ and $x = 600 \mu\text{m}$. This is likely due to the fuel diffusing laterally into the anode catalyst layer from the edge of the bubble.

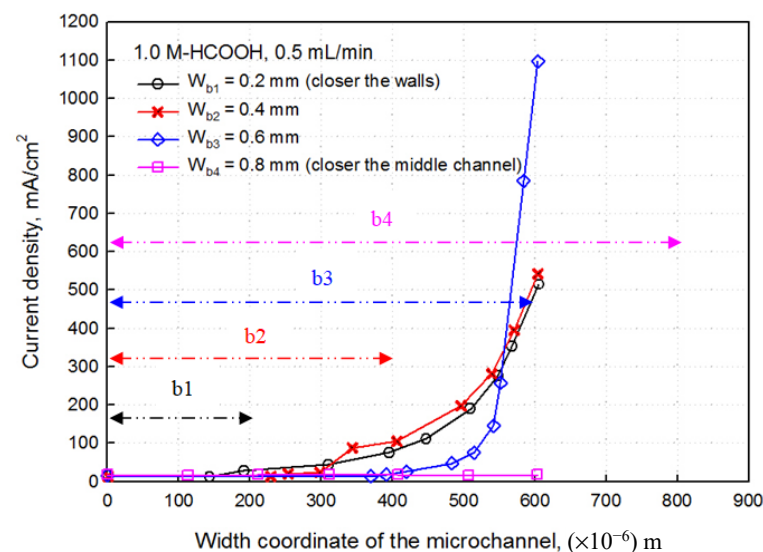


Figure 7. The local current density distribution on the anode surface with four different sizes of blunt object in the channel performed on 0.5 mL/min with inlet 1.0 M-HCOOH.

Initially, the CO_2 bubble has a width of 0.2 mm before becoming a larger elliptic bubble, both in the middle of the anode surface-edge wall having a width of 0.4 mm and 0.6 mm, respectively. Following this, the bubble becomes elongated and fully developed closer to the channel center with a final width of 0.8 mm. The current density is higher at the bubble width distance of approximately 0.6 mm at the edge of the anode surface near the center of the channel. This is due to the greater concentration of fuel consumed on this side compared to the other side. In addition, this result will accelerate the electro-oxidation reaction to produce a larger current density.

The gas bubble evolution indicated in Figure 8a corresponds with the size of the generated CO_2 bubble observed in the experiment [15]. To investigate the performance of the fuel cell with a gas bubble generated in the microchannel, the bubble blockage was placed along the anode surface with different positions in the middle of the electrode and closer to the center of mixing reactants. Figure 8b reveals that the cell performance varies depending on the blockage positions in the microchannel. The cell performance would be higher if the blockage position shifted away from the center of the microchannel toward the anode side. The maximum power densities for the fuel cell operated at a volumetric flow rate of 0.5 mL/min at a fuel concentration of 1.0 M in Figure 8b were found to be approximately 35.3 and 32.2 mW/cm^2 as the bubble stays at the center of the anode and closer to the center of the microchannel, respectively. These findings are consistent, which shows that the cell performance is affected by the evolution of gas bubble positions on the anode catalyst layer surface. Test results further suggest that the low performance of the fuel cell occurs if the CO_2 gas bubble occupies closer to the interface region in the channel.

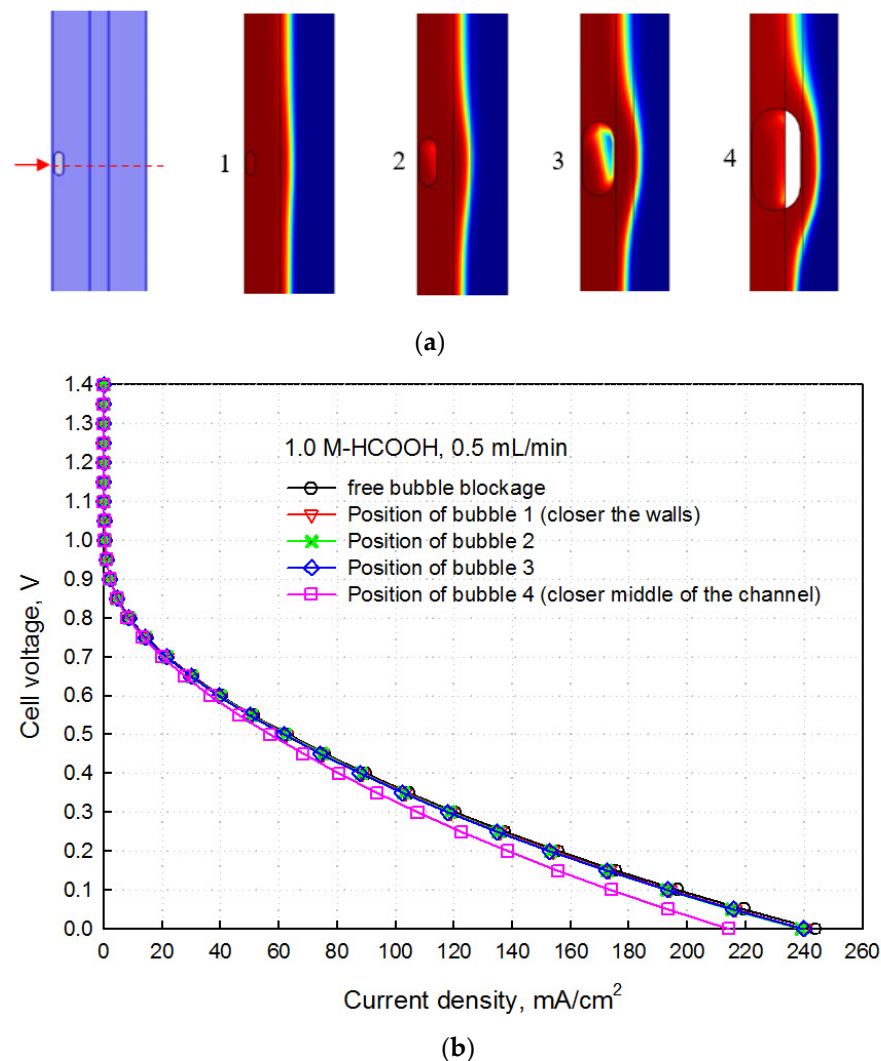


Figure 8. The simulation study of gas bubble growth: (a) The effect of blockages of different sizes on the fuel concentration distribution at 0.5 M-HCOOH at the volumetric flow rate of 0.7 mL/min; (b) The effect of blockage size on the I–V curve of the MFC at a fuel concentration of 1.0 M and volumetric flow rate of 0.5 mL/min.

In contrast, a slightly higher performance fuel cell results from the gas bubble occupying the sidewall of the anode catalyst layer along the microchannel. The carbon dioxide gas will usually be produced at the fuel cell anode electrode regardless of whether or not an electrolyte solution is being used. Gas bubbles are running over the entire anode catalyst layer surface, and their fluctuations become large and elongated, which were then pushed downstream before vanishing after reaching the end of the electrode to the channel outlet.

4. Conclusions

The effects of bubble blockage on the crossover current and the performance of an air-breathing DFAMFC were numerically studied in this paper. A three-dimensional DFAMFC model having static blunt objects staying on the anode side in the microchannel to simulate the gas bubble in the practical DFAMFC was built, with formic acid flowing over the anode.

The results showed that the total crossover current on the cathode, defined as the integral value of the local crossover current over the entire width of the cathode, increases as the static, blunt object (bubble) width increases from 0.2 mm to 0.8 mm at volumetric flow rate of 0.5 mL/min with inlet $[\text{HCOOH}] = 1.0$ M. The significant fuel crossover decreases the open circuit voltage of the DFAMFC. However, in contrast to the cathode crossover

current, the crossover current on the anode seems to be insignificant. Besides lowering the open circuit voltage, the static bubble staying on the anode also makes the shrouded anode catalyst layer inactive to the fuel without producing electric current.

This study also found that the low performance of the MFC came about if the CO₂ gas bubble moved closer to the interface region in the microchannel. Conversely, a slightly higher cell performance will be obtained if the gas bubble moves closer to the sidewall of the anode catalyst layer along the microchannel. The maximum power densities for the DFAMFC operated at a volumetric flow rate of 0.5 mL/min at a fuel concentration of 1.0 M were found to be approximately 35.3 and 32.2 mW/cm² as the bubble stays at the center of the anode and closer to the center of the microchannel, respectively.

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