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Multi-Effects of gravity and geometric flow channel on the performance of continuous microbial fuel cells

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Abstract

Nowadays microbial fuel cells (MFCs) are a rapidly evolving field and studied extensively because of their simultaneous dual functions of decomposing organic waste matter and eco-power generation. Now, facing their low power density, multiple effects including various gravity conditions ranging from 0 G to 2 G and three kinds of geometric flow channel (serpentine channel, serpentine tapered channel and bio-mixer channel) in MFCs were studied because of their ability to significantly impact the performance of MFCs. Numerical simulation technology, with its significant lessening of time needed and saving experimental costs required was used in this study. Results show that a better power performance was found at a condition of 0.125 G and Reynolds number Re=41.3 regardless of flow channel in MFCs. In addition, the bio-mixer channel of the flow channels in MFCs will have a better performance than the other two channels because of its lower pressure drop and higher power generation. These findings will
provide useful information on enhancing the performance of MFCs, especially with the application of low gravity conditions in the future.

Keywords: microbial fuel cells (MFCs), numerical simulation, effects of gravity, flow channel, eco-power, organic waste matter.

Introduction

A microbial fuel cell produces energy through organic waste from microbial metabolism. The microorganism transfers energy to the polar plate by means of medium (Rabaey and Verstraete 2005, Pasupuleti et al. 2015). Microorganisms are types of micro-scale creatures, which can be found at high altitude (low gravity field) and on the ground (normal gravity field), thus each microorganism has different environment suitability (Strašák et al. 2002, Baker et al. 2004). Besides, micro-scale creatures can be applied to compact cells or small sensor and runner designs can distribute microorganisms and substrate uniformly. Therefore, the designs can conduct experiments at high altitude (low gravity field) and on the ground (normal gravity field), to analyze the influence of gravity field on microorganisms. The experimental mode will consume extremely high costs, thus the technology of numerical analysis is adopted and applied in this study because it can save costs and time.

The numerical analysis in fuel cells is a mature technology. It can reduce costs and the model design, parameter design and operating conditions can easily be changed. The numerical analysis of microbial fuel cells shall be conducted by a biological chemistry metabolism electricity production system; therefore, microorganisms and chemical reactions shall be considered (Zeng
et al. 2010). The microorganism fuel cell model designed by Zhang et al. (1995) to simulate the relationship between microorganisms adding substrate and current output received preliminary achievements. In addition, the value of a maximum current density of 2.11 μA/cm² obtained by using the numerical simulation was found to show a huge discrepancy in the experimental value 1.11 μA/cm² undergoing the same operational conditions. Later, the microbial model was modified by Wen et al. (2009) by way of combining the mechanism of electron transfer and kinetic reaction in MFCs. A maximum current value of 25 mA was obtained in contrast to the experimental value.

In 2004 Baker et al. indicated that controlling the factor of gravity seems to have a more obvious response to microbial activity than other factors. Baker et al. (2004) further indicated that with micro-gravity applied by using the method of centrifugal force at E. coli total cell counts were significantly higher with rotation speeds at 40 rpm under modeled reduced gravity compared to normal gravity. In addition, Arunasri et al. (2013) also indicated that K12 of E. coli could be cultured at a low gravity condition of 1×10⁻³, and a growth rate microorganism number would appear in a logarithmic form. According to these findings, it could be pointed out that a condition of low gravity will passively affect bacteria. Because of this it could be reasonably expected to benefit the bio-chemical reaction in the microbial metabolism process. Therefore, the effect of gravity on the performance of MFCs would be worthy of studying because of its effects having been rarely noted previously.

To summarize, realizing the effects of gravity ranging from 0 G to 2 G, undergoing a modified numerical simulation on the performance of a continuous channel of microbial fuel cells with
different kinds of geometric flow channel, would be the main aim in this study. These findings will provide useful information on enhancing performance of MFCs, especially under the application of low gravity conditions in the future.

**Parameters and Physical Model of Design**

In the numerical simulation process, the key technology of altering the exchange current will be used for showing the adherent uniformity phenomena of microorganisms on the surface of electrodes. As for the model validation, two cases shown in Figure 1 have been confirmed to show its feasibility before study. The anode exchange current density with increments of $1 \times 10^3$ A/m$^3$ ranging from $6 \times 10^3$ to $1 \times 10^4$ A/m$^3$ would be set and executed. Results in Figure 1a show that when the exchange current density is set as $8 \times 10^3$ A/m$^3$, a value of current density with 0.36 mA/m$^2$ in the continuous MFCs is achievable and similar to the experimental cases (Min and Logan 2004) for the same studied cases. In this study, the value of the exchange current density with 8000 mA/m$^3$, which is identical to the same experimental conditions (Min and Logan 2004), would be set for the following series of studies.

In this study a continuous MFC channel with different kinds of flow channel will be executed by using the analysis of numerical simulation. Some assumptions would be made and addressed as follows:

1. Steady state operation;

2. Isothermal System;
3. Work flow must be laminar and flow incompressible;

4. Diffusion layer, catalyst layer and thin film layer are all set as an isotropic and homogenous porous materials;

5. Physical characters of viscosity and density are set as constant;

6. Uniform distribution of microorganisms on the surface of electrodes;

7. Impact of biofilm within the initial state and short term period in MFCs was neglected;

**Physical Modeling Design**

In this study, a three dimensional model with XYZ axis will be utilized and is shown in Figure 2 as the numerical simulation model of MFCs. Here, the anode and cathode chamber will be designed with flow channels, with the membrane electrode assembly being the main components of this system (Sivertsen and Djilali 2005). The electro-chemical reaction will occur in the main components addressed previously (Sivertsen and Djilali 2005). In addition, the catalyst layer (CL) and the diffusion layer (GDL) will be combined with electrodes into a biocatalyst electrode at the anode part of the MFCs (Zhang et al. 2014, Wang et al. 2014). Similarly, the gas diffusion layer was integrated into the component of the cathode electrode. In this study, three kinds of flow channel would also be investigated in a continuous channel of MFCs under different cases of gravity and Reynolds number. Therefore, the three channels of flow mode (serpentine channel, serpentine tapered channel and bio-mixer channel) would be considered. Although Figures 3-5 should be unified in scale, the ratio of channel and rib width will be set in an optimal
dimensional region of about 0.50 for eliminating the effects of the ratio of channel and rib width. In addition, the output electricity performance will be calculated per reaction area of electrode whose area is the same as the area of the flow channel at the same inlet operational Reynolds number. Related statements will be addressed later. The three kinds of flow channel comprised of two nonconductive plates bolted together, containing input/output were designed. The serpentine flow channel was designed as a rectangular channel in a serpentine path 0.7 cm wide and 0.4 cm deep. The serpentine tapered channel was designed at a constant reducing value of 0.2 mm in width. The bio-mixer channel was using split and recombination (SAR) for increasing the interaction. Figures 3-5 and Table 1 show their flow structure and flow geometric dimensions, respectively. Here, the serpentine tapered type of flow channel was reduced at a constant value of 0.2 mm in width; Another type of bio-mixer channel with higher mixing efficiency and lower pressure drop (Wang et al. 2009) would become a suitable flow type in MFCs. Table 2 indicates the electro-chemical parameters with their workable values in this continuous channel of numerical simulation MFC model (Logan et al. 2007; Logan et al. 2006; Nguyen and Wu 2005; Lorenzo et al. 2009; Lal and Reji 2012).

**Numerical Method**

These studied cases were numerically simulated using a commercial CFD software package, CFD-ACE+. A multi-physics package based on the Finite-Volume method was also applied. The program was run on a 2.8 Ghz Pentium IV processor with 2GB of RAM memory for the CGS solver. Mesh-independent tests were performed before the studies took place. An upwind method for solving the multi-block unstructured grid of cells, whose numbers were set as N=46000,
107000 and 135000 in respect to serpentine channel, serpentine tapered channel and bio-mixer channel, were used as the 3D computational domain inside the MFC system.

The convergence criterion was assumed to be $\pm 10^{-5}$ for the residual of the discrete governing equation in the simulation. The Reynolds number is canned to influence the flow field by viscous force and inertial force. Here, the Reynolds number shown in (1) is defined as:

$$\text{Re} = \frac{V D}{\rho}$$  \hspace{1cm} (1)

$V$ represents the velocity, $\rho$ is the density, $D$ is the inlet width of flow channel, $\mu$ indicates the dynamic viscous of fluid.

Therefore, the research is using Reynolds number to influence current density on the continuous microbial fuel cell performance.

For the boundary conditions used in the simulation process, a constant inlet velocity of anode/cathode flow chamber calculated from a given Reynolds number ranging from 4.13 to 41.3 was used for steady-state analysis. Although the channel flow was laminar, a rather fine mesh was needed to account for the detailed features of the sorting mechanism. The time for each run spanned from 2 hours up to 3 hours. Here, the system temperature was set at 303 K, the C$_6$H$_{12}$O$_6$ was used as the anode reactant and the oxygen was utilized as the cathode reactant.
Results and Discussion

In this study two topics related to gravity effect and different kinds of flow channel in MFCs will be investigated. More details of results will be addressed as follows:

A. Effect of gravity in microbial fuel cell

As for the effect of gravity on the performance of continuous MFCs within different inlet flow velocity, and different strength of gravity fields ranging from 0 to 2 G undertaking three kinds of flow geometric channels in MFCs would be applied in cases of the same working voltage of 0.6 V but at two inlet Reynolds numbers (Re) of 4.13 and 41.3 respectively. Figure 6 shows the variations of current density in the three channel MFCs for different gravity intensities at Re=4.13 (i.e., low speed inlet flow). From the results of Figure 6, a maximum current density would be found at the condition of 0.125 G, except for the serpentine tapered channel in MFCs at Re=4.13. This result indicated that a relative low gravity would give a positive effect on the current performance at a lower inlet flow velocity of MFCs except for the case of the serpentine tapered channel. Here, the power density of MFCs with the kinds of serpentine channel, biomixer channel and serpentine taper channel obtained were 7.8mW/m², 14.53mW/m², and 4.488mW/m², respectively. Nonetheless, when controlling the flow rate in MFCs a corresponding current would be produced (Pharoah 2005; Kjeang et al. 2008). Therefore, a higher flow inlet velocity of Re=41.3 would be utilized in MFCs. Similar results shown in Figure 7 indicate that a maximum current density of MFCs would be obtained in the case of a gravity intensity of 0.125 G regardless of the three kinds of inlet flow channel. This evidence indicated
that a higher inlet flow velocity of MFCs would enhance the current performance of MFCs, especially highly impacting the case of the serpentine tapered channel because the initial inlet flow of that channel would be converted into another flow channel with a high flow intensity in the condition of a lower gravity and higher flow velocity. Gravity of 0.125 G and Re=41.3 was found suitable for the three kinds of flow channel in that this condition could also produce a better power generation in MFCs. Here, the power density of MFCs with the serpentine channel, bio-mixer channel and serpentine taper channel show amounts of 7.8mW/m², 14.53mW/m², and 38.76mW/m², respectively.

As for the effect of gravity field on the microbial metabolism rate, Baker et al. (2004) indicated that the metabolism of microorganisms would be enhanced in a condition of a low gravity field. In their study a method of centrifugal force with 40 rpm would be necessary and required for giving a better microbial metabolic rate. Results of Baker et al. (2004) showed that a reduction in the influence of a low gravity field could raise electricity. Besides, raising the Reynolds number could also improve electricity production in a tapered design of the system. This evidence shows that the effects of suitable gravity strength and inlet Reynolds numbers would give a positive impacting microbial metabolic rate and also enhance the power performance of a continuous channel of MFCs.

**Different kinds of flow channel applied in MFCs**

On the report that different flow geometry of MFCs would produce different flow mixing, flow patterns and even influence the performance of the system, three kinds of flow geometric channels were designed. A serpentine channel, serpentine tapered channel and bio-mixer channel in a
continuous MFC channel seems to be worthy of studying in cases of gravity fields ranging from 0 G to 2 G, making all the microorganism and substrate solution uniform. Figures 8-10 show the flow velocity image field in the case of a gravity intensity of 0.125 G and inlet Reynolds number Re=41.3. Figure 8, with bio-mixer channel MFCs, showed that the obstacles in MFCs can not only make flows split and recombine to produce a higher flow mixing and very lower pressure drop (14 N/m²), but also that the effect on the flow field is overall beneficial to the power generation of the system. Therefore, the flow mode of the bio-mixer channel in MFCs under the consideration of net power generation should be considered in the future. Tsan et al. (2011) showed that a bio-mixer channel with effective mixing performance was utilized in a micro-flow field of rumen microbial fuel cells (RMFCs). The conclusions found in this study are consistent with the report by Tsan et al. (2011). Conversely, the serpentine taper flow channel shown in Figure 9 was designed by way of using a constant decreasing ratio of 0.5 mm of flow channel width design in MFCs for improving the flow mixing performance, while also inducing a very higher pressure drop (52606.8 N/m²). Similar results shown in Figure 10 for the serpentine channel of MFCs whose pressure drop is 117.5 N/m² could be found because of originating from the same serpentine prototype. According to previous reports, the serpentine channel and serpentine tapered channel would have a relative higher pressure drop and further induce a negative effect on the performance of MFCs. Contrarily, the bio-mixer channel in MFCs would provide a higher mixing performance and very lower pressure drop. This bio-mixer channel structure in MFCs could be predicted to be able to provide a better overall performance. Seeing these interesting results, more effort could be taken with further experimentation in the future.
Finally, facing the organic degradation within the wastewater, it will be well known that an MFC whose system is very different from traditional aerobic or anoxic wastewater treatment systems because it is a type of hybrid system with possessing the ability of bio-chemical degradation and electricity generation simultaneously (Logan, 2005). At the microbial level, this is an anaerobic treatment technology. In early studies the amount of current generated in microbial fuel cells was very low, but in the past few years there have been substantial increases in power generation. Although this study executed would mainly focus on power generation of MFCs undertaking cases of different gravity effects, power gained would also be generated by way of biological decomposition of compounds and wastewaters. Therefore, it is shown that power generation rates are constantly increasing, and it can also be expected that a wastewater treatment technology based on a MFC should be possible within only a few years (Logan, 2005).

Conclusion

In this study, various cases of gravity conditions ranging from 0 G to 2 G and three kinds of geometric flow channels (serpentine channel, serpentine tapered channel and bio-mixer channel) in MFCs were studied to assess their corresponding effects on the performance of MFCs. Some results found are addressed as follows:

First, the gravity 0.125 G and Re=41.3 was found suitable for three kinds of flow channel and that this condition could also produce a better power generation in MFCs. The higher Reynolds number in MFCs would produce a better current density regardless of flow channel. Second, the highest current density would be obtained for the case of a serpentine channel in MFCs in the case
of Re =4.13 and 0.125 G. But by increasing the flow velocity to Re=41.3, the highest current
density would be found in the case of a serpentine tapered channel in MFCs with 0.125 G and
Re=41.3. The serpentine channel and serpentine tapered channel would have a higher pressure
drop and further induce a negative effect on the performance of MFCs. Finally, the bio-mixer
channel obstacles in MFCs can not only make flows split and recombine to produce a higher flow
mixing and very lower pressure drop (14 N/m²), but also the effect on the flow field is overall
beneficial to the power generation of system. In addition, this study executed would focus on
power generation of MFCs undertaken cases of different gravity effect but power gained should
be generated from defined compounds and wastewaters. These findings will provide useful
information on enhancing the performance of MFCs, especially with the application of low
gravity conditions or remote environment in the future.

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Reference


Table 1. Dimensions of three kinds of flow channel in continuous MFC model

<table>
<thead>
<tr>
<th>Parameter Value (mm)</th>
<th>Serpentine channel</th>
<th>Serpentine tapered channel</th>
<th>Bio-mixer channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel length of electrodes</td>
<td>6.3</td>
<td>20</td>
<td>37</td>
</tr>
<tr>
<td>Channel width of electrodes</td>
<td>0.4</td>
<td>1.8-0.2 mm with a constant decreasing ratio of 0.5 mm</td>
<td>27</td>
</tr>
<tr>
<td>Channel depth of electrodes</td>
<td>0.7</td>
<td>1.8</td>
<td>37</td>
</tr>
<tr>
<td>Total length</td>
<td>8.7</td>
<td>21.7</td>
<td>37</td>
</tr>
<tr>
<td>Anode of the electrode</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffusion layer thickness at cathode</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Value 1</td>
<td>Value 2</td>
<td>Value 3</td>
</tr>
<tr>
<td>--------------------------------------------------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>Catalyst layer thickness at cathode</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Membrane thickness</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface to Volume ratio (1/m)</td>
<td>250</td>
<td>0.02</td>
<td>0.037</td>
</tr>
</tbody>
</table>
Table 2. Physical values of transfer characteristics and electrochemistry parameters

<table>
<thead>
<tr>
<th>Geometry and condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity of Membrane</td>
<td>0.28</td>
</tr>
<tr>
<td>Porosity of Electrode · GDL and CL</td>
<td>0.4</td>
</tr>
<tr>
<td>Permeability of Electrode · GDL and CL (m²)</td>
<td>$1.76 \times 10^{-11}$</td>
</tr>
<tr>
<td>Permeability of Membrane (m²)</td>
<td>$1 \times 10^{-18}$</td>
</tr>
<tr>
<td>Average pore size of Electrode · GDL and Membrane (m)</td>
<td>$1 \times 10^{-6}$</td>
</tr>
<tr>
<td>Average pore size of CL (m)</td>
<td>$1.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>Conductivity of Electrode · GDL and CL (1/Ωm)</td>
<td>53</td>
</tr>
<tr>
<td>Conductivity of Membrane (1/Ωm)</td>
<td>$1 \times 10^{-20}$</td>
</tr>
<tr>
<td>Property</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Thermal conductivity of GDL and CL layer (W/ mk)</td>
<td>1.3</td>
</tr>
<tr>
<td>Thermal conductivity of Membrane (W/ mk)</td>
<td>0.455</td>
</tr>
<tr>
<td>Transfer coefficients at anode</td>
<td>0.5</td>
</tr>
<tr>
<td>Transfer coefficients at cathode</td>
<td>1.5</td>
</tr>
<tr>
<td>electrode and GDL and CL conductivity</td>
<td>53</td>
</tr>
<tr>
<td>Electrical heat conductivity of electrode</td>
<td>200</td>
</tr>
<tr>
<td>Electrical Conductivity of electrode</td>
<td>4.2</td>
</tr>
<tr>
<td>Exchange current density for anode reaction (A/m³)</td>
<td>8000</td>
</tr>
<tr>
<td>Exchange current density for cathode reaction(A/m³)</td>
<td>1.06×10⁻⁸</td>
</tr>
</tbody>
</table>
Figure 1. Anode Exchange Current Density and Current Density Changes (Fig. a: simulation versus Min and Logan; Fig. b: simulation versus Wang et al.)
Figure 2. Schematic of continuous microbial fuel cell model
Figure 3. A serpentine flow channel of a continuous microbial fuel cell model (Min and Logan 2004); Unit: mm.
Figure 4. A bio-mixer channel of a continuous microbial fuel cell model (Wang et al. 2009); Unit: mm.
Figure 5. A serpentine tapered channel of continuous microbial fuel cell model; Unit: mm.
Figure 6. Variations of current density of different gravity forces in respect to three kinds of flow channels in MFCs and flow conditions of Re=4.13.
Figure 7. Variations of current density of different gravity forces in respect to three kinds of flow channels in MFCs and flow condition of Re=41.3.
Figure 8. The flow velocity image of bio-mixer channel in continuous of microbial fuel cell in the case of 0.125G and inlet Re=41.3.
Figure 9. The flow velocity image of serpentine taper channel in continuous of microbial fuel cell in the case of 0.125G and inlet Re=41.3.
Figure 10. The flow velocity image of serpentine channel in continuous of microbial fuel cell in the case of 0.125G and inlet Re=41.3.