微生物燃料電池流場最佳化：提升微流道效力探討

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摘要

微生物燃料電池性能的改善是目前重要且極需被克服的一個課題，研究擬以商用軟體(CFDRC)於不同深寬比及雷諾數流場條件下，針對仿生型、網狀型及兩種傳統流道(平行式與蛇型)之流道設計、壓力分佈、壓降及速度分佈等參數進行分析。分析結果得知，仿生型流場因能產生較大質量流量及較小壓阻，使得整體系統性能表現最佳，這些研究成果將有助於未來微生物燃料電池系統的設計。

關鍵詞:微流道、壓阻、微生物燃料電池

Optimization of Flow in Microbial Fuel Cells: An Investigation into Promoting Micro-channel Effectiveness

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Abstract

An important obstacle to overcome in the advancement of microbial fuel cell (MFC) technology is improving the effectiveness of the micro-channel components in a MFC system. Through the use of a commercial computational fluid dynamics (CFD) simulator, this study analyzed four micro-channel designs and collected data pertaining to velocity and pressure distribution, and pressure drop. Factors considered in the study included inlet aspect ratios and variable inlet Reynolds numbers. Simulation outputs and experimental testing all indicated that an innovative biometric configuration yielded the best combination of all the parameters, producing the most consistent mass flow rate and the second-lowest pressure trend. Other designs were deemed less effective due to detrimental characteristics such as inconsistent flow patterns or undesirable pressure levels. These findings would be useful to the further design of microbial fuel cell system.

Keywords: micro-channel, pressure drop, microbial fuel cell (MFC)

1. Introduction

With the increasing miniaturization of portable devices and their growing rates of energy consumption, the demand for suitable power sources will soon outpace conventional battery technology [1]. An innovative replacement that has been proposed is the microbial fuel cell, a power source that harnesses the metabolic processes found in micro-organisms to produce energy. The most common type of microbial fuel cell involves the use of glucose as the fuel source. In an anaerobic chamber that serves as the anode for the fuel cell, microbes consume the biofuel and in the process produce carbon dioxide, hydrogen protons, and electrons [2]:

$$C_6H_{12}O_6 + 6H_20 \rightarrow 6CO_2 + 24e^- + 24\,H^+ \quad (1)$$

Electron mediators then carry the electrons to an anode, where they travel outside the cell and establish a current along a conducting path to the cathode. The protons move across a semi-permeable barrier called a proton exchange membrane into the cathode chamber, where they recombine with the electrons and O_2 to produce water. Thus, such a power source would theoretically only require water, oxygen, and the presence of a biofuel. The byproducts of the energy production would be carbon dioxide and water, making the system not only reusable, but also clean. This concept has also been applied to a variety of other electron producers, such as the white blood cell [3] or the photosynthetic process of chloroplasts [4]. The availability of a microbial fuel cell able to handle commercial power needs has a significant impact on portable handhelds, micro-machines, and biomedical applications.

In order for this to be feasible, research into optimizing the effectiveness of such a system must first be conducted. This study investigated the geometry of the anode, which is comprised of several micro-channels laid out to establish a flow field. This allows the electron mediators in the anode chamber to flow through the micro-channels and deposit electrons directly onto the anode surface. This study identified potential flaws in flow field designs that would otherwise decrease the effectiveness of a microbial cell, such as clogging in the micro-channels [5] and acceptable pressure levels to reduce the risk of damage to biological microorganism. Also, a flow field design thought to be an improvement over an existing design was tested and evaluated.

2. Procedure

The simulations were performed using CFD-ACE+, a CFD/Multi-physics software commercially licensed by the CFD Research Corporation. All models were composed of multiple unstructured blocks and analyzed using an upwind, algebraic multiple-grid solving method. For these simulations, water with properties evaluated at a standard temperature and atmosphere was utilized as the medium fluid. A uniform, steady-state flow was set as the inlet boundary condition.

The four flow field models utilized were a conventional pattern of parallel micro-channels, a serpentine micro-channel design, a biometric design hypothesized to have the best performance out of the fields considered, and a grid design that served as the genesis of the biometric design (see Figure 1). The flow fields were typically 50 mm by 60 mm, with the standard micro-channel width being in the range of 10 mm to 20 mm. Each simulated design incorporated a number of cells ranging from 67,000 to 123,000. The parameters considered in the simulations were the inlet aspect ratio, defined as:

$$AR = \frac{W}{D} \quad (2)$$

where W is the width of the inlet and D is the depth of the micro-channel; and the Reynolds number of the inlet flow, defined as

$$\mathrm{Re} = \frac{\rho V_s D_h}{\mu} \quad (3)$$

$$D_h = \frac{4A}{U} \quad (4)$$

where ρ is the density of the fluid, V_s is the flow speed, D_h is the hydraulic diameter, μ is the viscosity of the fluid, A is the cross-sectional area of the inlet, and U is the wetted perimeter of the inlet. Recorded data included flow visualizations of flow speed and pressure, the pressure drop over the entire system, and the mass flow rate through the channels.

3. Results and Discussion

A consistent mass flow rate throughout the flow field system promotes the most effective use of space since it provides a uniform distribution of reactants over the reaction surface. In addition, it reduces the potential for clogging and the subsequent decrease in effectiveness. The biometric and the grid design had the most consistent mass flow rates of all the systems, which was evident from their low standard deviation values as compared to the other designs (as depicted in Figure 3). The large deviation value for the conventional design was found to originate from the micro-channels in the center, which received relatively little flow as compared to the outer micro-channels. It is worth noting that since the serpentine design has only one available path for flow to travel, there is no deviation in its mass flow rate and thus its standard deviation is impossible to represent correctly. However, the use of a single serpentine micro-channel increases the possibility of clogging.

Pressure distribution is an important issue for flow fields when their use in microbial fuel cells is considered since extreme pressures are detrimental to biological entities subjected to the flow. A large pressure also indicates the need for increased power in order to ensure a steady flow through the system. From the data compiled in Figure 4, the conventional design ranked the lowest in overall pressure drop trends, with the biometric, grid, and serpentine following behind in that order. The graph in Figure 4 omits the data for the serpentine design due to the increased magnitude of its values in relation to that of the others.

For the reasons mentioned above, the biometric design was considered to be the most effective configuration out of the four considered. While the conventional design had the second-lowest pressure drop, it suffers from the flaw of a relatively-unused center, thereby reducing its effectiveness. This inherent defect was also confirmed experimentally in a flow test. The serpentine design, while eliminating the problem of unused micro-channels, leaves itself susceptible to clogging and requires undesirable levels of pressure to operate. A series of flow tests verified the fact that the pressure drop in the serpentine design outmatched that of the other designs.

Other observations of interest were the effects of changing the inlet aspect ratio and inlet Reynolds number. Figure 3 shows that the deviations in the mass flow rate for each design increased when the inlet aspect ratio was decreased while the inlet Reynolds number was held constant. In addition, when the inlet Reynolds number was varied, the pressure drop at an aspect ratio of 4 was higher than those at an aspect ratio of 2. The determination of a definite trend requires the collection of further data points; however, these results provide a direction for further studies in the effectiveness of flow fields with varying inlet aspect ratios and Reynolds numbers.

The authors of this paper realize the need for a direct method of estimating the efficiency of a design, and though two distinct methods have been developed from the energy equation for turbulent flow and the works of Singh *et al.* [6], a lack of viable justification for either method have led to the exclusion of a direct estimate in this report. Further research must be completed before such results can be accurately presented.

4. Conclusions

This project analyzed four micro-channel designs and collected data pertaining to flow and pressure distribution, and pressure drop. Various factors like inlet aspect ratios and varying Reynolds numbers were considered in the study. Simulation outputs and experimental testing all led to the formulation of the following observations: First, an innovative biometric configuration yields the best combination of all the parameters, producing the most consistent mass flow rate and the second-lowest pressure trend. Second, other designs suffered from flawed characteristics such as ineffective flow patterns or undesirable pressure levels.

Acknowledgments

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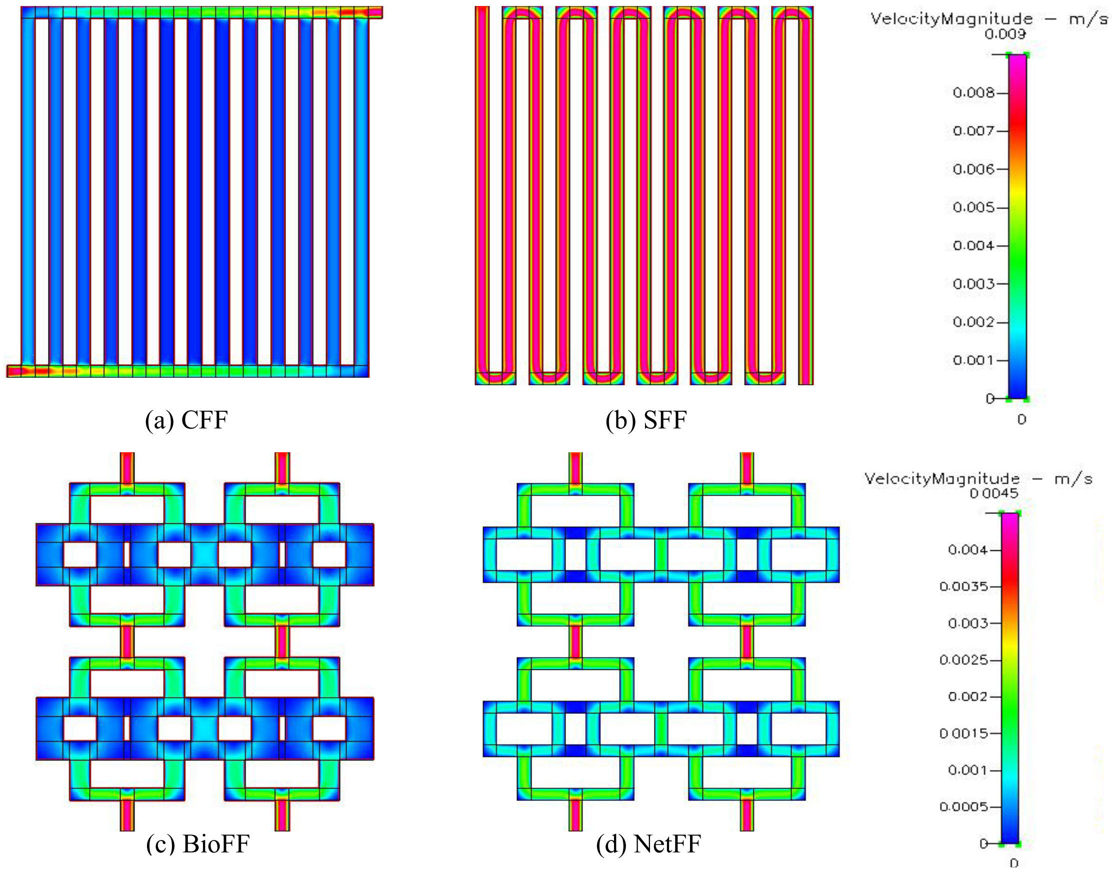

Figure 1: Flow visualizations of flow speed for (a) conventional flow field at AR = 2, inlet Re = 10; (b) serpentine flow field at AR = 2, inlet Re = 10; (c) biometric flow field at AR = 2, inlet Re = 5; (d) grid flow field at AR = 2, inlet Re = 5. Note the region of minimal flow in the middle of the CFF (a) design.

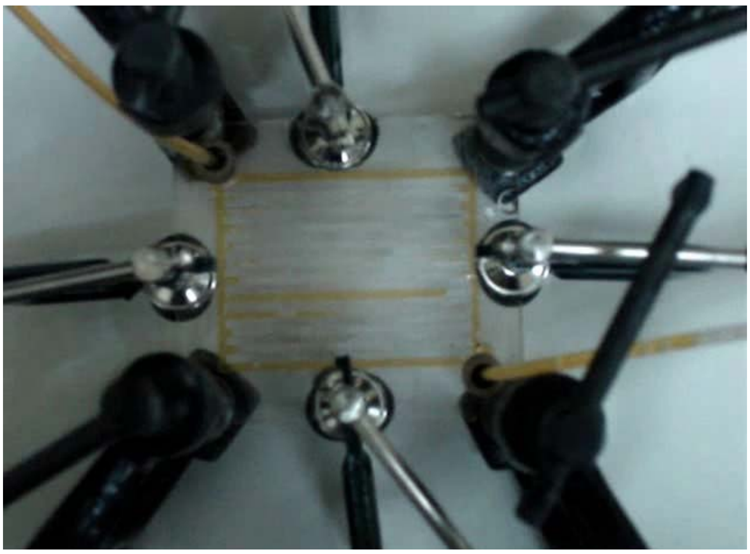

Figure 2: Certain results and phenomenon were confirmed using simple experiments. This photo shows the flow in the CFF design when flow is initially established. Note the preference of the liquid towards the outer channels, and the "dead region" in the inner channels that occurs as a result.

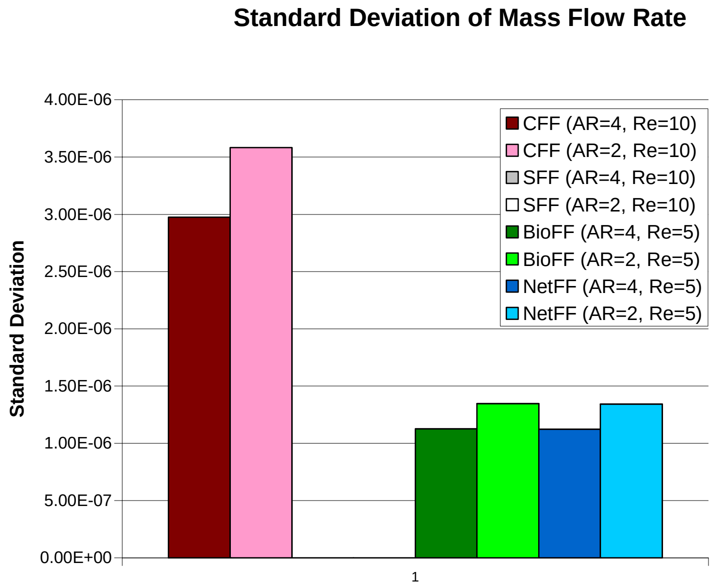

Figure 3: The BioFF and NetFF designs have the lowest deviation in mass flow rate, while the CFF design has the most. Due to the lack of deviation in the SFF design, its standard deviation is impossible to represent. The inlet Reynolds number for the BioFF and NetFF designs have also been adjusted so that their inlet mass flow rate matched those of the CFF and SFF designs at the same aspect ratio.

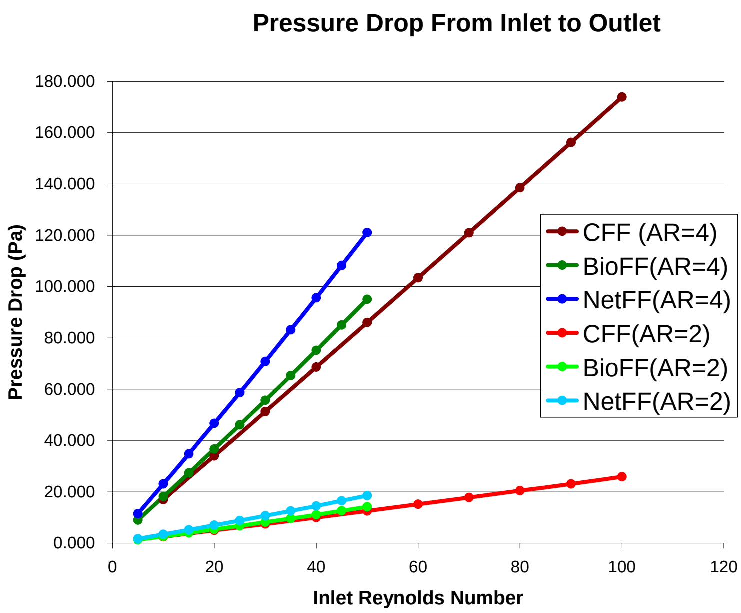

Figure 4: Pressure data for SFF has been omitted due to its relatively massive values (100-600 Pa). Overall pressure trends indicate the CFF design has the lowest pressure drop, with the BioFF and NetFF being second and third.