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First steps towards a constructal Microbial Fuel Cell

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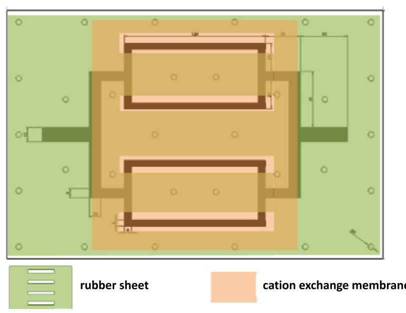
HIGHLIGHTS

- A constructal-inspired approach is tested in a 2D double chamber MFC prototype.
- Regular and singular pressure drops are considered for the entropy generation.
- The determination of entropy generation allowed the fluid distribution optimization.
- Stability and robustness of the bioelectrochemical system are shown up to 10 weeks.
- The potential of the constructal approach in MFC is shown.

GRAPHICAL ABSTRACT



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ABSTRACT

In order to reach real operating conditions with consequent organic charge flow, a multi-channel reactor for Microbial Fuel Cells is designed. The feed-through double chamber reactor is a two-dimensional system with four parallel channels and Reticulated Vitreous Carbon as electrodes. Based on thermodynamical calculations, the constructal-inspired distributor is optimized with the aim to reduce entropy generation along the distributing path. In the case of negligible singular pressure drops, the Hess–Murray law links the lengths and the hydraulic diameters of the successive reducing ducts leading to one given working channel. The determination of generated entropy in the channels of our constructal MFC is based on the global hydraulic resistance caused by both regular and singular pressure drops. Polarization, power and Electrochemical Impedance Spectroscopy show the robustness and the efficiency of the cell, and therefore the potential of the constructal approach. Routes towards improvements are suggested in terms of design evolutions.

1. Introduction

Reducing the environmental impact of human activities together with contributing to energy production with the help of natural entities is a challenge that is becoming a reality with the recent development of Microbial Fuel Cells (MFCs). MFCs are able to reduce organic charge in wastewater. They simultaneously and directly produce electrical energy, although still in limited quantities at the present time (Rabaey and Verstraete, 2005; Logan et al., 2006; Logan and Regan, 2006; Kim et al., 2007; Lovley, 2008; Rinaldi et al., 2008; Watanabe, 2008; Du et al., 2007; Oliviera et al., 2013). Organic wastes and wastewaters are among the most sustainable and cost-effective feedstocks for MFCs (Hawkes et al., 2010). Practical implementation in wastewater treatment plants can now be considered, however some technological, microbiological and economic challenges are to be solved (Rozendal et al., 2008; Oh et al., 2010).

The reactor design is one of the key features for wastewater depollution and electricity production efficiency. One approach

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consists in observing and copying Nature's great successes in minimizing resistances and optimizing mass and energy transfers; treelike shapes in the vegetable world or in lungs' bronchi and alveoli architecture in physiology are examples.

Based on these observations, the constructal approach was initially developed in order to improve heat transfers (Bejan, 1997). This approach has been used for solving flow distribution problems by optimizing branching, lengths and diameters ratios in two or three dimensions (Wechsatol et al., 2002; Tondeur and Luo, 2004; Luo and Tondeur, 2005). This concept can be applied to various systems, among them fuel cells (Liu et al., 2010). The geometry of water or gas delivery channels can be tackled by simulation thanks to this approach (Ramos-Alvarado et al., 2012; Arvay et al., 2013).

To our knowledge, this is the first time that the design of a MFC is undertaken via a constructal or similar approach (Lepage et al., 2011). Tsan et al. (2011) studied the effect of biometrics flow channels with various obstacles in a rumen MFC at different Reynolds numbers. The presence of obstacles provides better mixing and standardization of the flow together with power output enhancement. In the early times of MFCs, Min and Logan (2004) tested the ability of a single channel flat plate air–cathode MFC.

In the present work, the constructal approach is used in a feed-through MFC as a tool to improve mass and energy transfers by decreasing the pressure loss between the input and the output of the system. As a first step, a two-dimensional system with four parallel channels is described. The double chamber system is run with Reticulous Vitreous Carbon (RVC) as electrode material under continuous flow. Polarization and power curves are presented, together with Electrochemical Impedance Spectroscopy (EIS) analyses for a broad description of the system.

2. Methods

2.1. Calculations

The constructal approach is a recent theory aiming at improving systems efficiencies by minimizing entropy generated by mass transfer resistances. This approach is particularly well adapted to the study of flow distribution and collection problems in multichannel reactors. It appears of high interest for the geometrical optimization in the case of Microbial Fuel Cells, because of the high resident time that is needed in the reaction chamber. By the way, the resort to multichannel reactors should help managing high organic flows in future compact microbial reactors.

For Hagen–Poiseuille flows, the hydraulic resistance Rh_i caused by a regular pressure drop ΔP_i^{reg} in a tube of diameter D_i and length L_i is written as:

$$Rh_i = \frac{\Delta P_i^{reg}}{\dot{m}_i} = \frac{128\nu}{\pi}\frac{L_i}{D_i^4} \tag{1}$$

where $\dot{m}_i$ is the mass flow in kg s^{-1} and ν the kinematic viscosity in Pa s when the geometric variables are expressed in meters (SI units).

In the case of rectangular channels (width w_i and depth d_i), the hydraulic diameter Dh_i is used to assimilate the section to that of a circular channel through the relation:

$$Dh_i = 4\frac{A_i}{P_i} = 2\frac{w_i \cdot d_i}{w_i + d_i} \tag{2}$$

with being the channel cross section area and P_i the wet perimeter.

For right angles and bifurcations the singular pressure drops ΔP_i^{sing} have to be taken into account by the addition of an equivalent length $L_{eq,i}$:

$$L_{eq,i} = \frac{K_i^{sing} D_{h,i}}{64/Re_i} \tag{3}$$

with Re_i the Reynolds number. K_i^{sing} is the singular pressure drop coefficient. According to fluid mechanics literature (Idelchik, 2008) and to basic experiments, this parameter is set to 1.13 for right angles and 1.57 for tees. Thus, the global hydraulic resistance caused by the regular and singular pressure drops in a tube of diameter Dh_i and length L_i can be written:

$$Rh_i = \frac{\Delta P_i^{reg} + \Delta P_i^{sing}}{\dot{m}_i} = \frac{128\nu}{\pi}\frac{(L_i + L_{eq,i})}{Dh_i^4} \tag{4}$$

In the case where $\Delta P << P$ and after linearization, ρ being the density of the fluid, the associated generated entropy S_i in the tube i is expressed as (in W K^{-1}):

$$S_i = \frac{\Delta P_i \dot{m}_i}{\rho T} = \frac{Rh_i \dot{m}_i^2}{\rho T} \tag{5}$$

The goal is optimal flow network design by minimizing entropy generation along the flow path. In the case of negligible singular pressure drops, this leads to the Hess–Murray law that links the length and the hydraulic diameter of one given channel to the following one (Wechsatol et al., 2002):

$$\frac{L_i}{L_{i+1}} = \frac{Dh_i}{Dh_{i+1}} = 2^{-1/3} \tag{6}$$

Let us now consider the flow network of Fig. 1, corresponding to a four-channel distributor (or collector), the approach developed here for the distributor being applicable to the collector with the help of symmetry considerations.

In this distribution scheme, Q^{tot} being the global flow at both the inlet and the outlet, the electrolyte volumetric flows Q_i through the subsequent channels are interconnected by:

$$Q_5 = Q^{tot}, Q_4 = Q_3 = Q^{tot}/2 \text{ and } Q_2 = Q_1 = Q^{tot}/4 \tag{7}$$

2.2. Design

A first prototype of a Microbial Fuel Cell inspired from the constructal theory has been dimensioned in order to highlight system efficiency gain in multichannel reactors and to validate the approach (Fig. 2). Optimal design was not able to be reached in this first stage because of technical limitations (square sections, constant depth and right angles). However, in a first approximation, channels lengths and square section sides are set using Hess–Murray law and rounded to the next millimeter. The reported dimensions in Table 1 show that the Hess–Murray ratio is well preserved for widths and lengths in every fork. It is then believed that the principle of the constructal approach remains the connecting thread for this first attempt in MFCs.

As the reactive area of the system is related to channel 1, its length L_1 was chosen to ensure a sufficient residence time for the electrolyte in the reaction chamber. Indeed, in such living systems,

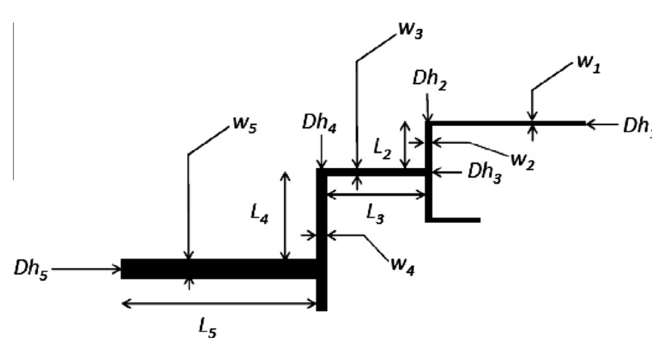

Fig. 1. Principle of the constructal series. Dh_i are the hydraulic diameters and w_i and L_i are respectively the widths (equal to the depths) and the lengths for each fork.