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Review

Mass transfer and performance of membrane-less micro fuel cell: A review

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ARTICLE INFO

Article history:
Received 17 July 2013
Received in revised form
18 September 2013
Accepted 25 September 2013
Available online 5 December 2013

Keywords:
Mass transport
Laminar flow
Membrane-less fuel cell
Microfluidic fuel cell

ABSTRACT

Membrane-less micro fuel cells (MMFCs) are high potential alternative power sources compared to conventional batteries. They use the advantage of laminar flow without the presence of a membrane to separate the anode and the cathode. This article is a wide-ranging review of recent studies on mass transfer, performance, modelling advances and future opportunity in MMFCs research. The discussion focuses on the critical factors that limit the performance of MMFCs. Because MMFCs are diffusion-limited, most of this review focuses on design considerations to enhance the power density output. Moreover, the current status of computational modelling for MMFC systems to upgrade the cell performance will be presented. The review also identifies the challenges and opportunities available for increasing cell performance and making the MMFC a practical application device in the future.

1. Introduction

A fuel cell is an electrochemical conversion device. It converts the chemical energy in the fuel directly into electrical energy based on the electrochemical reaction between the supplied fuel and the oxidant [1,2]. Many studies have focused on the development of a new portable energy source, which had led to the rapid development of various types of fuel cells [3]. Membrane-less micro fuel cells (MMFCs) are a promising example of portable power sources due to their simple structure, which does not require a proton exchange membrane (PEM) [4,5]. MMFCs are also known as co-laminar fuel cells. They are a new promising energy source because they are easier to miniaturise than proton exchange membrane fuel cells (PEMFCs). MMFCs eliminate ohmic losses and reduce fouling problems due to the membrane. They also significantly reduce the size of the fuel cell, are simpler to fabricate and involve simpler water management [6]. Moreover, MMFCs use liquid fuel, which has a higher energy density compared to gaseous fuel. This difference is very important for portable power source applications to produce higher power output [7].

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0360-3199/$ – see front matter
http://dx.doi.org/10.1016/j.ijhydene.2013.09.135

Mass transport is the important key elements in an MMFC. An MMFC system requires improved mass transfer to better utilise fuel and produce a higher power output (power density). The mass transfer of the fuel and the oxidant in the system also need to be controlled to reduce the mixing region of the two liquids because the interface between the liquids is the only thing to act as the membrane. Hence, the key element to enhance mass transfer in an MMFC system is to reduce the mixing of the liquids (fuel and oxidant) and the depletion region at the electrode surface at both the anode and cathode. MMFCs most commonly operate at room temperature and ambient pressure and utilise the laminar flow phenomena of the two liquids that flow side-by-side in the microchannel [8,9]. The heat transfer during laminar flow and the microchannel system are mainly focused on heat sinks to cool the electronic device [10]. Overall, there is a need to better understand the mass and heat transport to improve the fuel cell performance and operating stability in MMFC systems.

This article primarily covers the mass transport of the MMFC system. Section 1 introduces the MMFC system, and Section 2 focuses on the description of mass transport in the MMFC system. Section 3 discusses the heat transport in the MMFC system, and then followed by Section 4, which focuses on the performance of the MMFC system. In Section 5, the discussions focus on the advancement of modelling and simulation in the MMFC field. Section 6 focuses on the challenges and opportunities available to improve MMFC performance. Finally, Section 7 presents the conclusions of this review article.

2. Mass transfer in MMFC

In general, the working principle of MMFCs starts with the combination of the liquid fuel and oxidant from two different streams under laminar flow conditions. At a junction, both streams merge and flow over the anode and cathode electrodes placed on opposing walls within the microfluidic microchannel [8,11–13] at a Reynolds number below approximately 2100. The dimensions of the microchannel are defined as less than 1 mm and greater than 1 μm, while the fluid flows in the channel are known to be microfluidic [14]. At a low Reynolds numbers, the viscous effects and surface forces tend to be more dominant than the inertial effects and body forces [15,16]. The fuel and oxidant react at the electrodes while the two liquid streams and their common liquid–liquid interface provide the required ionic conductance to complete the fuel cell chemistries. The hydrogen ions (protons) move from the anode to the cathode while the electrons move via the external circuit through the load, which generates electricity (Fig. 1).

Certain hydrocarbons, such as methanol and formic acid, are safer and yield higher energy densities because they can be stored in liquid form under ambient conditions. Hence, MMFC research had led to the use of various combinations of fuels and oxidants to utilise this advantage. Different fuel/oxidant combinations provide different energy density values. Some MMFCs have been demonstrated with methanol [17–23,49], vanadium [24–33], formic acid [8,34–40,49], hydrogen saturated electrolytes [41–44], gaseous electrolytes [45,46], and peroxide [47,48]. These fuels have been tested in both basic, acidic, and mixed media [17,49–51]. In addition, there were also MMFCs demonstrated with biofuels such as ethanol [49,52–54], glucose [55–63] and glycerol [64]. The factors that affect mass transfer in MMFCs are summarised in Table 1.

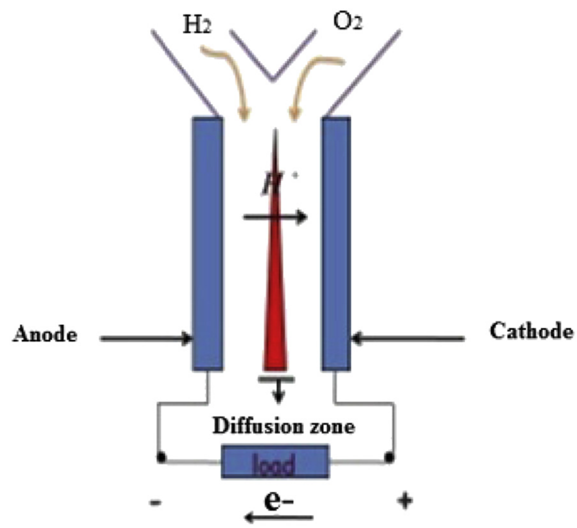

Fig. 1 – MMFC theoretical design.

2.1. Mixing region

One the factors that affects mass transfer in the MMFC system is the formation of the mixing region/inter-diffusion zone that occurs at the centre of the microchannel (Fig. 2a). When the anolyte (fuel) and catholyte (oxidant) travel towards the outlet of the microchannel, the laminar nature of the flow prevents convective mixing of the two solutions and sequesters the fuel and oxidant largely to their own sides of the channel. However, diffusion in a direction transverse to the flow creates a thin region around the liquid–liquid interface in the middle of the microchannel where the solution contains both fuel and oxidant; this zone is called the mixing region. In general, the mixing width is minimised in the middle of the channel cross-section and maximised near the wall. This difference causes the mixing width to have an hourglass shape in the channel cross-section (Fig. 2b).

In the MMFC system, the degree of mixing depends on the diffusivities of the species and the time they are in diffusional contact. The mixing in the microchannel can be controlled using the parameters involved in the Peclet number (*U*: average velocity, *H*: channel height, and *D*: diffusivity of

Table 1 – Factors affect mass transfer in MMFCs system.

No	Factor
1	Volumetric flow rate
2	Fuel and oxidant concentration
3	Microchannel geometry
4	Electrode geometry and placement