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Enhanced diffusion in polymer electrolyte membrane fuel cells using oscillating flow

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ABSTRACT

This study investigates the enhancement of the oxygen diffusion rate at the cathode of a proton exchange membrane fuel cell (PEMFC) due to pure oscillating flow. A unit cell of PEMFC using hydrogen fuel and oscillating air was tested. The experimental results show that the non-dimensional effective diffusivity varies linearly with the square of the Womersley number, when the Womersley number is close to unity. The non-dimensional effective diffusivity varies linearly with the Womersley number itself when the Womersley number is much larger than unity. Similar trend has been confirmed from the theoretical approach. Under the experimental conditions in this study, the reaction rate of oxygen increased linearly with respect to the sweep distance. The experimental results showed that a power density of 115.4 mW/cm^2 was obtained from the unit cell with oscillating flow, which is comparable to that obtained with forced flow. Therefore, an oscillating flow is found to be able to increase the concentration of the oxygen in the channel of PEMFCs, and consequently enhances mass-transfer, similarly to the use of forced flow using blowers or compressors.

1. Introduction

Lithium ion secondary batteries are one of the most widely employed power supplies for portable electronics. However, secondary batteries have some drawbacks such as aging, which causes their performance and charging capacity to decline considerably with time regardless of the intensity of their usage [1,2]. As an alternative, the fuel cells are receiving great attention as a potentially promising power source for various applications due to the high energy storage characteristics [2,3].

Driven by these needs, there has been considerable R&D (research & development) on the Proton Exchange Membrane Fuel Cell (PEMFC). In particular, there has been active research on the electrochemical aspects of PEMFCs [4,5]. However, there are some major problems such as cathode flooding, difficulties in optimizing operating conditions, as well as elucidating the electrochemical characteristics. Recently, many studies have focused on understanding of the physical factors that affect the system performance, such as water transport [2,6,7], temperature [8,9], humidity, differential pressure effect [8–12], and so on.

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Nomenclature

A	area of the cross-section of the channel, m^2
C	concentration, mol/m^3
C_S	number depending on the shape of the cross-section of the channel
d	hydraulic diameter of the cathode channel, m
D	diffusivity, m^2/s
f_c	function depending on the shape of the channel
F	Faraday constant, C/mol
j	current density, A/cm^2
J	molar flux, $mol/(s \cdot m^2)$
J_c	oxygen reaction rate, $mol/(s \cdot m^2)$
l	typical distance across the channel, m
n	number of electrons transferred in the reaction
R	symbol that is used to represent component transport due to augmentation
Sc	Schmidt number, ν/D
x	axis of the channel, m
V	tidal volume, m^3

Greek letters

α	Womersley number
δ	thickness of the GDL (gas diffusion layer)
ν	kinematic viscosity, m^2/s
ω	angular velocity, rad/s

Superscripts

o	bulk state in the channel
*	reaction surface

Subscripts

add	addition
c	cathode
ch	channel
eff	effective
G	GDL

One of the major challenges for the portable fuel cells is the minimization of the system size. To minimize the size of a fuel cell system, an air-breathing type of system may be considered [13]. However, the power output of an air-breathing fuel cell turns out to be too low and unstable due to the low diffusion flux and high probability of flooding, which highly depends on the ambient operating conditions [6]. If the reaction rate is higher than the diffusion rate in an air-breathing fuel cell, the fuel cell will not be able to increase the current density any further. Also, if flooding occurs in a fuel cell, either the fuel cell ceases to operate (i.e., voltage drops) or its performance becomes unstable. It is possible to solve these problems by using forced convective flow.

In this paper, we introduce pure oscillating flow to enhance diffusion at the cathode. The oscillating flow system can be of a smaller volume than a forced convection system. In a pure oscillating system, the initial concentration profile of concerned media, which is oxygen in this study, is flat in the channel; then, the concentration profile becomes a forward parabola when a forward oscillating pulse is applied. Such profile has a wide area that can augment diffusion. The materials with higher concentrations are transmitted to the low-concentration region. Then, the concentration profile becomes a backward parabola when a backward oscillating pulse is applied. The high concentration states are transmitted into this profile. Therefore, the materials of higher concentration are delivered to those of lower concentration through pure oscillating flow. The flow oscillator periodically generates air flow in and out of the channel. When air flows in the channel, it carries along oxygen into the channel. Then, the oxygen is transferred into the gas diffusion layer (GDL) due to molecular diffusion. Oscillating flow is different from the conventional forced flow, which means there is no net flow of nitrogen along the channel. For this reason, we have assumed that the oscillating flow is diffusion flow in the form of an effective axial diffusion coefficient, $D_{eff,ch}$.

In terms of the enhancement of mass transfer and mixing by oscillating flow, numerous reports have been published thus far. Bellhouse et al. [14] pioneered the investigation of how large fluid oscillations can improve fluid mixing and mass transfer in a furrowed channel. To verify the key parameters of oscillating flow, analytical studies have been conducted of axial dispersion in steady, laminar flow within a tube by Watson [15] and Kim and Shin [16]; experimental studies have been conducted by Joshi et al. [17], Kurzweg et al. [18], and Jaeger and Kurzweg [19]. Nishimura and Kojima [20] experimentally studied flow patterns and mass-transfer characteristics in a symmetrical sinusoidal wavy-walled channel for pulsating flow and showed that the combination of flow separation and fluid oscillation leads to a significant enhancement in the mass-transfer rate under laminar-flow conditions. Krantz et al. [21] explored the use of axial vibrations for a membrane tube bundle to increase the transfer of oxygen to the intra-lumenal flow; they were able to enhance the mass-transfer coefficient by a factor of at least 2.65. Nishimura et al. [22] performed an experimental study of mass transfer with a high Schmidt number in grooved channels for pulsating flow, focusing on the influence of the oscillating frequency. They revealed that high transport enhancement was realized in laminar flows and at intermediate Strouhal numbers.

Our study focuses on the application of the principle which, as described above, is the enhancement of mass transfer through oscillating flow in the cathode channel of fuel cells. The main purpose of this paper is to establish the feasibility of the application of pure oscillating flow to PEMFCs. Two important, non-dimensional parameters are introduced, which respectively represent the oscillating frequency and the oscillating amplitude. This study shows how these factors affect a unit cell's performance and the efficiency.

2. Experimental setup

To verify the effect of pure oscillating flow, an experiment was conducted using a PEMFC unit cell of the air-cooled type. The experimental setup appears in Fig. 1. Fig. 1(a) shows a piping