

Multistage polymer electrolyte fuel cells based on nonuniform cell potential distribution functions

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Abstract

In this paper, a novel multistage polymer electrolyte fuel cell concept is introduced according to which the cell potential is subject to a variation along the channel direction. A commonly used condition in which the cell potential is uniformly distributed along the flow direction is replaced herein by a generalized condition in which the cell potential is nonuniformly distributed along the flow direction. It is shown that the proposed multistage fuel cell concept involving nonuniform cell potential distribution functions allows to simultaneously generate electric power at various cell potentials without a reduction of the maximum electric cell power density. The proposed multistage fuel cell concept further allows for enhanced maximum electric cell power densities compared to the traditional concept involving a uniform cell potential distribution. An analytical model is used to perform quantitative calculations based on this concept. A conjugate gradient algorithm is implemented to optimize the cell potential distribution function along the flow direction. © 2005 Elsevier B.V. All rights reserved.

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1. Introduction

Polymer electrolyte fuel cells (PEFCs) have the potential to be established as novel energy conversion devices due to potentially high efficiencies and high power densities. In portable applications, the available volume for the fuel cell and fuel storage is limited. Miniaturization and the increase in electric power demand of portable applications require that fuel cells be continuously optimized with respect to maximum electric power densities and efficiencies. This can be achieved, for example by optimization of the geometric structure and the operating conditions of the fuel cell.

Several studies have been published addressing geometric optimization of the flow structure and the diffusion zone [1–10]. Cha et al. [4] investigated the effect of channel width on the performance of polymer electrolyte fuel cells. Earlier contributions addressing geometric optimization issues are due to He et al. [1] and Natarajan and Van Nguyen [3]. Porous materials as fluid distributors in polymer electrolyte fuel cells have been investigated in [5] based on a three-dimensional single-phase model. Improved electric power densities are predicted compared to traditional channeled systems due to reduced effective lengths at which the transport phenomena occur. Multi-scale tree network channels as fluid distributors constructing double-staircase polymer electrolyte fuel cells [9] and pyramidal direct methanol fuel cells [7] have been recently introduced. Such multi-scale flow structures obey more favorable scaling laws than existing fuel cell flow structures. A net power density has been introduced [7,9] that is defined as the difference

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Nomenclature

Latin symbols

b	catalyst layer width, m
C	constant
c	molar concentration, mol m^{-3}
D	diffusion coefficient, $\text{m}^2 \text{s}^{-1}$
E	cell potential, V
F	Faraday constant, $96,485 \text{ C mol}^{-1}$
h	channel height and width, m
i_{ex}	volumetric exchange current density, A m^{-3}
j	mean current density, A m^{-2}
k	index
L	total channel length, m
Le	Lewis number
l	thickness, m
m	number of discontinuities
Nu	Nusselt number
n	number of stages
P	electric power, W
Pr	Prandtl number
R	universal gas constant, $8.314 \text{ J K}^{-1} \text{ mol}^{-1}$
Sh	Sherwood number
T	cell temperature, K
U	open circuit potential, V
v	inlet flow velocity, m s^{-1}
z	number of electrons

Greek symbols

α	transfer coefficient
$\tilde{\beta}$	dimensionless parameter
$\tilde{\gamma}$	dimensionless parameter
κ	mass transfer coefficient, m s^{-1}
λ	length of a single stage, m
λ_{C}	characteristic length of oxygen consumption, m
λ_{D}	characteristic length of diffusion losses, m
η	cathode overpotential, V
ξ	inlet mole fraction of oxygen
$\vec{\phi}$	overpotential vector
$\vec{\vartheta}$	parameter vector
Ψ	performance parameter

Subscripts

b	diffusion layer
c	catalyst layer
h	in the channel
k	related to the k th stage
O_2	oxygen
ref	reference
st	standard case

Superscripts

\sim	dimensionless
s	stoichiometric

between the electric power density and the pumping power density required for fluid circulation. In these studies [7,9], it is recognized that it is imperative that fluid flow irreversibilities be considered in constraint optimization of polymer electrolyte fuel cells. A common method of these studies is to investigate fuel cell designs in which the transport phenomena occur at reduced effective lengths compared to the existing traditional counterparts, since irreversibilities caused by the various transport processes are due to the finite size of the energy conversion device. The aim of the present study is not on the geometric optimization aspects but rather on the optimization of the operating conditions of the fuel cell. Polymer electrolyte fuel cells are generally operated under a constant cell potential distribution along the channel [11–17]. Existing fuel cell models are usually solved based on this assumption [11–17].

In this paper, a novel multistage polymer electrolyte fuel cell concept is introduced according to which the cell potential is subject to a stepwise or continuous variation along the channel direction. A common boundary condition in which the cell potential is uniformly distributed along the flow direction is replaced herein by a boundary condition in which the cell potential is non-uniformly distributed along the flow direction. An ana-

lytical model is used to perform quantitative calculations based on this concept. A conjugate gradient algorithm is implemented to optimize the cell potential distribution function along the flow direction targeting at maximizing the electric cell power density.

2. The multistage fuel cell concept

In Fig. 1, the proposed multistage fuel cell concept is shown. The fuel cell has a length L and it is separated along the channel direction into n independent stages of length λ , given by

$$\lambda = L/(m + 1) = L/n, \quad (1)$$

where m is the number of discontinuities of the cell potential distribution function. Each stage has its own cell potential E_k . It is assumed that no physical or chemical interactions can occur between different stages. The proposed concept could be realized using segmented current collector plates that were originally developed to perform locally resolved current density measurements [18]. Such current collector plates are divided into electrically isolated segments allowing applying individual cell potentials to each segment. The concept could also

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