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Flow distribution in the manifold of PEM fuel cell stack

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Abstract

In this study, the pressure variation and the flow distribution in the manifold of a fuel-cell stack are simulated by a computational fluid dynamics (CFD) approach. Two dimensional stack model composed of 72 cells filled with porous media is constructed to evaluate pressure drop caused by channel flow resistance. In order to simplify this model, electrochemical reactions, heat and mass transport phenomena are ignored and air is treated as working fluid to investigate flow distribution in stacks. Design parameters such as the permeability of the porous media, the manifold width and the air feeding rate were changed to estimate uniformity of the flow distribution in the manifold. A momentum-balance theory and a pressure-drop model are presented to explain the physical mechanism of flow distribution. Modeling results indicate that both the channel resistance and the manifold width can enhance the uniformity of the flow distribution. In addition, a lower air feeding rate can also enhance the uniformity of flow distribution. However, excessive pressure drop is not beneficial for realistic applications of a fuel-cell stack and hence enhanced manifold width is a better solution for flow distribution.

Keywords: Fuel cell; Stack; Manifold; Porous media; Gas pressure; Flow distribution

1. Introduction

A proton exchange membrane (PEM) fuel cell is an electrochemical device where chemical energy is directly converted into electricity by using hydrogen as fuel and oxygen as oxidant [1]. A single PEM fuel cell can offer a voltage of ∼0.6–0.7 V. In order to increase the voltage sufficient for practical operations, many single cells are serially connected to fabricate the fuel-cell stack. Sufficient reactant feed is necessary for each cell to attain high performance and stable operation of stacks. The gas manifolds play a key role in the uniform distribution of reactant gases to the individual cells. A good manifold design is important to achieve the above requirement. An uneven flow distribution will result into performance loss as well as the stack may cease to function.

Till now most of the PEM fuel cell modeling works mainly focus on electrochemical, heat and mass transport phenomena in a single cell. The single cell models reported by Bernardi and Verbrugge [2,3], Springer et al. [4], Nguyen and White [5], Gurau et al. [6], are some of the examples. Recently, the Pennsylvania State University [7–12] in the US and University of Victoria [13–15] in Canada are reporting impressive modeling job.

The above mentioned single cell models deal with the construction of the fuel cell model based on the numerical techniques to simulate the related phenomena that occur within the fuel cell. The model parameters are normally verified with the experimental results. The models help to predict the performance characteristics and understand the physical phenomena that occur within the fuel cell.

In recent years, increasing number of researchers are focusing on the modeling of fuel-cell stack. The models are mainly focusing on the flow distribution and water-thermal management of stacks. Usually, the modelers ignore the complicated issues like electrochemistry and transport process in order to simplify the models. Koh et al. [16] have reported a numerical model to investigate pressure variation and flow distribution of stacks. This model considers channels filled with porous media to evaluate pressure drop caused by channel configuration. In addition, it compares flow distribution for different overall gas flow patterns. Karimi et al. [17] have developed a stack model with fluid

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Nomenclature

a	link coefficient
$\vec{F}_f$	wall shear force (N)
K	permeability (m^2)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
n	normal direction relative to outlet ports
N	number of cells
$\dot{p}$	production rate of κ ($m^2\,s^{-3}$)
P	pressure (Pa)
$\dot{Q}$	total mass flow rate of stacks ($kg\,s^{-1}$)
S	source term
$\vec{S}$	pressure action area (m^2)
t	time (s)
T_{in}	turbulence intensity
U	velocity vector ($m\,s^{-1}$)
$\vec{V}$	velocity vector ($m\,s^{-1}$)
x	Cartesian coordinates (m)

Greek letters

Φ	physical value
Γ	exchange coefficient
δ	tensor
ε	turbulent dissipation rate ($m^2\,s^{-3}$)
ϕ	porosity
κ	turbulent kinetic energy ($m^2\,s^{-2}$)
μ	viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
τ	shear stress ($N\,m^{-2}$)

Subscripts and superscripts

C	empirical constants
eff	effective property which accounts for porosity
in	inlets
i,j	components of a vector in Cartesian coordinates
sys	system
t	turbulent
σ	empirical constants
ϕ	general dependent variable

mechanics method. Reactant species such as hydrogen, oxygen, nitrogen, etc. were introduced into this model so that it can evaluate the relationship between the consumption rate of reactants and stack output power. Yu et al. [18] have proposed a water-thermal management model to investigate PEM fuel-cell stacks made from Ballard power system, Canada. This model can predict temperature, voltage, power, efficiency, etc. under steady and transient operations of stacks, respectively. Promislow and Wetton [19] proposed a steady heat transfer model of PEM fuel-cell stacks composed of parallel cooling channels and infinitely thin membrane electrode assembly (MEA). This model predicts not only the local temperature difference between coolant and MEA, but also the cell temperature variation.

The stack modeling mentioned above is mainly concerned with developing a numerical model characterizing gas flow distribution and water-thermal management. The above models were based on numerical analysis but not on computational fluid dynamics. These models could not investigate detailed stack flow field configuration and transport phenomena. Although simplified models can evaluate stack performance characteristics rapidly, it is also possible to obtain wrong results due to the over-simplification of the model.

Experimental data associated on the gas or coolant flow distribution is usually difficult to obtain. Therefore, indirect measurements like voltage or temperature distribution are used to understand the physical phenomena that occur in a fuel-cell stack. Due to the lack of experimental data, fuel-cell stack numerical models only provide theoretical explanations and understanding about performance characteristics. In this study, since there is no appropriate experimental data available, physical mechanism about flow distribution is investigated only by using purely theoretical approach. But it is indeed an available and acceptable method for studying phenomena that could not be experimentally measured or calculated.

This study presents a computational fluid dynamics model of PEM fuel-cell stack to investigate pressure variation and flow distribution. A two-dimensional model consisting of 72 channels filled with porous media is implemented for the theoretical analysis. The momentum balance theories proposed can explain pressure variation and pressure drop model can characterize the correlation between pressure variations and flow distribution. In addition, the influences of design parameters on flow distribution regarding channel flow resistance, manifold width and air feed rate will be discussed in detail.

2. Mathematical model

Stack two-dimensional model is shown in Fig. 1(a) and (b). The gases enter manifolds through inlet ports, and then are distributed into each cell and reach the electrodes through diffusion. After the electrochemical reactions are completed, un-reacted gases and products are discharged into manifolds from cells and then leave stacks through outlet ports. This flow field networks constitute an overall gas transport path. Besides simplifying stacks into two-dimensional model, other basic assumptions are as follows:

1. the flow is steady;
2. the flow is turbulent;
3. the incompressible air is used as working fluid;
4. electrochemistry, heat and mass transport phenomena are ignored;
5. the gravity force is ignored and reference pressure for 1 atm is set; and
6. the channels are filled with porous media.

Flow-field governing mechanism considered is turbulent. In order to simulate turbulent flow, κ–ε model is used to solve related transport equations. In addition, since channels are filled with porous media, treatment of porous media flow analysis is considered within turbulent model [20]. Governing equations are given as below: