Water transport in the proton exchange-membrane fuel cell: Comparison of model computation and measurements of effective drag

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Abstract

Water transport through the membrane of a PEMFC was investigated by measurement of the net drag under various feed gas humidity. Measured data were compared with computed results obtained using a two-dimensional cell model. Considering the change in the gas content related to the flow configuration, the humidity of the supply gas, reaction rates, and the mass balance of each gas species were derived at five sections along the flow channels. By solving these mass balance equations, the water transport rates and current density distribution were obtained along the flow channels for various feed gas humidity. The results for net drag computed from the model show a similar tendency, but are slightly higher than the measured values. This suggests that there is a certain resistance related to water transport at the cathode membrane interface in association with water production. The cause of this water transport resistance is discussed.
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Keywords: Proton exchange membrane fuel cell; Water transport; Water management; Net water drag; Capillary effect

1. Introduction

The proton exchange membrane fuel cell (PEMFC) has attracted a great deal of attention in the last decade as a promising candidate for a high-efficiency low-emission power source in both mobile and stationary applications. For mobile use, fuel cells are usually operated under a relatively high current density in order to achieve higher power density. For stationary use, fuels cell are usually operated under moderate current density, in order to achieve higher efficiency. However, there are still many problematic issues that must be overcome. One major problem is the water management of fuel cells. The operation of a state-of-the-art PEMFC requires careful water management. At low humidity, the proton exchange membrane and electrode assembly (MEA) lose water, which leads to a rapid increase in ohmic resistance. Conversely, if too much liquid water is present in the cell, the pores in the electrodes will be filled with water and the passage of reactant gases obstructed. In other words, the operating conditions and MEA components have to be well matched in order to avoid membrane dehydration and cathode

flooding. In addition to the experimental approach, models for water management are useful to understand the processes that govern water transport. A clear understanding of water transport processes will assist the optimization of fuel cell operating conditions and relevant electrode structure.

Several experimental results have been reported in the literature for the water transport in proton exchange membranes (PEM), such as the net drag coefficients measured by Janssen et al. [1]. Although their investigation was mainly related to the effect of humidity, the humidity of the inlet gas was limited to a dry or wet condition. Ren et al. reported measurements for the electro-osmotic drag of water of a PEM in a direct methanol fuel cell (DMFC) [2]. The experiments were performed under the condition that the water flux across the membrane was exclusively driven by the electro-osmotic drag. Dong et al. reported current distribution, species distribution, and HFR (high frequency resistance) data, using a single serpentine flow channel in a co-flow arrangement, under mainly low-humidity conditions [3]. Experimental data suggest that humidification of the anode, rather than the cathode, was demonstrated as a most critical factor for achieving high performance at the inlet region.

It is useful that these experimental results are compared with computed results from a cell model. In addition to exper-

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Nomenclature

a_j	activity of water in stream j (anode, cathode)
C	concentration of water in the membrane (mol cm^{-3})
D_w	diffusion coefficient of water $(\text{cm}^2\,\text{s}^{-1})$
e	ratio of actual to apparent surface area
f_j	fraction j (solid s, open o) of porous surface
F	Faraday constant $(96,485\,\text{C mol}^{-1})$
i_0	exchange current density (A cm^{-2})
I	local current density (A cm^{-2})
m	molar flow rate (along flow direction)$(\text{mol s}^{-1}\,\text{cm}^{-2})$
n_d	electro-osmotic drag coefficient
N_w	molar flux of water (perpendicular to the MEA) $(\text{mol s}^{-1}\,\text{cm}^{-2})$
p	pressure (kPa)
r	pore radius
R	gas constant $(8.314\,\text{J mol}^{-1}\,\text{K}^{-1})$
S	surface area of the catalyst layer (cm^2)
t_d	dew point of feed gas (°C)
T	temperature (K)
V_o	open circuit voltage (V)
x	coordinate along the gas channel
y	coordinate perpendicular to the MEA

Greek symbols

α	net drag of water per proton
γ	surface tension
δ	thickness
ε	porosity of the electrode
η	over-potential for the ORR, V
ζ	stoichiometry
θ	contact angle
ρ	density of the catalyst layer
σ	conductivity of the membrane $(\Omega^{-1}\,\text{cm}^{-1})$
τ	tortuosity factor

Subscripts

a	anode
c	cathode
in	inlet
m	membrane
out	exit
sat	saturation
v	vapor

imental investigation, much research has been performed for PEMFC modeling, which range from one-dimensional to three-dimensional models [4–11]. A one-dimensional model neglects the variation in the water content of the membrane, and the gas concentration along the flow channel. In order to investigate the distribution of gaseous species, the water content of the membrane, the current density and the net water transport along the flow channel, two-dimensional models have been developed.

Nguyen et al. developed a combined heat and mass transfer model for a co-flow configuration under the condition that all of the water in the electrodes is in the vapor phase [7]. Janssen presented a two-phase, two-dimensional, along-the-channel model [8]. The model explains the water transport in electrodes under saturated and non-saturated gas conditions, by applying the concentrated solution theory under the assumption of uniform current density at all locations. During PEMFC operation with unsaturated reactant gases, especially at low stoichiometric flow rates, liquid water is likely to appear in the cathode. Pasaogullari and Wang modeled the two-phase flow and transport in the air cathode of a PEMFC, and concluded that capillary action is dominant inside the two-phase zone [9]. Recently, three-dimensional models have been developed to investigate the distribution of current density and temperature in the MEA and gas diffusion layer (GDL), and the distribution of gas velocity and gaseous species in the cross section of the GDL and flow channel under higher power density [10,11].

There have been few reports concerning the comparison of water net drag experimental results and computed simulation results. The purpose of the present work is to compare experimental net drag data, obtained under various reactant gas humidity and different operation modes, with the results computed using a relatively simple two-dimensional cell model.

2. Measurements of net drag

2.1. Experimental apparatus for net drag measurement

The change of water content in both the anode and the cathode flow channels was measured under various cell-operating conditions. A 25 cm² MEA was constructed using a Nafion112 membrane with a platinum loading of $0.5\,\text{mg cm}^{-2}$ on both the anode and cathode. The MEA was mounted between two graphite current collector plates, each of which contained a serpentine channel machined to a width of 1 mm and a depth of 1.0 mm. The MEA was installed between two gaskets in order to prevent gas leakage. A counter flow configuration was used. Table 1 gives the specifications for the MEA.

The cell was operated at constant temperature, which was controlled by an electric heater. The feed gas humidity was controlled by bubbling of the gas through water that was maintained at a set-point temperature. At the exits of the gas flow channels, the water vapor was condensed in cold traps and the amount of water was measured at both the anode and the cathode. Before loading the platinum catalyst, a thin, hydrophobic, microporous layer was applied to the interface of the catalyst layer/GDL.

Table 1
Parameters used for the test cell

Parameter	Symbol	Value
Membrane equivalent weight	E	1200
Membrane thickness	δ_m	50×10^{-4} cm
Membrane dry density	ρ	1.84
Catalyst layer thickness	δ_{cat}	10×10^{-4} cm
GDL thickness	δ_{GDL}	300×10^{-4} cm
Tortousity factor	τ	5