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Asymptotic analysis for the inlet relative humidity effects on the performance of proton exchange membrane fuel cell

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HIGHLIGHTS

- A novel inlet humidification efficiency (IHE) model is proposed.
- The IHE model could carry out the dynamic inlet humidification efficiency.
- The contours of species distribution are shown to make up the experiments.
- The inlet humidification efficiency is 57% at 40% RH (70 °C operating temperature).

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ABSTRACT

In order to study the inlet relative humidity (RH) effects on the performance of proton exchange membrane fuel cell (PEMFC), the inlet humidification efficiency (IHE) model is proposed. The total water content of PEMFC is consisted of two parts including the internal electro-migration water content and the external water content of the humidified gas. The dynamic inlet humidification efficiency is derived. The current density of PEMFC is calculated by the incorporating parameters including inlet humidification efficiency and water content of the humidified gas in the IHE model. Firstly, the schedule diagram of calculation is given and the geometric model is established according to actual size of PEMFC. The computational meshes are partitioned by using the software (Gambit). The IHE model is imported into the computational fluid dynamics software (Fluent). Secondly, the experimental system is established and experiments have been done at the operating temperature of 70 °C and at 40% RH, 55% RH, 70% RH, 85% RH and 100% RH, respectively. Finally, the contours of H_2O molar concentrations (both in anode channels and cathode channels), membrane water content (MWC) and polarization curves of the IHE model, the Fluent model and experimental are compared and analyzed at above experimental conditions. The results show that the species distribution uniformities of the IHE model such as H_2O molar concentrations (both in anode channels and cathode channels) and MWC are the best when the PEMFC at 100% RH. When the operating temperature is 70 °C (40% RH and 350 mA/cm^2), the accuracy of the IHE model is improved by 79% compared with the Fluent model. When the operating temperature is 70 °C (40% RH and 350 mA/cm^2), the inlet humidification efficiency reaches 57%.

1. Introduction

In recent years, owing to the environmental pollution problems and major concerns on the depletion of petroleum based energy resources, the interests of the various types of clean power sources and renewable energies are more focused [1–6]. Among them, proton exchange membrane fuel cell (PEMFC) is a new kind of the renewable energy-conversion device which directly converted the chemical energy of hydrogen and oxygen into electrical energy and heat through the electrochemical reactions [6–15]. PEMFC has high energy conversion, high efficiency, low emissions, highly reliability, low operation temperature (20–90 °C) with the consequent quick start-up and other advantages [5,8,16–22]. However, there are several issues in commercialization of PEMFC [20]. Among them, one of the most important issues is water management problem, which is mainly managed two parts including both the water content of humidified gas and the electro-migration water content. The water content of the humidified gas is affected deeply by relative humidity (RH). Hence, many

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Nomenclature

ϕ_{wh}	water content produced by electrochemical reactions, mol/(cm^2·s)
n_d	electro migration coefficient
I	current density, A/cm^2
F	Faraday constant, 96,487 C/mol
λ	water content in proton exchange membranes
α	water saturation
P_{WV}	water vapor pressure, Pa
P_{sat}(T)	saturation pressure, Pa
ϕ_{wih}	water content of the humidified gas, mol/(cm^2·s)
d	humidity ratio, g/kg
Q_m	mass flow, kg/s
φ	relative humidity, %
P_s	water vapor saturation pressure, Pa
P	atmospheric pressure, Pa
Q_{m,H_2}	H_2 mass flow, kg/s
λ_{H_2}	H_2 excess coefficient
N	series connection cell number
$Q_{m,Air}$	air mass flow, kg/s
ϕ_w	total water content of PEMFC, mol/(cm^2·s)
e_{ih}	inlet humidification efficiency

Abbreviation

PEMFC	proton exchange membrane fuel cell
RH	relative humidity
IHE	inlet humidification efficiency
MWC	membrane water content
MEA	membrane electrode assembly
CFD	computational fluid dynamics
PEM	proton exchange membrane

researchers took active steps to research the effects of RH on the performance of PEMFC and improve the performance of PEMFC.

Owing to a lot of difficulties in measuring species movement and distribution inside PEMFC, numerical simulation has become an effective research method to solve above problems at a certain extent. Several researchers conducted some researches mainly through numerical simulation, which could be categorized as one-dimensional model, two-dimensional model and three-dimensional model. For one-dimensional model, Karpenko-Jereb et al. [23] described the dependence of diffusion and electro-osmotic coefficient using linear functions through establishing a model for development describing charge transport and water in the fuel cell. This model considered three driving forces including electrical potential, concentration and pressure gradients. For two-dimensional model, Lei et al. [24] described the liquid water profiles inside the membrane electrode assembly (MEA) through a two-phase flow, along-the-channel, non-isothermal model, which was taken into account all the major transports and electro-chemical processes except for the reactant species crossover through the membrane. For three-dimensional model, Houreh and Afshari [25] developed a model which was consisted of a set of coupled equations including conservations of mass, momentum, species and energy to study and compare the performance of humidifiers with counter-flow and parallel-flow configurations. The results revealed that at dry side, an increase in temperature and a decrease in mass flow rate resulted in a better humidification performance. Iranzo et al. [26] presented a CFD 50 cm^2 fuel cell model to predict the liquid water distributions inside the fuel cell. The model was validated against a piece of experimental data. The results revealed the model values matched well the experimental values. They also compared the local liquid water distributions predicted by the model with the liquid water distributions of the real cell. The qualitative results showed a good agreement between them.

However, the numerical simulation on the PEMFC may not be sufficient and accurate, experimental study can be complimentary to the simulation. Several researchers also did experimental researches from two aspects: single fuel cell and fuel cell stack. For single fuel cell, Zhang et al. [27] studied three operational parameters including back pressure, RH and air stoichiometry had influences on the performance of PEMFC. Their results showed that the performance of PEMFC was better with the increase of the RH, but the stability sustained. For fuel cell stack, Nandjou et al. [28] conducted the durability test to study and quantify effects on automotive application. In the test, they investigated the local performance by in situ measurement of a printed circuit board. They found that local deposits in the cell were caused by water evaporation and the probability of the bipolar plate corrosion increased largely with accumulated water condensation. F. Migliardini et al. [29] conducted the experiments on PEMFC stacks of three different sizes. Then they analyzed humidification problems of PEMFC and considered the internal and external humidification methods. The effects on humidification methods of membrane hydration were evaluated by its power loss rate and the performance of stacks. The external humidification was effective in most operating conditions. But the effects of external humidification were limited when the stacks had high temperature, low load or the membrane is in a dry state.

Many researchers made valuable achievements in the field of RH for the performance of PEMFC through simulation and experiments, but they qualitatively studied the effects from the variation trend and did not have a quantitative analysis for the RH effects on the performance of PEMFC. In this paper, firstly, the inlet humidification efficiency (IHE) model is proposed. The inlet humidification efficiency is calculated by the internal electro-migration water content and the external water content of the humidified gas in the IHE model. Furthermore, the current density of PEMFC is calculated by the inlet humidification efficiency and the water content of the humidified gas. Secondly, the schedule diagram of calculation is given and the geometric model is established according to actual size of PEMFC. The computational meshes are partitioned by using the software (Gambit). The IHE model is imported into the computational fluid dynamics software (Fluent). The experimental system of PEMFC is established. The experiments are conducted at the operating temperature of 70 °C, at 40% RH, 55% RH, 70% RH, 85% RH and 100% RH, respectively. Finally, the contours of H_2O molar concentrations (both in anode channels and cathode channels), membrane water content (MWC) and the polarization curves of the IHE model, the Fluent model and experimental are compared and analyzed at above experimental conditions.

2. IHE model

The IHE model introduces the item of electro-migration water content in Springer [30] model ϕ_{wh}, which is water content produced by electrochemical reactions. This item is related to the current density of PEMFC.

The water content of electro-migration in the proton exchange membrane is:

$$\phi_{wh} = n_d \frac{I}{F} \tag{1}$$

where ϕ_{wh} is the water content produced by electrochemical reactions (mol/(cm^2·s)), I the current density (A/cm^2), F Faraday constant (96,487 C/mol), n_d electro migration coefficient [31] namely the number of water molecules per proton transfer and λ is water content in proton exchange membranes namely the number of water molecules per sulfonic acid group.