Experimental and thermodynamic approach on proton exchange membrane fuel cell performance

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ABSTRACT

The present work is employed in two sections. Firstly the effect of different parameters such as pressure, temperature and anode and cathode channel depth on the performance of the proton exchange membrane (PEM) fuel cell was experimentally studied. The experimental result shows a good accuracy compared to other works.

Secondly a semi-empirical model of the PEM fuel cell has been developed. This model was used to study the effect of different operating conditions such as temperature, pressure and air stoichiometry on the exergy efficiencies and irreversibilities of the cell.

The results show that the predicted polarization curves are in good agreement with the experimental data and a high performance was observed at the channel depth of 1.5 mm for the anode and 1 mm for the cathode. Furthermore the results show that increase in the operating temperature and pressure can enhance the cell performance, exergy efficiencies and reduce irreversibilities of the cell.

1. Introduction

Increasing global energy consumption has had and will continue to have many detrimental effects on the earth's environment. One of the most noticeable results is the growing problem of air pollution around the earth [1]. On the other hand the depletion of fossil fuel and increase of oil price lead to new energy sources. The energy conversion technology which receives considerable attention recently is the fuel cell, a potential replacement for the conventional internal combustion engine.

The PEM fuel cell is an electrochemical energy conversion device, which converts the chemical energy of hydrogen and oxygen directly and efficiently into electrical energy, with waste heat and liquid water as by-products. A PEM fuel cell powered automobile using hydrogen, offers several advantages, such as low temperature operation and quick start-up that is compatible with renewable energy sources and can obtain a power density competitive with the internal combustion engine. However, the major barriers which are hindering the commercialization of PEM fuel cell powered automobiles are cost and hydrogen infrastructure.

One of the means of reducing the cost of PEM fuel cell powered automobile is by improving the performance of the PEM fuel cell itself. A proven method of enhancing the performance of energy and exergy analysis of the systems is optimization of operating conditions of the cell such as operating temperature, pressure and the gas channel depth. Djilali and co-workers [2,3] using a three-dimensional computational model for a single cell with an active area of 25 cm^2 and single-serpentine flow field, investigated the influence of this parameter on the cell performance. Recently Maher [4] has been investigating the effect of these parameters on cell performance by using the semi-empirical equations. Atul Kumar and Reddy [5] studied the effect of channel depth of the anode side on the hydrogen consumption using computational modeling.

Cownden et al. [6] performed the exergy analysis of the hydrogen fuel cell power system for bus transportation. Their work showed the usefulness of the thermodynamic analysis in determining the irreversibilities in different system components. Kazim [7,8] has conducted exergy analysis of a PEM fuel cell at specified operating voltages of 0.5 and 0.6 V. They reported the exergy efficiency of the PEM fuel cell at different operating conditions.

The present study experimentally investigated the effect of different parameters such as pressure, temperature and channel geometry at different operating voltages.

As experimental cost is too high a semi-empirical model was used to evaluate the polarization curve and finally exergy analysis was carried out to optimize the operating parameter for best performance of the cell.

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Nomenclature

A	cell area (cm^2)
C_p	specific heat ($kJ\,kg^{-1}\,K^{-1}$)
$C_{O_2}^{interface}$	oxygen concentration at the cathode membrane/gas interface ($mol\,cm^{-3}$)
ex	exergy ($kJ\,kg^{-1}$)
$F=96,485$	Faraday constant ($C\,mol^{-1}$)
h	enthalpy ($kJ\,kg^{-1}$)
h_c	channel depth (mm)
I	current (A)
i	current density ($A\,m^{-2}$)
K	specific heat ratio
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
P	pressure (atm)
$P_{H_2}^*$	partial pressure of hydrogen at anode catalyst/gas interface (atm)
$\dot{Q}$	rate of heat lost (W)
r_M	membrane-specific resistivity for the flow of the hydrated protons ($W\,cm^2$)
S	entropy ($kJ\,kg^{-1}\,K^{-1}$)
T	temperature (K)
V	cell potential (V)
$\dot{W}$	power (W)
x	mole fraction

Greek letters

β	semi-empirical coefficients for calculation of activation overpotential
ε	cell efficiency (%)
η_{act}	activation overpotential (V)
η_{diff}	diffusion overpotential (V)
η_{ohmic}	ohmic overpotential (V)
λ	stoichiometry
μ	chemical potential ($J\,mol^{-1}$)

2. Fuel cell component

The PEM fuel cell system considered in the present study is a single cell with an active area of 25 cm^2 and single-serpentine flow field [9] geometries. The width and land width of the channel were selected to be 1 and 0.8 mm respectively.

The channel depth of 1 and 1.5 mm was considered for empirical work. For a bipolar plate, non-porous graphite [10] is selected.

A Nafion 117 membrane with 4 mg Pt cm^{-2} for the anode and cathode was employed as a membrane electrode assembly. On both sides of the MEA, there were 270-mm thick carbon papers that acted as diffusion layers. The experimental setup is shown in Fig. 1.
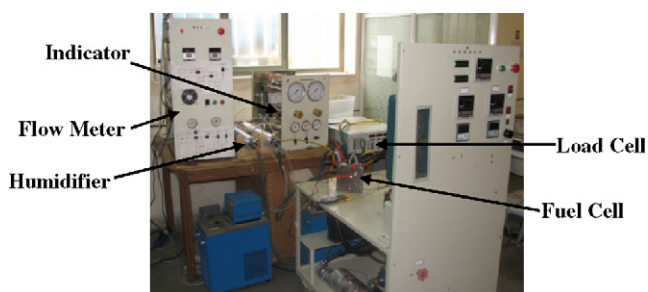

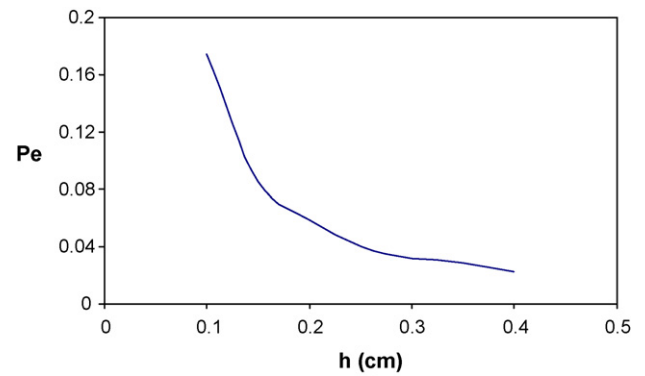**Fig. 1.** Single cell with the experimental setup.

Fig. 2. Relative influence of convection (as determined by the Peclet number) for various channel depths.

3. Selection of channel dimension

3.1. Anode side

Kumar and Reddy [5] have simulated the performance of the anode side of the PEM fuel cell. Their work shows that for high hydrogen consumptions, the optimum dimensions for the channel width, land width and channel's depth were 1.5, 0.5 and 1.5 mm, respectively. But by considering the principle that an increase in the ribs' width causes diffusion mass limitation beneath the ribs and decreasing the sectional area of the channel can increase velocity of the gas in the channel and help in the removal of water droplet and lastly because of the construction problem and possibility of ribs breaking, the dimensions of the channel's width and land width were selected 1 and 0.8 mm respectively.

For the channel depth two dimensions of 1 and 1.5 mm for empirical work were considered.

3.2. Cathode side

Watkins et al. [11] studied the optimal dimensions for a bipolar channel on the cathode side of the fuel cell. They claimed the most preferred range to be 1.14–1.4 mm for the channel width, 0.89–1.4 mm for the rib width. So based on considering the principles which are presented in the anode side, the dimensions of 1 and 0.8 mm are used for channel width and rib width respectively.

For a selection of the channel depth at the cathode side, consider the two primary mechanisms for mass transport in fuel cells, binary diffusion and convection. In Refs. [12,13] these two mechanisms were considered and it was shown that if the convection dominates the transport, the cell would have a better performance.

One of the important criteria that influencing the convection is Peclet number, which compares the relative importance of the convection versus diffusion.

As it is distinguished in Refs. [12,14] the Peclet number depends on many parameters, so by holding porosity, permeability, channel length, channel and ribs width constant, the effect of the channel depth on the Peclet number was considered.

As is shown in Fig. 2, by increasing the channel depth, for the cathode side, more than 2 mm, the Peclet number will decrease and then the convection phenomenon and cell performance decrease especially in high current density.

So according to the result of this section and similar to the anode side, the two dimensions of 1 and 1.5 mm for the empirical work were considered.

As mentioned before in this section a semi-empirical model was employed to reduce the number of tests for evaluation of polarization curve.