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Effect of changing the water balance on electro-osmotic flow in an elliptical single proton exchange membrane fuel cell

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ABSTRACT

In this study, the effect of water balance variation on electro-osmotic flow in a fuel cell with elliptical cross section has been investigated experimentally. By changing the humidity on both sides of the fuel cell, required data for electro-osmotic flow and back diffusion were calculated. In addition, using the balance equations for water's mass at anode and cathode, the values of the electro-osmotic flow and back diffusion in different current densities were found. Results show that variations of the electro-osmotic flow and back diffusion change linearly with current density and slope of the curves increase by increasing in humidity. Besides, after a certain value, humidity raise has a negligible effect on curves of electro-osmotic flow and back diffusion. In other words, there is an optimum value for humidity at anode and cathode side. Based on the results, it was determined that increasing in humidity at anode side has a more desirable effect than the cathode. For instance, when cathode and anode had the humidity level of 0% and 70% respectively, maximum current density of the fuel cell was recorded about 0.86 A/cm^2 but when cathode and anode had the humidity level of 70% and 0% respectively, maximum current density of the fuel cell was obtained about 0.512 A/cm^2. Using available equations, electro-osmotic coefficients were also calculated and their variations with respect to current density and humidity level were outlined. Results show that electro-osmotic coefficient remains constant with respect to current density, while it increases with increasing the humidity. In this work, electro-osmotic coefficients varied between 0.636001 and 1.632476, which were in a good agreement with the values in other related papers.

1. Introduction

Since the world's energy resources and reserves are limited, humans look everyday for ways to maximize the efficient use of available energy resources. One of the energy converters in which the chemical energy of fuel converts to electric energy is the fuel cell. It, with no long history, has received much attention by researchers and scientists in recent decades. There are different kinds of fuel cells that can be used in various operating and environmental conditions as Proton Exchange Membrane Fuel Cell (PEMFC) is one of them.

One of the issues of particular importance in the PEM fuel cell is the wettability of membrane. Wettability of membrane increases proton conductivity from the anode to the cathode and loss of water makes proton conductivity difficult. In the PEM fuel cell membrane, the proton, moving from the anode to the cathode, transfers water molecules with it, so the anode water decreases as a result. Loss in anode water and consequently, the increase in the cathode water impairs the fuel cell performance and results in a drop in the efficiency. Checking the water content in various parts of the fuel cell is an important issue on which various researches, tests and modeling. Clearly, there are no sufficient researches and tests in this area and certainly, more research is needed in this regard.

Karimi and Li [1] modeled the electro-osmotic flow in the polymer membrane along with electro-kinetic effect, and determined the key parameters affecting the PEM fuel cell performance. Mulyazmi et al. [2] investigated the water balance in a PEM fuel cell based on the water transport phenomena. In this investigation, the diffusion of water from the cathode side to the anode side of the cell was observed to not occur at 20% relative humidity at the cathode and 58% relative humidity at the anode. Yan et al. [3] examined the water balance in the PEM fuel cell measuring the net drag coefficients under different conditions. They also studied the effects of water balance in the membrane on the fuel cell

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performance under various operating conditions. Luo et al. [4] presented a new method based on hydrogen pump to measure the electro-osmotic drag coefficient and proton conductivity in Nafion 117 membrane under similar condition to operating PEM fuel cell. Zhang et al. [5] investigated the transport of water vapor from the cathode to the anode and the effect of water vapor on the performance of a single cell high temperature PEM fuel cell using a commercial PBI-based membrane electrode assembly (MEA). Rakhshanpouri and Rowshanzamir, a seven-layer theoretical model proposed that included anode and cathode inlet channels, GDLs, CLs, and the Nafion 117 proton exchange membrane. The mathematical model was a one-dimensional, steady-state, isothermal and isobar to describe the water transport phenomena in PEM fuel cell [6]. Zhou et al. [7] studied the effects of pressure and water on a single PEM fuel cell. Karpenko-Jereb et al. presented the development of a 1D model describing water and charge transport through the polymer electrolyte membrane in the fuel cell. The dependencies of diffusion and electro-osmotic coefficients on the membrane water concentration described by linear functions [8]. Tiss et al. [9] developed a two-dimensional computational fluid dynamics model of PEM fuel cell by taking into account the electrochemical, mass and heat transfer process occurring in the cathode compartment. This model included the effect of water content in the membrane swelling phenomenon. Zhang et al. [10] analyzed the water balance within a PEM fuel cell, and introduced multiple equations as the functions of input and output pressures of the fuel cell gas flow, the input relative humidity, temperature, pressure losses across the flow channels and the partial pressure of the reactants. Bezmalinović et al. carried out a study of water transport in a high temperature phosphoric acid doped polybenzimidazole (PBI) membrane fuel cell stack. Tests with different stoichiometries of dry cathode and different humidity levels of anode are performed. The water transport was a strong function of current density but it also depended on stoichiometry and humidity level [11]. Perng et al. [12] investigated how modified flow field affected non-isothermal transport characteristics and performance of the PEM fuel cell by the finite-volume SIMPLEC method coupled with preconditioned conjugate gradient methods. The results demonstrated that the narrowed flow channel with ribs opposite the protuberant catalyst layer surface had the best increase rate in cell performance. Husar et al. [13] measured water transport in situ through the membrane regarding the separate mechanisms in a PEM fuel cell. Park and Caton using water balance tests, obtained electro-osmotic drag coefficients (n_d) in Nafion 115 membrane under different conditions as a function of humidity and thermodynamic conditions [14]. Park investigated the effect of polytetrafluoroethylene coated gas diffusion medium on the water content in the membrane electrolyte. Numerical simulation suggested that the optimum water saturation was between 0.1 and 0.3 at the gas diffusion medium to hydrate the membrane electrolyte sufficiently without significantly blocking the diffused species under non-humidification conditions [15]. Cha et al. [16] the effects of the clamping force on the water transport and performance characteristics of a PEM fuel cell experimentally investigated with variations in the relative humidity and current density. The water transport characteristics were analyzed by calculating the net drag coefficient. Dai et al. reviewed the experimental studies and modeling works on the water transport and balance in various components of MEA [17]. Li et al. [18] reported the preparation and characterization of porous polybenzimidazole membranes doped with phosphoric acid. In addition, they tested the performance and stability of the porous PBI membrane in high-temperature proton-exchange-membrane fuel cells. Liso et al., a novel mathematical zero-dimensional model formulated for the water mass balance and hydration of a polymer electrolyte membrane. This model incorporated all the essential fundamental physical and electrochemical processes occurring in the membrane electrolyte and considered the water adsorption/desorption phenomena in the membrane [19]. Saeed et al. [20] studied several variables in order to evaluate the performance of PEM fuel cell with an active area of 25 cm^2. Also, they added SiO_2 particles to the Nafion polymeric matrix using sol–gel method in order to increase the performance of membrane. Das et al. [21] for investigating the water transport in the cathode catalyst layer (CCL) of a PEM fuel cell performed a one-dimensional analytical solution of water transport across the CCL using the fundamental transport equations. Hsieh et al. [22] conducted time-dependent measurements of pressure drop in different flow fields on the cathode of a PEM fuel cell with different flow rates and temperatures on current distribution. In addition, they investigated the effects of pressure drop, flow rates and cell temperature on water accumulation. Bao and Bessler developed a two-dimensional single-phase model for the steady-state and transient analysis of polymer electrolyte membrane fuel cells. They used the model to analyze the effects of operating conditions on current output and water management, especially net water transport coefficient along the channel [23]. Mahmoudi et al. [24] investigated numerically the effects of inhomogeneous compression of GDL at the cathode side of PEM fuel cell with interdigitated flow field on water management and cell performance. Jeon et al. studied the effect of cathode relative humidity on the PEM fuel cell focusing on its self-developing function [25]. Misran et al. [26] have experimentally investigated the effect of the water content within the PEM fuel cell membrane in the dry and humidity 100% states at different temperatures by electro-osmotic drag coefficient, back diffusion coefficient.

In this paper, we focused specifically on electro-osmotic coefficient and the level of its changes was obtained by the change in water balance and the empirical relationships. Also the relationships related to the water mass balance were analyzed. In this research experimental setup, the water balance change was created by changing humidity in the anode and cathode inlet gases and the humidity changed between dry and 100% states. By changing the humidity and recording the data of different parts of the fuel cell and using the existing empirical and thermodynamic equations, electro-osmotic drag coefficients were calculated and analyzed at different states. It should be noted that besides electro-osmotic flow, back diffusion flow was also studied due to its relationship with the water balance in the membrane.

2. Experimental setup

The dimension of mentioned fuel cell is 4.5 cm × 9.5 cm × 10.1 cm. The MEA is constructed using catalytic-coated membrane method [27,28]. Nafion ionomer is used as a proton conducting membrane in the MEA and the loading of Pt electrocatalyst (IERC Research Center, M. Nasr) on both anode and cathode is 4 mg/cm^2 [29]. Also, the gas diffusion layers on both sides of proton exchange membrane are made of carbon clothes and the bipolar plates as a conductor of electric current are made of graphic. The stainless steel plates are used to maintain the MEA. In addition, the channels are in form of four serpentine flow fields with an elliptical cross-section. The dimensional characteristics of single PEM fuel cell are shown in Table 1.

To achieve the required data, in addition to the single fuel cell, equipments such as rotameter, pressure gauge, humidifier, thermometer, condenser, gas capsule and digital scale were also needed that were all used in a workbench. Fig. 1 shows a schematic of the experimental setup.

In this work, the oxygen was used instead of air on the cathode side. The pressure of hydrogen and oxygen were considered 2 bar in all tests and the fuel cell temperature was also considered