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The influence of humidification and temperature differences between inlet gases on water transport through the membrane of a proton exchange membrane fuel cell

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HIGHLIGHTS

- Water transport tendency is quantified by calculation of collected water mass.
- This transport is proved by the effect of temperature gradient of two electrodes.
- Electro-osmosis and back diffusion were suppressed by temperature gradient.
- The suppression effect to electro-osmosis was more than to back diffusion.
- Water transport direction can be controlled by modifying the heating temperature.

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ABSTRACT

This paper discusses the effects of humidification and temperature differences of the anode and cathode on water transport in a proton exchange membrane fuel cell. Heaters are used to cause a difference in gas temperature between two electrodes before the gases enter the fuel cell. The results show that when the temperature of the cathode is higher than that of the anode, the electro-osmotic drag is suppressed. In contrast, when the temperature of the anode is higher than that of cathode, it is enhanced. These effects are more significant when the temperature difference between the anode and cathode is greater. The same trends are seen with back diffusion. Three cases are tested, and the results show that the suppression due to the temperature difference occurs even when the relative humidity is low at the hotter side. The water transport tendencies of electro-osmotic drag and back diffusion in different situations can be expressed as dominant percentages calculated by the water masses collected at the anode and cathode. The suppression effect due to the temperature difference is relatively insignificant with regard to back diffusion compared to electro-osmosis, so water tends to accumulate on the anode rather than the cathode side.

1. Introduction

Polymer electrolyte membrane fuel cells (PEMFC) are considered to be an attractive power source for automotive applications, as well as stationary power systems, due to advantages such as high power density, low operating temperature, high energy efficiency, low noise, and absence of polluting emissions. However, the key challenge of this clean energy with regard to commercialization is its high cost. Water management is a critical issue in the operation of a PEMFC [1–3], and water transport in such devices mainly occurs in three ways. The first is electro-osmotic drag from the anode to cathode when the cell is under an electronic load. The second is back diffusion from the cathode to anode when there is a water activity gradient across the membrane [4]. The third is hydraulic permeation when there is a pressure differential across the membrane [5]. In a membrane electrode assembly (MEA), the membrane should be kept well-hydrated to ensure good proton conductivity. If the membrane is over-saturated, the excess water will block the gas access and cause a decline in performance. In contrast, drying of the membrane will increase its ohmic resistance and decrease the

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proton conductivity [6], also harming performance.

Many researchers have studied the water transport phenomena in MEA, and most of the related works include experimental results and modeling predictions/comparisons [7–25]. However, there is no consensus in the literature on a broad range of issues, with Kim and Mench noting that there are no consistent conclusions on the various water transport behaviors [7]. For example, Lu et al. [8] report that electro-osmotic drag dominates water transport through the membrane for a fully humidified anode and partially humidified cathode. Under partial humidification of both anode and cathode, the net water transport coefficient is a negative value, indicating strong back diffusion of water through the membrane. Kim and Mench [7,9] report that temperature-dependent flow in a PEMFC occurs in two primary modes: (i) thermo-osmosis in the pure membrane only, and (ii) phase-change-induced flow, which occurs when there is any gas phase and a temperature gradient in the catalyst layer (CL), micro porous layer (MPL) or gas diffusion layer (GDL). The phase-change-induced flow is found from the hot to the cold side of the MEA, while thermo-osmosis moves counter to the direction of the phase-change-induced flow. For hydrophobic diffusion media (DM) and MEA cases, the dominant water transport mode is phase-change-induced flow, which is stronger than thermo-osmosis in the membrane. This is because the temperature difference across the membrane is small (~0.4 °C), leading to a low level of thermo-osmosis, and the diffusion flux in the membrane is non-limited and high, due to the significant phase-change-induced flow in the DM. Eikerling et al. [10] suggest that back transport (back diffusion) is determined by Darcy flow, i.e. by a pressure difference between the anode and cathode. In contrast, Janssen and Overvelde [11] report that the effective drag is determined by the humidity of the inlet gases, which is determined by stoichiometry, temperature and pressure. Qu et al. [12] report that the performance decay of a fuel cell is due to the low water content of the membrane. Changes in the air flow rate and relative humidity have significant effects on the water uptake of the membrane. Lee et al. [13] define an alpha criteria to determine the net water transport phenomenon, and this is linked with membrane conductivity, anode and cathode activation losses, and current density, and this method can even determine the direction of water movement through the membrane. Glavatskiy et al. [14] present numerical results indicating that while thermal osmosis can be significant at interfaces, it is not comparable to diffusion. They find a non-monotonous behavior of the water flux as a function of the reservoir properties, such as pressure and temperature, which are dependent on the water activity. Fu et al. [15] report that water is transported from the high temperature side to low temperature side, and suggest that the transport mechanism is driven by the concentration gradient. Thomas et al. [16] report that water transport through the membrane is weakly dependent on the humidification of the gases, and that water flows mostly in vapor form through the porous media of the MEA from the hot to cold side of the cell. They also suggest that variations in the saturation pressure seem to induce water transport [17]. Darling et al. [18] report that water management characteristics of PEMFC depend upon the heat and mass transport properties of cathode gas diffusion layer. High thermal resistance drives water to cathode and lowers the humidity in cathode. High mass transport resistance drives water to anode and raises humidity in anode. Verma et al. [19] present a detailed computational modeling of dynamic performance of PEMFC. In particular, for low humidity operations, water transport dynamics plays a dominant role in determining the time taken to reach steady state. Srouji et al. [20] find that back diffusion is reduced when the cell operating temperature is increased. The liquid water overshadowing the cathode catalyst sites and its contribution to promoting back diffusion are key factors with regard to the anode dry-out limit. Afshari et al. [21] report that the temperature distribution is the most important parameter affecting the water transport. An increase in temperature enhances the saturation concentration and causes large sections along the channel length to be free of liquid water. He et al. [22] report that it is reasonable to humidify the anode inlet gas at a lower temperature than the cathode by decreasing electro-osmotic drag to prevent flooding on the cathode side. Husar et al. [23] measure water transport due to electro-osmotic drag, diffusion and hydraulic permeation. They find that the amount of water transport with hydraulic permeation is at least an order of magnitude lower than that seen with the other two mechanisms. They also report that the back diffusivity increases with temperature and decreases with pressure, and the electro-osmotic drag coefficient depends strongly on the cell current density, as well as the temperature. There are also some studies which discuss the relation between water transport and the materials being used. Yau et al. [24] find that the presence of MPL on the side of the cathode GDL enhances the back diffusion of water to the anode and reduces passage of water to the gas channels. Kitahara et al. [25] also find that if the size of MPL pores is minimized then this can restrict water transport to GDL, and avoid drying up the membrane. Magnetic resonance imaging measurements have also been used to observe water transport behavior through the membrane during operation [26,27]. Although these studies have found various mechanisms that influence the direction of water transport, their results often differ significantly, due to the use of different combinations of materials, such as membranes, gas diffusion layers, micro porous layers or polytetrafluoroethene (PTFE) content. High temperature PEMFC is studied as alternative for overcoming these classical problems of low temperature for many years [28,29]. This paper aims to find out the differences in water transport phenomena due to specific combinations of materials, and the relation between the water flux direction and operating conditions, such as humidification, temperature, and the stoichiometry of gases.

More specifically, this study measures the amount of water collected in the outlet gases of the anode and cathode to explore the water transport phenomena which are influenced by differences in temperature and humidification. This method can quantitatively verify the water transport tendency from one electrode to the other.

2. Experimental procedures

The PEM single cell tested in this paper is air-cooled. The experimental set-up is presented in Fig. 1. The bypass pipeline near

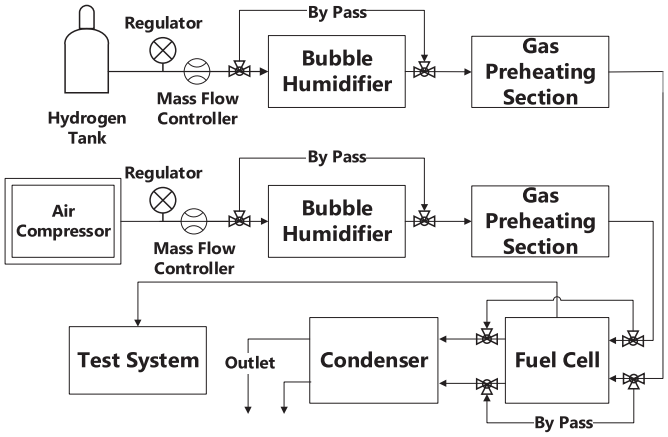

Fig. 1. Schematic of the experimental setup.