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Effect of a ribbed surface on the water transfer characteristics of a porous plate

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ABSTRACT

Porous plates are commonly used in the external humidification devices employed in proton exchange membrane fuel cells. In this study, the effect of a ribbed surface on the water transfer characteristics of a porous plate is investigated experimentally to elucidate the process by which heat and mass is transferred from a high-temperature, high-humidity gas (wet air) through porous media to a low-temperature, low-humidity gas (dry air). Experimental results show that a porous plate with ribs can promote the water transfer between the two gases and that the water transfer ability of the plate is markedly improved when the ribbed side is oriented toward the humidified gas.

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) can potentially become one of the cleanest available energy utilization devices owing to their advantages such as low operating temperature, high energy density, and zero discharge. At present, Nafion-based membranes are the most widely used type of solid electrolyte membrane in PEMFCs; however, their conductivity depends on the water content [1]. Therefore, to ensure adequate water content, PEMFCs require humidification to improve the proton conductivity of the proton exchange membrane and thereby improve the fuel cell performance.

In general, humidification can be in the form of external humidification, internal humidification, or self-humidification. External humidification uses an extra humidifier to provide steam for the PEMFC; common external humidification methods include a bubble humidifier, spray humidifier, enthalpy wheel humidifier, and planar membrane humidifier [2,3]. Compared to the other three humidifiers, a planar membrane humidifier affords advantages such as a simple structure, minimal drop in gas inlet and outlet pressures, low weight, and low cost. A planar membrane humidifier primarily comprises a high-temperature, high-humidity gas channel; a low-temperature, low-humidity gas channel; and a porous media plate. Inside the humidifier, temperature and water vapor concentration gradients cause water to pass through the porous media plate from wet air to dry air. Although planar membrane humidifiers have a simple structure, water vapor condenses and vaporizes on the membrane surface. Both processes are accompanied by heat transfer and are complex coupling processes. Many studies have tried to improve the performance of plane membrane humidifiers. Yan et al. [4] developed a planar membrane humidifier for kilowatt-scale PEMFCs. They discussed heat and mass transfer in a humidifier and analyzed its performance in terms of the dew point approach temperature, water vapor transfer rate, and water recovery ratio. Park et al. [5] introduced a one-dimensional analytical model to quantitatively examine the humidifying capacity of a Nafion™ membrane humidifier. They calculated the water permeability for different thicknesses of the Nafion™ membrane.

A porous plate affords better mechanical strength than a membrane and is more convenient to install in a humidifier. However, most studies have focused on planar membrane humidifiers, and only a few studies have focused on porous plate humidifiers. This study designs a humidifier with a porous plate instead of a membrane. In our previous study, constant-temperature water was used to replace the high-temperature, high-humidity exhaust of a fuel cell to study the effect of the thickness and porosity of the porous plate, diameter of the stomata, coefficient of thermal conductivity, channel size, and flow rate and temperature of the gas on the movement of water [6]. Accordingly, the heat and water transfer characteristics between wet and dry air through the porous plate were studied, and it was found that an increase in the wet air temperature improved water recovery whereas increases

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Nomenclature

m_w	water mass transfer rate (g/s)	d_{di}	absolute humidity of dry inlet air (g/m^3)
$m_{H2O,di}$	water mass flow rate in dry inlet air (g/s)	d_{do}	absolute humidity of dry outlet air (g/m^3)
$m_{H2O,do}$	water mass flow rate in dry outlet air (g/s)	d_{wi}	absolute humidity of wet inlet air (g/m^3)
$m_{H2O,wi}$	water mass flow rate in dry outlet air (g/s)	φ	relative humidity of wet air (%)
r_w	water recovery ratio (%)	T	temperature of wet air (°C)
P	total gas pressure (Pa)	v	volumetric flow rate of dry air (m^3/s)
Pw	water vapor pressure (Pa)	F_{da}	mass flow rate of dry air (g/s)
Ps	saturated water vapor pressure (Pa)		
d	absolute humidity (g/m^3)		

in the relative humidity and flow rate were not conducive to the water recovery process. The water recovery ratio was found to be 40% [7].

2. Experimental device and measurement method

2.1. Experimental device

The experimental system used in this study comprised a dry air circuit and a wet air circuit. The detailed system design and associated equipment parameters can be referred from [7]. Fig. 1 shows a schematic diagram of how water transfers through the porous plate under counter flow conditions.

Fig. 2(a) shows an experimental ribbed porous plate, and Fig. 2(b) shows the size and shape of the ribs. The size of the ribbed area is 100 × 28 mm; this is the same as that of the experimental measurement section. The ribs protrude above the surface of the porous plate and are distributed on only one side of the plate; the other side of the plate is smooth. In addition, the ribbed porous plate has the same porosity as the smooth porous plate. The porosity is 20%. The thermal conductivity is 20 W·m^{-1}·°C^{-1}. The thickness of the porous plate is 1 mm.

During the experiment, the two gases had equal flow rates and counter flow conditions. The two-channel gas flow rate is 6 L·min^{-1}. The wet air inlet temperature is 70 °C. The relative humidity of wet air was varied as 20%, 26%, 60%, and 70%. The dry air temperature is 25 °C. The relative humidity of dry air is 0%. By varying the relative humidity of the wet air, the corresponding changes in the water transfer characteristics during the process could be evaluated.

2.2. Calculation of experimental data

In this study, the main test parameters of interest are the temperatures of wet and dry air and the relative humidities of the inlet and outlet. These data can be further analyzed to obtain the water transfer and recovery ratio; these, in turn, can then be used to characterize the water transfer performance of the porous plate humidifier.

Water transfer refers to the water mass transferred from wet air through the porous plate to dry air. Under steady-state conditions, the water transfer is the difference between the outlet water content and the inlet water content of dry air. The water transfer m_w can be expressed as

$$m_w = m_{H_2O,do} - m_{H_2O,di} = (d_{do} - d_{di})\,v \tag{1}$$

where d_{di} is the absolute humidity of dry air at the inlet (g/m^3); d_{do}, the absolute humidity of dry air at the outlet (g/m^3); and v, the dry air volume flow rate (m^3/s).

The water recovery ratio is a dimensionless parameter that refers to the ratio of water transfer to water content of wet air at the inlet. The higher the water recovery ratio, the better is the humidifier performance. The water recovery ratio r_w can be expressed as

$$r_w = \frac{m_{H_2O,do} - m_{H_2O,di}}{m_{H_2O,wi}} \times 100\% = \frac{d_{do} - d_{di}}{d_{wi}} \times 100\% \tag{2}$$

where d_{wi} is the water content of wet air at the inlet (g/m^3). The water content of air can be calculated as

$$d = 0.622 \times \frac{P_w}{P - P_w} = 0.622 \times \varphi \frac{P_s}{P - P_w} \tag{3}$$

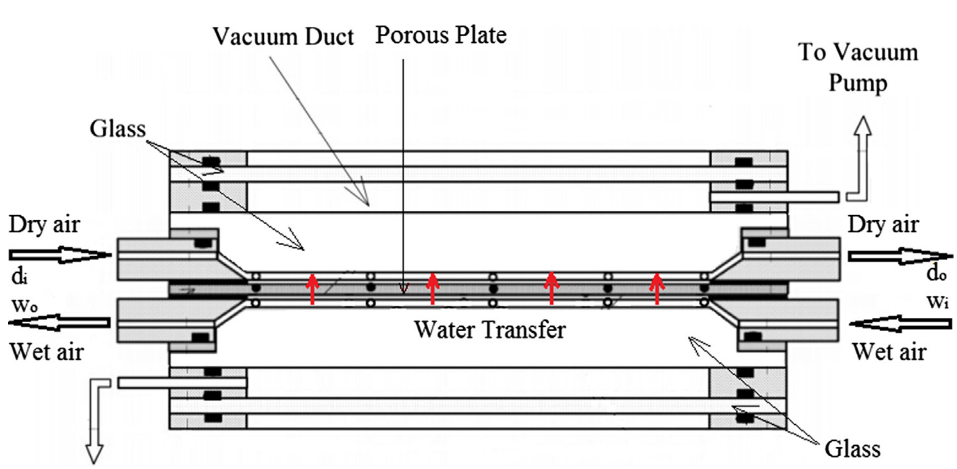

Fig. 1. Schematic of water transfer through the porous plate (counter flow).