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Characteristics of heat and water transfer through a porous plate

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ABSTRACT

In this study, an experimental measurement system was established to examine the heat and water transfer process for a porous plate in the self-humidifying system of a fuel cell. The physical parameters of the fluid flow and porous plates were evaluated for their effects on the heat and water transfer characteristics of the porous plates. The results showed that using a countercurrent flow and increasing the inlet temperature and relative humidity of the humidifying gas can improve the heat transfer and water transmission on both sides of the porous plates. Meanwhile, using a countercurrent flow, increasing the inlet temperature of the humidifying gas, and decreasing the relative humidity can improve the water recovery rate. In addition, increasing the porosity of the porous medium can promote water transfer.

1. Introduction

The proton exchange membrane fuel cell (PEMFC) is an efficient and pollution-free power source. Vehicles powered by such fuel cells are expected to be a widely competitive candidate for the next generation of vehicles. During the operation of a PEMFC, the membrane electrode (MEA) forms hydrated protons due to hydration. Protons need to be hydrated before they can move in the membrane, so the conductivity of the membrane depends on its water content [1]. A low water content for the membrane will hinder proton transfer in the membrane and reduce the PEMFC performance. Therefore, actual fuel cell vehicle applications require a separate fuel cell humidifier to add water to the cathode reaction gas (usually air) before it enters the fuel cell to ensure the water content of the proton exchange membrane [2,3].

A humidifier with porous media is widely used to humidify the inlet air of the fuel cell cathode [4]. It contains a dry air flow path and a wet air or liquid water channel. These two paths are separated by porous media that can be penetrated by water. Compared with several other humidifying methods, this method has a simple structure and does not form a large pressure drop, so it is an ideal way to humidify fuel cells [5]. In the heat-mass transfer process, condensation occurs on the high-temperature side, evaporation occurs on the low-temperature side, and water moves through the porous plate. Each process is also accompanied by heat transfer, so these are complex coupling processes. The internal separation of the humidifier device mainly adopts planar membrane or porous plate. Many scholars have studied the heat and mass transfer process inside the planar membrane humidifier. Yan et al. [6] designed and tested the planar membrane humidifier for the 1 kW PEMFC. From the tests, it was found that increasing the air flow rate increased the WVTR. However, the DPAT and the WRR were not improved by increasing the WVTR as the air flow rate is higher than the optimal value. Cave and Merida [7] designed a straight and single channel humidifier which adopted the persulfonic Nafion membrane as the water exchange membrane and the counter flow configuration as the water exchange approach. They studied the effects of the air flow rate on the water exchange properties of the humidifier by measuring the gas temperature and humidities. Chen et al. [8] presented an experimental study and model validation of an external membrane humidifier for PEMFC. Their researches indicate that the water transfer rate increases significantly with increasing the water channel temperature and the flow rate. Nevertheless, there are still many problems to be solved in the design of a humidifier using a plate as the porous medium. In particular, the mechanism of its heat and mass transfer and the influence of the relevant parameters are not yet clear. Many scholars have researched the heat and mass transfer of porous plates for different purposes. For example, Udell [9,10] and Zhao and Liao [11] performed experimental and theoretical analyses, respectively, on the gas–liquid two-phase flow driven by the evaporation of capillary force within a porous medium. They used porous media with dimensions of φ54 mm × 254 mm and 40 mm × 99 mm × 29 mm, respectively. Wang [12,13] proposed a multiphase multicomponent mixed-flow model that is suitable for the internal phase change of porous media. Based on this multiphase multicomponent mixed-flow model, Wang and Cheng [14,15] studied

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the diffusion and movement of non-water-soluble contaminants in aqueous soils, and You and Liu [16] studied the material movement in the cathode of a PEMFC. Hao and Cheng [17] studied the water movement in a PEMFC gas diffusion layer by using the lattice Boltzmann method (LBM), and Zhu et al. [18] simulated the movement of droplets from the gas diffusion layer of the PEMFC to the flow channel.

In the above studies, however, the theoretical research focused on a relatively large scale, and the experimental research used porous media with a large size. Research on fuel cells has mainly been focused on the two-phase flow in the gas diffusion layer; there has generally been no exploration of the heat and mass transfer on the surface of the porous media. Therefore, in order to ascertain the influence of the fluid state parameters and physical parameters of porous plates on the heat and water transfer of the fuel cell, the heat and mass transfer in the exhaust water recovery and reutilization of the porous plate were studied. The present author [19–21] previously studied the effects of the porous plate thickness, porosity, pore diameter, thermal conductivity, flow path size, gas flow rate, and temperature on the water moving characteristics by using water at a constant temperature instead of the exhaust of a high-temperature and high humidity fuel cell. Based on earlier research work, the present study established a set of experimental test systems for heat and water passing through a porous plate from high-temperature and -water gas to low-temperature drying gas. By using different porosities to measure the characteristics of heat and water transfer through porous media, the influence of the fluid flow parameters, flow direction, and porosity of porous media on the hot-humid transfer performance was examined to provide a basis for the actual design of a humidifier.

2. Experimental device and principle

Fig. 1 shows the experimental system used to measure the heat and water transfer characteristics of a porous plate. It is composed of a high-temperature and high-humidity circuit and a low-temperature drying circuit. The diagram shows the experimental system under the concurrent flow condition. In the high-temperature and high-humidity circuit, air flows from the air compressor through the air filter into the water tank. The water temperature in the tank can be adjusted according to the experimental conditions. Saturated wet air flows out of the tank. By adjusting the water temperature in the tank and heater power before the experimental section, humidified gas with different levels of temperature and humidity can be obtained. At the same time, in the low-temperature drying circuit, ambient air is compressed by the air compressor and flows through the air filter and heater into the experimental measurement section. Its flow direction can be the same as the humidifying gas (co-current) or different (countercurrent). By adjusting the valve opening and heater power, gases can be obtained at various levels of humidification at a given flow and temperature. In the figure, d_i and d_o represent the dry air inlet and outlet, respectively, and w_i and w_o represent the wet air inlet and outlet respectively. The two experimental gases have the same flow rate, which is measured by a flowmeter set in the circus. Temperature and humidity meters are set at both the inlets and outlets of the two gases so that the heat and water transfer through the porous media can be calculated. In this experiment, the thermometer and Hygrometer use Vaisala series HMT330 temperature and humidity meter, and the precision of temperature and relative humidity is ±0.2% (full scale, FS) and ±3% FS. Flowmeter is XFV065Y1G16L1DC with ±1% FS of precision.

Fig. 2 shows the water transfer diagram of the test section. The high-temperature and humidity flow channel (i.e., humidifying flow path) is on the lower side, and low-temperature and humidity flow channel (i.e., humidified flow path) is on the upper side. The high-temperature and humidity gas is cooled on the porous plate surface, and some of the water vapor is condensed. At the same time, the low-temperature drying gas on the other side of the porous plate, which absorbs heat and water through the porous plate, is heated and humidified. Because of the flow channel structure, the relative humidity of the gas in the runner is difficult to measure. But when the wet air pressure is certain, its temperature and relative humidity are closely related, so the relative humidity can be judged indirectly by measuring the temperature. Therefore, 5 pairs of thermocouples with a diameter of 0.25 mm were arranged along the gas flow direction in two gas flow channel. The channel cover plate of the experimental device uses glass, so the entire channel inside is visualized. The cover plate of the channel is composed of two glass panels, and the middle of the two boards is vacuumed to achieve the adiabatic purpose.

3. Experimental results and analysis

Table 1 presents the basic parameters of the flow channel, porous plate, and fluid used in this experiment. In the further analysis, the values in this table were used if no special instructions were specified. Note that, because of the sizes of the flow channel and sensor, the temperature and relative humidity were measured at the fluid inlet and the adjustment target for the different experimental conditions. The values differed from those at x = 0 on the flow path along the path coordinate.

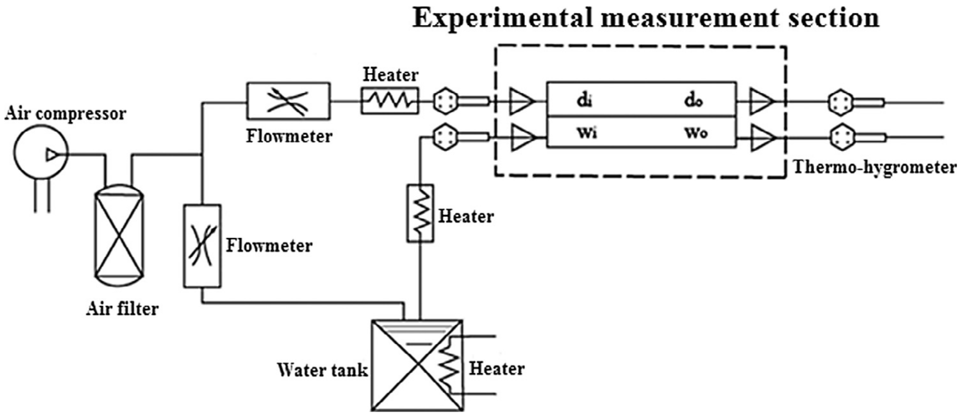

Fig. 1. Schematic diagram of experimental measurement device (co-current).