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Heat and mass transfer of a planar membrane humidifier for proton exchange membrane fuel cell

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ABSTRACT

The proton exchange membrane fuel cell (PEMFC) becomes more important as an alternative energy source recently. Maintaining proper water content in the membrane is one of the key requirements for optimizing the PEMFC performance. The planar membrane humidifier has the advantages of simple structure, low cost, low pressure drop, light weight, reliable performance and good gas separability. Thus, it is a common external humidifier for PEMFCs. In this work, a planar membrane humidifier for kW-scale PEMFCs is developed successfully. The heat and mass transfer of humidifier is discussed and its performance is analyzed in term of dew point approach temperature (DPAT), water vapor transfer rate (WVTR) and water recovery ratio (WRR). The DPAT of the humidifier with the counter flow approach reaches about 6 °C under inlet dry air of 50 °C and 60% RH and inlet humid air of 70 °C and 100% RH. The rate of pressure loss of the humidifier is 5.0×10^2 Pa/min at the torque of 7 N m, which reaches the standard of commercial planar membrane humidifiers. From the tests, it is found that increasing the air flow rate increases the WVTR. However, the DPAT and the WRR are not improved by increasing the WVTR as the air flow rate is higher than the optimal value. In addition, increasing the inlet temperature or the humidity of dry air decreases the WVTR and the WRR. Nevertheless, the DPAT is improved at elevated inlet temperatures or humidities of dry air. Furthermore, the performance of the humidifier with the counter flow approach is better than that with the parallel flow approach. The DPAT difference between the two flow approaches reaches up to 8 °C.

1. Introduction

The proton exchange membrane fuel cell (PEMFC) is considered one of the most promising clean energy technologies nowadays. It can be applied to vehicles and stationary power generators. PEMFCs have the advantages of zero emission, low noise level, high energy density and high reliability. Compared to other types of fuel cell, a PEMFC has a better dynamic power response and a faster start-up speed due to a low operating temperature. However, the low operating temperature (lower than 100 °C) results in a two-phase flow of water in the PEMFC. Thus, water management becomes a critical issue for maintaining a stable performance output and a long operating life [1,2]. Currently, the Nafion®-based membrane is the most common solid electrolyte used in the PEMFCs. This type of proton exchange membrane needs to be moisturized to maintain a hydrated state [3–8]. As a result, it is necessary to humidify the PEMFCs to ensure a high proton conductivity of the proton exchange membrane and to ensure a high fuel cell performance.

Presently, the common humidification methods for the PEMFCs can be divided into three types, the external humidification, the internal humidification and the self-humidification. Among these three humidification methods, the external humidification is the most common for an air-pumping PEMFC system. The external humidification method uses an additional humidifier to supply water vapor to the PEMFC. Thus, the humidification performance of this method is stable and the humidity level is controllable. The common external humidifiers include the gas bubbling humidifier, the enthalpy wheel humidifier, the tubular membrane humidifier and the planar membrane humidifier [9–13]. Compared to the other three humidifiers, a planar membrane humidifier has more advantageous positions, such as simple structure and design, low cost, low pressure drop between the gas inlet and the outlet, light weight, reliable performance and good gas separability. Moreover, the geometry of a planar membrane humidifier is usually rectangular and the materials of the humidifier body are usually engineering plastics, such as polypropylene, polyethylene and

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Nomenclature

$\dot{m}_{H_2O,do}$	the water mass flow rate in the dry outlet air flow (g/s)
$\dot{m}_{H_2O,di}$	the water mass flow rate in the dry inlet air flow (g/s)
$\dot{m}_{H_2O,wi}$	the water mass flow rate in the humid inlet air flow (g/s)
M_w	the molecular weight of water (kg/mole)
M_a	the molecular weight of air (kg/mole)
P	the total pressure of gas (Pa)
P_w	the partial pressure of water vapor (Pa)
T_{wi}	the dew point temperature of humid inlet air (°C)
T_{do}	the dew point temperature of dry oulet air (°C)
$\dot{v}$	the volumetric flow rate of dry air (m^3/s)

Greek symbols

a_{do}	the absolute humidity on the dry outlet air side (g/m^3)
a_{di}	the absolute humidity on the dry inlet air side (g/m^3)
ω	the humidity ratio (g/g)
ω_{do}	the humidity ratio of dry outlet air (g/g)
ω_{di}	the humidity ratio of dry inlet air (g/g)
ω_{wi}	the humidity ratio of humid inlet air (g/g)

polyacetal, which are light, low-cost and easy to fabricate. The planar membrane humidifier mainly comprises the flow channel plates of dry gas, the flow channel plates of humid gas and the water exchange membranes. During the operation, the humidifier recovers heat and water vapor generated from the PEMFC cathode by integrating the humidifier with the PEMFC. In the humidifier, water diffuses from the humid gas side to the dry gas side due to a temperature gradient and a water concentration gradient across the membrane. The humid gas into the humidifier is usually outlet air of the PEMFC and the dry gas into the humidifier is usually supplied from an air compressor. Fresh humidified air flows to the cathodic inlet of the PEMFC to moisturize the proton exchange membranes in the PEMFC and as well becomes the cathodic reactant of the PEMFC. The circle of water between the humidifier and the PEMFC forms a self-sustainable humidification mechanism.

The gas humidity affects the performance and stability of a PEMFC system, especially for a high power PEMFC system. Therefore, the critical design issues of a humidifier, including the outer geometry, the flow channel design, the sealing design and the membrane selection, need to be studied thoroughly. The operating parameters, including the inlet temperatures of gases and the flow rates of gases, are as well important to the performance of a humidifier. The water exchange membrane is one of the key components in the planar membrane humidifier. The membrane needs to have a high water permeability, a high mechanical strength at the operating temperature of the PEMFC and a good gas separability. The Nafion®-based membranes meet the above criteria and therefore are suitable for the planar membrane humidifiers. The cost of the membrane is also an important issue for a humidifier because the cost of membrane accounts for a large proportion of the cost of the overall humidifier system. Thus, many researchers have focused on the membrane development [14–18]. With the growth of commercial PEMFC systems, the research and development of humidifiers becomes more and more important. The present literatures about planar membrane humidifiers are mainly associated with low power humidifiers or theoretical model verification. Only a few papers focusing on the planar membrane humidifiers for kW-scale PEMFC stacks can be found. As a result, we regard the development and performance analysis of a planar membrane humidifier for kW-scale PEMFC stacks as the subject in this work.

Zhang et al. [13] designed a spray type humidifier for the kW-scale PEMFC stack working at 90–95 °C. In this humidifier, heat exchange tubes were used to preheat the air and a nozzle was utilized to supply well-atomized water with a uniform droplet diameter. The results show that the relative humidity (RH) of outlet air increases at the beginning but decreases with time gradually due to the attenuation of the dew point temperature. Cave and Merida [16] 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 temperatures and humidities. Chen et al. [17] presented an experimental study and model validation of an external membrane humidifier for PEMFC. The humidification behavior of the membrane humidifier was studied at steady and dynamic operations. Their researches indicate that the water transfer rate increases significantly with increasing the water channel temperature, the air channel temperature and the air flow rate. In addition, the water vapor transfer coefficient of the Nafion® membrane increases exponentially as the membrane temperature increases. Hwang et al. [18] evaluated the performance of a planar membrane humidifier via studying its dew point approach temperature (DPAT), water recovery ratio (WRR) and water vapor transfer rate (WVTR). Their study shows that the DPAT increases sharply at the flow rates higher than 350 SLPM due to the inadequate WVTR limitation. Furthermore, at the low flow rates, increasing the inlet temperature of dry air decreases the DPAT. However, the DPAT is not influenced by the inlet temperature of dry air at the low flow rates. Houreh and Afshari [19] developed a three dimensional numerical model to compare the humidifier performances with the parallel flow configuration and the counter flow configuration. From their work, it is obtained that the humidifier performance with the counter flow configuration is better that with the parallel flow configuration. In addition, an increase in the inlet temperature of dry air or a decrease in the air flow rate results in a better humidifier performance.

2. Experimental setup

In this work, we designed and tested the planar membrane humidifier for the 1 kW PEMFC. The two main tests, the sealing test and the humidification test, were carried out. In the sealing test, the pressure holding test at the initial pressure of about 1.0×10^5 Pa(g) was employed to obtain the rates of pressure loss at different conditions. In the humidification test, the temperatures and the humidities of humidified air under different dry air temperatures, air flow rates and water exchange approaches were measured.

2.1. Setup and facilities

In this paper, the humidifier performance was tested via the test setup shown in Fig. 1. In the test setup, a bubbling type humidifier, two air mass flow controllers (MFCs), two float type mass flow controllers, a gas preheating subsystem, air tanks and a data acquisition subsystem are comprised. The bubbling type humidifier is provided by the Tension Energy Inc., Taiwan and the model num-