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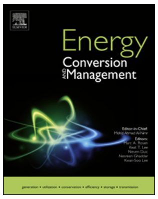

Performance evaluation of a multi-stage plate-type membrane humidifier for proton exchange membrane fuel cell

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ABSTRACT

The influence of channel dimension and altering dry air inlet conditions such as temperature and humidity on the humidification efficiency of a multi-stage plate-type membrane humidifier for kW-scale proton exchange membrane fuel cells is analyzed in terms of the dew point approach temperature, water recovery ratio, pressure loss, and the coefficient of performance. Investigating the effect of channel dimension reveals that the width and depth of the channel significantly affect the humidification performance. The results show that the increase of dry air inlet temperature and humidity leads to improving the dew point approach temperature, decreasing the water recovery ratio, slight increasing the pressure drop, and consequently decreasing the coefficient of performance. The minimum dew point approach temperature and maximum water recovery ratio occur at the flow rate of 30 L/min. The highest water recovery ratio, 73%, is achieved at the temperature of 50 °C and relative humidity of 40%. Moreover, the pressure loss increases with the increment of air flow rate and the coefficient of performance declines with the increase of air flow rate. Thus, it is recommended to select the minimum possible flow rate, dry air inlet temperature, and relative humidity as the efficient operating condition.

1. Introduction

Energy shortage crisis is of increasing importance due to the elevated energy demand for various science and technology developments, and its serious dependency on fossil fuels, considering their depletion through time. As an alternative way to produce energy, the proton exchange membrane fuel cell (PEMFC) has recently grabbed significant attention from the international community as a promising clean energy technology [1]. In fact, a PEMFC offers various benefits such as zero emission, low level of noise, high energy density, and high reliability. Furthermore, a PEMFC has a lower operating temperature than other types, which leads to better dynamic power and higher start-up speed. Sharaf and Orhan [2] reviewed the fundamentals and applications of fuel cells and highlighted the great advantage of fuel cell technology, offering the highly-desirable combination of eco-friendly operation and high efficiency. The application of the proton exchange membranes in fuel cells has been overviewed and discussed by Peighambardoust et al. [3] and the challenges and future developments in PEMFCs during the last decade were elucidated by Sopian and Daud [4]. Some researchers attempted to conduct research studies on the performance evaluation of PEMFCs. Wakizoe et al. [5] analyzed energy efficiency, power density, and the lifetime of PEMFCs with three types of membranes. They proposed that the desired membrane characteristics to obtain high levels of performance are low equivalent weight and high water content. Amirinejad et al. [6] and Marr and Li [7] investigated the performance of a PEMFC under various operating and design parameters. Their results showed that the most important factor affecting the performance of PEMFC was the mass transport limitation including the transport of reactant and oxidant gases to active sites of catalyst layer, the transport of the proton from the anode side to the cathode side through the membrane, and the transport of produced water from the cathode side to the anode side by back diffusion mechanism.

Low-temperature operation of PEMFCs (lower than 100 °C) leads to

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Nomenclature

COP	coefficient of performance
DPAT	dew point approach temperature (°C)
h	fluid level difference (m)
H	depth of the flow channel (mm)
h_a	specific enthalpy of dry air (kJ/kg)
h_w	specific enthalpy of water vapor (kJ/kg)
Δh	enthalpy difference of moist air at the inlet and outlet of the channel (kJ/kg)
$\dot{m}$	mass flow rate of dry air (kg/s)
M_w	molecular weight of water (kg/mole)
M_a	molecular weight of air (kg/mole)
P	pressure (Pa)
ΔP	pressure loss (Pa)
P_w	partial pressure of water vapor (Pa)
PEMFC	proton exchange membrane fuel cell
RH	relative humidity (%)
T_{wi}	dew point temperature of humid inlet air (°C)
T_{do}	dew point temperature of dry outlet air (°C)
W	flow channel width (mm)
WRR	water recovery ratio (%)

Greek symbols

ρ	fluid density (kg/m^3)
ω	absolute humidity (g/g)
ω_{do}	dry outlet air humidity ratio (g/g)
ω_{di}	dry inlet air humidity ratio (g/g)
ω_{wi}	humid inlet air humidity ratio (g/g)

the presence of two-phase water flow in fuel cells which demonstrates the vital role of water management to maintain a stable operation and a long operating life [8]. One of the key challenges for optimum fuel cell performance is to maintain a proper water content in the membranes of the PEMFCs [9]. In this contribution, the humidification of PEMFCs has a significant contribution to enhancing the operational performance of the fuel cell and elevated proton conductivity [10]. Hereunto, three different humidification techniques including self-, internal, and external humidification are commonly employed for PEMFCs. One of the most applicable methods employed for PEMFCs is external humidification because the implementation of an additional humidifier for supplying water vapor can offer a stable and controllable humidity level [11]. Some studies have discussed the effect of humidification on the PEMFCs. Yan et al. [12] evaluated the net drag coefficient to determine the water balance in a PEMFC. They found that the level of humidification and the current load have a significant impact on water balance. The membrane resistance was also investigated and it was seen that it inversely varies with the feed gas relative humidity (RH). Chen et al. [13] investigated the application of a humidifier regarding the optimization of a PEMFC performance and showed that the water vapor transfer rate is directly proportional to the air flow rate. However, there was an optimum value for water recovery ratio (WRR) and dew point approach temperature (DPAT) due to the increase of the air flow rate over an optimal value. They also reported that the counter flow approach in the humidifier provides greater performance compared to parallel flow approach. In another study, Chen and Peng [14] developed a thermodynamic model capturing the most important dynamic parameters of humidifiers, including the air flow RH, temperature, flow rate, and pressure. In fact, they optimized the performance of the humidifier in steady-state conditions and then conducted a predictive modeling to investigate the dynamic behavior of humidifier during transient operating conditions. Hwang et al. [15] showed that the pressure drop across the humidifier linearly increased as the flow rate was increased. On the other hand, there was a sharp increase in DPAT with increasing the flow rate over 350 L/min which was related to the size of the humidifier causing an inadequate water vapor transfer rate. Moreover, it was seen that WRR was reduced and DPAT was increased at conditions with higher wet inlet dew point, leading to the decrement of humidification performance. Park et al. [16] studied the employment of a gas-to-gas humidifier in PEMFCs due to their specific superiority such as no moving part and no need for extra power supply. They developed a mathematical approach for this contribution and examined the effects of geometrical parameters and operating conditions on the efficiency of the humidifier. Cahalan et al. [17] considered the external

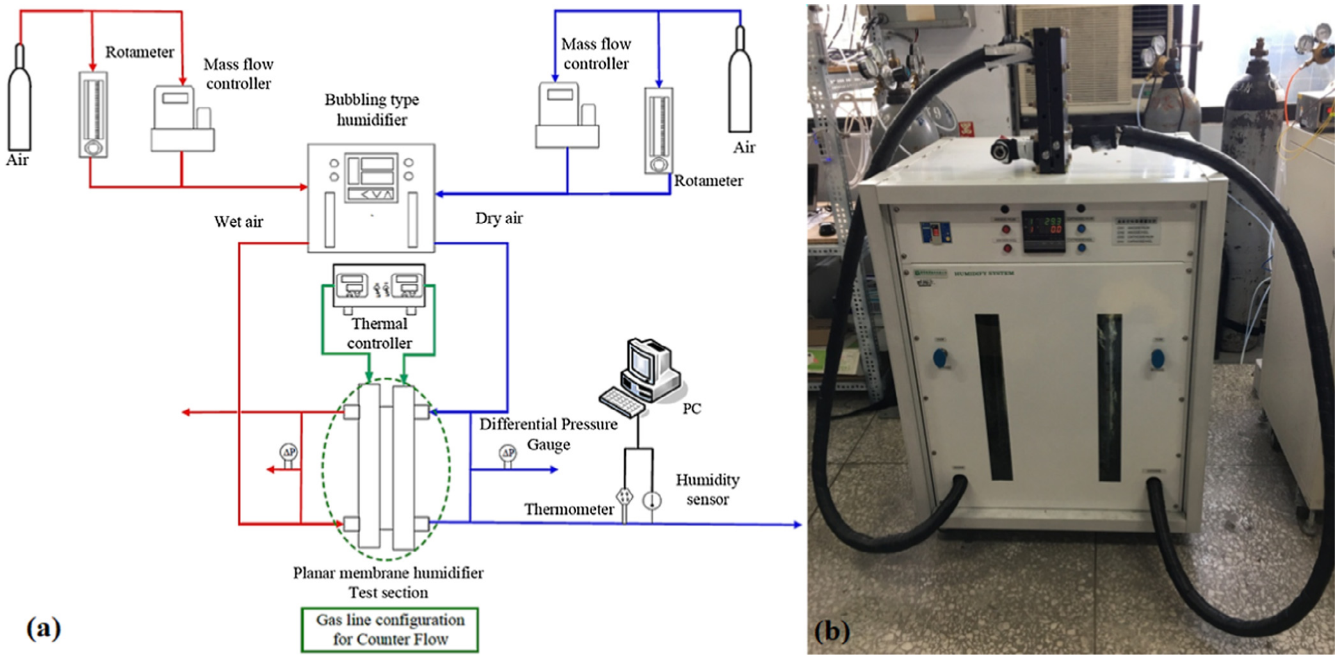

Fig. 1. (a) The test setup used for the humidification practice; (b) The photo of the test setup.