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Experimental study of gas humidification with injectors for automotive PEM fuel cell systems

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Abstract

A scaled gas humidification system using injectors for PEM fuel cell vehicles was developed and the humidification performance was evaluated under various operating conditions. The humidification system consists of an injector, a duplex enthalpy mixer and a water management apparatus. A dew point meter of the chilled mirror type was used to measure the humidity of the air and the hydrogen. Humidification performance was evaluated by measuring the dew point temperature of the humidified gases. Humidification performance was observed to be critically affected by the temperature of injected water and the gas flow rate in this study. The dew point of the humidified gas rose when the temperature of injected water increased, however, it dropped when the gas flow rate was increased. Experimental results show that the outlet temperature was 58.4 °C, dew point temperature of the humidified air reached 54.0 °C when the injection water temperature was 69.5 °C with the room temperature air flow rate of 200 L min^{-1}. Inlet gas temperature also affected the humidification performance and response time. In addition, a 50 cm^2 PEM fuel cell was tested to verify the effectiveness of the devised humidifier. When operated at 65 °C, the fuel cell showed an operating voltage of 0.5 V at a current density of 600 mA cm^{-2}.

Keywords: Fuel cell; Humidifier; Injector; Atomizer; Dew point temperature

1. Introduction

PEM (proton exchange membrane) fuel cells are regarded as suitable for vehicle power applications since they deliver high power density, which offers low weight, low cost and low volume. Moreover, PEM fuel cells operate at a low temperature, allowing for fast startups and immediate responses to changes in the demand for power. However, a critical requirement of PEM fuel cells is to maintain a high water content in the electrolyte to ensure a high ionic conductivity. The ionic conductivity of the electrolyte can be maintained high when the membrane is fully humidified, and offers a low resistance to current flow and so increases the overall efficiency of PEM fuel cells.

There have been attempts to run PEM fuel cells without extra humidification. Operation without any extra humidification is based on the principle that the electrolyte absorbs and retains water under the operating conditions. Self-humidification proposed by Büchi and Srinivasn [1] is a very simple method, but humidity control is difficult and this kind of humidification is not appropriate for large systems such as in automotive applications.

Another alternative is to control the water content by humidifying the incoming reactant gases entering fuel cells, which is so called the ‘external humidification’ or ‘preconditioning’ in which the humidification process mainly takes place outside of the fuel cell stack. This method can reduce the volume of PEM fuel cells, but needs an additional humidification apparatus. There are some types of external humidification for automotive applications. Steam injection is a widely used method for air-conditioning, but it is not economic for automobiles as it needs much energy to generate steam. Injecting liquid water directly into the fuel cell stack can be considered as another option. This is compact, easily controllable and moreover, this method does not need much energy for humidification. The downside of the direct water injection is the possibility of flooding in the fuel cell.

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Nomenclature

B	transfer number
C_D	discharge coefficient
D	droplet size (m)
DP	dew point temperature (°C)
h	enthalpy
K	evaporation constant
L	length
m	mass flow rate (kg s^{-1} or g s^{-1})
p	pressure (Pa)
Re	Reynolds number
RH	relative humidity (%)
RT	room temperature (°C)
SMD	Sauter mean diameter
t_d	droplet lifetime
T	temperature (°C)
V	velocity

Subscripts

i	injection
in	inlet
o	original
out	outlet
v	vapor

Membrane humidifiers are widely used for automotive applications. Chow et al. [2] have reported a gas humidification method based on membranes. Hydrogen and oxidant gases are humidified by passing the gas on one side of the membrane and de-ionized water on the other side before entering the fuel cell (liquid-to-gas method). In such arrangements, de-ionized water is transferred across the membranes to the fuel and oxidant gases like air. Usually, this kind of humidifier is based on the planar structure similar with PEM fuel cell stacks except electrodes and GDL (gas diffusion layer), they are expensive (over $10,000 for an 80 kW class fuel cell vehicle in 2004) and the durability of the humidifier is not so high. Another form of membrane humidifier uses hot and humid exhaust gas to humidify dry incoming gases through membranes. Generally, this ‘gas-to-gas’ membrane humidifier has numerous tubular bundles made of Nafion® membranes. As this kind of humidifier directly uses the moisture contained in the exhaust gas, the water management system (including water retrieval and water storage) can be simplified. Moreover, one of advantages, which can be derived in such a membrane-based humidification, is that it is possible to humidify gases at temperatures close to the operating temperature of the fuel cell as the humidification system works as a heat exchanger also. It is known that this type of humidifier can attain RH of about 40% at the PEM fuel cell operating temperature (about 65 °C). However, it is also pointed out that the humidity control is difficult and humidity is not sufficient in high power range of the system.

An “nthalpy wheel” is another form of external humidification for automotives. While the “wheel” rotates by an electrical motor, heat and moisture in the exhaust gas are transferred to the cold and dry air.

For commercialization of fuel cell vehicles, humidifiers must meet both high humidification performance and low energy consumption for humidification. Most important is high durability and low cost for manufacturing. However, it is difficult to meet all of these requirements simultaneously. As each humidification method has its own advantages and disadvantages, an ideal gas humidifying method for automotive applications can be a hybrid form of the above listed methods. Considering the merits and demerits of these humidification methods mentioned above, a novel design of a sub-scale gas humidifier using injector and enthalpy mixer was developed and its performance was evaluated under various operating conditions.

2. Technique

2.1. Gas humidifier

In this study, water injection into the enthalpy mixer is chosen (not direct injection into the fuel cell) in order to enhance the performance of humidification and to prevent water flooding or clogging in the gas channels of the fuel cell. The humidifier consists of three main parts—an injector, an enthalpy mixer and a water-retrieval unit.

2.1.1. Fine atomizer (impingement injector)

In order to determine the nozzle diameter of the injector, a plain orifice model is assumed as shown in Fig. 1 and numerical calculation is carried out. Firstly, initial values (outlet temperature, outlet quality, orifice diameter) are assumed to meet required mass flow of water (m_0) at certain temperature (T_0). Then, outlet specific volume can be acquired as Eq. (1).

$$v_2 = x_2 v_{2,v} + (1 - x_2) v_{2,l} \tag{1}$$

$$\rho_{2,l} = \frac{1}{v_2} \tag{2}$$

It is known that discharge coefficient of a plain orifice type injector is normally even as Reynolds number increases [3]. However, assuming the cavitation occurring in the orifice, dis-

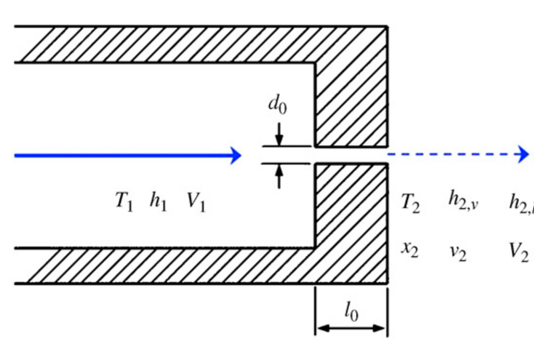

Fig. 1. A plain orifice model for the injector in this study.