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Research Paper

An experimental study on the cathode humidification and evaporative cooling of polymer electrolyte membrane fuel cells using direct water injection method at high current densities

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HIGHLIGHTS

- Proposal of a cathode humidification and evaporative cooling system for PEM fuel cells.
- An external-mixing air-assist atomizer is used to produce a very fine water spray.
- The system is effective in both cathode humidification and stack cooling.
- Increased water flow rate improves stack performance and evaporative cooling capacity.
- At a given water flow rate, lower stack temperatures cause greater humidification effect.

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ABSTRACT

Humidification and cooling are critical issues in enhancing the efficiency and durability of polymer electrolyte membrane fuel cells (PEMFCs). However, existing humidifiers and cooling systems have the disadvantage that they must be quite large to achieve adequate PEMFC performance. In this study, to eliminate the need for a bulky humidifier and to lighten the cooling load of PEMFCs, a cathode humidification and evaporative cooling system using an external-mixing air-assist atomizer was developed and its performance was investigated. The atomization performance of the nozzle was analyzed experimentally under various operating conditions with minimal changes in the system design. Experiments with a five-cell PEMFC stack with an active area of 250 cm^2 were carried out to analyze the effects of various parameters (such as the operating temperature, current density, and water injection flow rate) on the evaporation of injected water for humidification and cooling performances. The experimental results demonstrate that the direct water injection method proposed in this study is quite effective in cathode humidification and stack cooling in PEM fuel cells at high current densities. The stack performance was improved by humidification effect and the coolant temperature at the stack outlet decreased by evaporative cooling effect.

1. Introduction

Polymer electrolyte membrane fuel cells (PEMFCs) are considered to be among the most promising power sources for transportation, stationary and portable applications because of their high efficiency, high power density, low operating temperature, fast start-up, and eco-friendly exhaust. For these reasons, many studies in various fields have examined PEMFCs, and many achievements in the development of PEMFCs have been made in recent decades. Nonetheless, significant technical challenges still exist for commercialization of PEMFCs. Among these challenges are humidification and heat rejection, which have been recognized as very critical technical issues that must be addressed.

In a PEMFC, in which a polymer membrane (typically perfluorosulfonic acid, PFSA; Nafion®) is used as an electrolyte, humidification is required to achieve good performance because the ion conductivity of the PFSA membrane is determined by its water content. Therefore, humidification is one of the important operating conditions directly affecting fuel cell performance [1–5]. However, the conventional types of humidifiers that are widely used in current PEMFC systems, mostly external humidifiers, increase system volume, system complexity, cost, and parasitic power loss. These disadvantages are obstacles to commercialization of PEMFCs. In automotive applications in particular, compactness and simplicity are essential due to the limited space in vehicles.

Likewise, heat rejection of PEMFCs has very important effects on their performance and durability [6–9]. Although PEMFCs have very

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high energy conversion efficiency, they produce an amount of waste heat proportional to their electrical power output [9]. Furthermore, a higher temperature can accelerate the degradation of the membrane and catalyst and reduce the stack performance [10,11]. Thus, the heat generated should be removed effectively to avoid overheating of the stack components, especially the membrane, and to maintain a favorable operating temperature range, which is usually from 60 to 80 °C. Although many cooling methods exist, to obtain sufficient cooling capacity that can manage a large amount of heat generated by PEMFC in high power region, a very large heat transfer area is required [6,7,12–15]. However, when stringent space requirements must be met, the radiator size must be limited, and cooling capacity is thus restricted. In such cases, the stack temperature may rise above 80 °C, so its output power should be limited [16,17] to prevent overheating of the stack, especially under harsh heat rejection conditions, such as operation in summer. Given these challenges, a novel technique for humidification and cooling of PEMFCs is greatly needed.

Studies of systems for both humidification and evaporative cooling by water injection have been conducted [18–29]. However, it is difficult to identify practical applications or study dealing with both humidification and evaporative cooling issues at the same time. Furthermore, some of these systems require changes to the stack design or use of supplementary devices that consume electrical power or increase the manufacturing cost and system complexity. In contrast, the direct water injection method used in this study does not require a large external humidifier or air–water mixer but only a small nozzle. The stack design and coolant system do not have to be adjusted either. Through the nozzle, liquid water is atomized into fine, highly uniform droplets less than 100 microns in size. These droplets are then introduced directly into the reactant gas flow of the cathode channel. Using this method, simultaneous cathode humidification and evaporative cooling effects under various operating conditions were evaluated experimentally using a five-cell stack with an active area of 250 cm^2. The experiments involved high current densities, which require high humidification and cooling loads because of the large amounts of reactant gas flow and heat generated.

2. Methodology

2.1. Water injection

2.1.1. Air-assist atomizer

To facilitate evaporation of injected water in the cathode channel, it is important to atomize liquid water into very fine droplets because heat and mass transfer rates increase as the droplet size decreases and the total surface area increases. Taking into consideration this principle and the characteristics of a PEMFC system, particularly the air-providing part, we selected an external-mixing air-assist nozzle as the atomizer. This atomizer produces the finest droplets possible for a given liquid flow rate and air supplying pressure. In contrast to single-fluid atomizers that require high pressures to produce fine sprays, air-assist atomizers can produce fine sprays at relatively low pressures such as 50 kPa of pressure difference at minimum [30]. This atomizers also have several other advantages over internal mixing-type atomizers, including ease of control, fine atomization performance with high uniformity, and low likelihoods of malfunctioning, and erosion [30]. Furthermore, the liquid may be introduced either under pressure or without excess pressure using an external-mixing air-assist atomizer. Accordingly, without a pump, the nozzle is able to atomize and discharge liquid water using just a high-velocity air stream [31]. Although this type of nozzle requires a high air-to-liquid ratio (ALR) in terms of the mass flow rate ($ALR = \dot{m}_{air}/\dot{m}_{liq}$), PEMFC systems have air-providing devices such as a blower or compressor that can accommodate high air flow rates.

The nozzle specifications were based on the range of air flow rates of a five-cell PEMFC stack with an active area of 250 cm^2. Assuming that the water required for injection is supplied from the water produced in the PEMFC, the water production rate of the stack was also considered. The mass flow rate of the cathode inlet air and the PEMFC water production rate are determined as follows.

$$\dot{m}_{air,in} = \frac{I \cdot N \cdot M_{air}}{4F \cdot x_{O_2}} \cdot \lambda_{cathode} \tag{1}$$

$$\dot{m}_{water,product} = \frac{I \cdot N \cdot M_{water}}{2F} \tag{2}$$

The cathode stoichiometric ratio $\lambda_{cathode}$ defines the ratio between oxygen feed (into the fuel cell) and oxygen consumption (in the fuel cell). When the cathode stoichiometric ratio (SR) and current density are 2.0 and 1.2 A/cm^2, respectively, which are typical values for general operating conditions at high current densities, the mass air flow rate and the water production rate are 1.075 g/s and 0.140 g/s, respectively. The spray should have a narrow angle and centralized pattern to avoid as much as possible the droplets impinging with the inner surface of the tubes, because the nozzle orifice is positioned in the air providing tubes of cathode inlet. Considering all of the above factors, we selected an external-mixing air-assist nozzle with a round spray pattern. Fig. 1 shows a schematic illustration of the coaxial, external-mix air-assist nozzle (Spraying Systems Co., Chicago, Illinois, USA, SU1A setup) used in this study and its spray pattern. This nozzle requires an air flow rate of 17 l/min (= 0.341 g/s at 20 °C, 1 bar) at 1.5 bar of air supplying pressure and has a spray angle of 18° with a round pattern [32]. These characteristics are quite suitable, given the selection criteria stated above.

The spray droplet size is a crucial parameter of the atomization process. Because of the complex and random nature of the atomization process, the spray can be regarded as a spectrum of droplet sizes distributed around some defined mean droplet size. At present, the most widely used mean diameter definition may be the Sauter mean diameter ($SMD = D[3,2] = d_{32} = \sum n_i d_i^3 / \sum n_i d_i^2$, where n_i is the number of droplets per unit volume in size class i and d_i is the droplet diameter) for air-assist atomizer [33]. Eq. (3) is a semi-empirical droplet size correlation for water and aqueous solutions of glycerol derived by Walzel [30]. According to Hede et al., Walzel's equation is the best choice for use in estimating the droplet size in atomized aqueous solutions, including water [30].

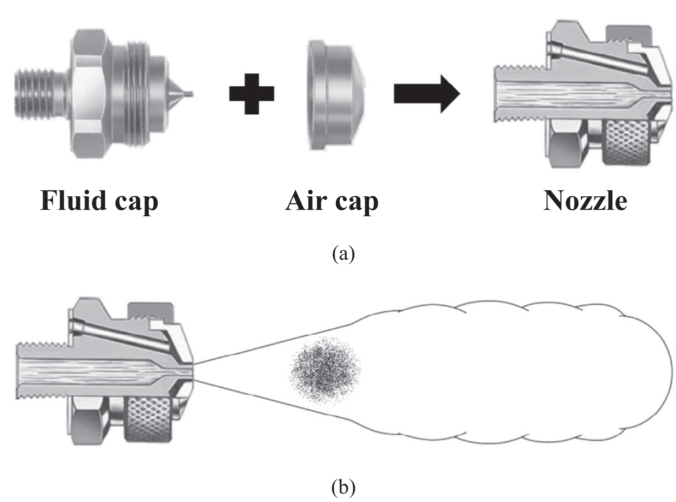

Fig. 1. Coaxial external-mix air-assist nozzle; (a) schematic, (b) round spray pattern.