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A comparison of temperature distribution in PEMFC with single-phase water cooling and two-phase HFE-7100 cooling methods by numerical study

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ABSTRACT

Thermal management has been considered as one of the critical issues in proton exchange membrane fuel cell (PEMFC). Key roles of thermal management system are maintaining optimal operating temperature of PEMFC and diminishing temperature difference over a single fuel cell and stack. Severe temperature difference causes degradation of performance and deterioration of durability, so understanding temperature distribution inside a single fuel cell and stack is crucial. In this paper, two-phase HFE-7100 cooling method is suggested for PEMFC thermal management and investigated regarding temperature change inside a fuel cell. Also, the results are compared to single-phase water cooling method. Numerical study of temperature distribution inside a single PEMFC is conducted under various conditions for the two different cooling methods. Fuel cell model considering mass transfer, electrochemical reaction and heat transfer is developed.

The result indicates that two-phase HFE-7100 cooling method has an advantage in temperature maintenance and temperature uniformity than single-phase water cooling method, especially in high current density region. It is also revealed that the cell temperature is less dependent on system load change with two-phase cooling method. It indicates that the fuel cell system with two-phase cooling method has high thermal stability. In addition, the effect of coolant flow rate and coolant inlet pressure in two-phase HFE-7100 cooling method are discussed. As a result, two-phase cooling method showed reliable cooling performance even with low coolant flow rate and the system temperature increased as coolant pressure rose.

Introduction

Fuel cell has recently emerged as an alternative power source in the future. In particular, proton exchange membrane fuel cell (PEMFC) is popular for vehicle and portable applications because of its high power density, high efficiency and fast response. For widespread commercialization of PEMFC, technological developments are still indispensable. One of the challenging issues for better performance of PEMFC is thermal management because maintaining proper operating temperature is directly connected to performance of PEMFC. However, thermal management of PEMFC is difficult because of relatively lower operating temperature. When it comes to high

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power PEMFC or harsh operating conditions, inability of removing heat at high current densities is considered as a limiting factor to guarantee performance of PEMFC [1–5]. Other key point of thermal management of PEMFC is maintaining uniform temperature over a cell and between cells. It also makes thermal management of a fuel cell complex. Temperature distribution inside fuel cell could cause degradation of performance and deterioration of durability [3,6]. Cooling system using water has been widely used especially for automotive applications. This system, however, normally involves large parasitic power consumption and fuel cell temperatures could increase up to around 90–95 °C under certain conditions [4,7]. Therefore, a large number of studies about diverse cooling technique for PEFMC have been carried out recently. Among many techniques, phase change cooling system has been focused due to its high cooling capacity, low coolant flow rate and system compactness [3,6–8]. One approach of phase change cooling is evaporative cooling. Hwang and Kim [9] developed simultaneous evaporative cooling and humidification system using direct water injection system. By injecting water droplet into cathode gas stream, it humidified the reactant gases. This system also removed heat by evaporation of water droplet inside a fuel cell stack. The experimental results, however, indicate that evaporative cooling method shows only 10% of heat rejection rate by the existing water cooling method. In other words, the cooling capacity of evaporative cooling method in Ref. [9] is not enough to replace existing cooling system. Weber and Darling [10] numerically studied the evaporative cooling system with porous bipolar plate, which allows water to transport. The liquid water moved toward gas channel through porous media and had humidification and evaporative cooling effect. As a result, porous bipolar plate was effective to improve the performance of a fuel cell, however, it was difficult to determine what affected mainly the performance enhancement between humidification effect and cooling effect from water transport through porous bipolar plate.

The other approach of phase change cooling is boiling cooling system. There are growing number of interest in boiling cooling system especially in the field which demands high heat dissipation and low operating temperature [6,7,11]. Soupremanien et al. [12] conducted experimental study about the thermal performance of single-phase and boiling flows in order to optimize the channel configuration for PEMFC cooling. They examined the effects of the hydraulic diameter, the aspect ratio and the width of the channel for boiling flow with single rectangular channel. Garrity et al. [3] investigated two-phase cooling performance with single cooling plate for PEMFC application. The driving force of coolant flow was gravity and density difference, so there was no coolant pump. They investigated wall temperature under the range of heat flux generated in PEMFC. Oseen-senda et al. [13] experimentally studied wall temperature and flow instability for boiling cooling system using pentane and numerically developed simplified steady and dynamic models to calculate wall and liquid temperature. Soupremanien et al. [12], Garrity et al. [3] and Oseen-senda et al. [13] investigated the possibility of applying boiling cooling to PEMFC, but they only examined the characteristics of boiling cooling system in the environment appropriate for PEMFC cooling. This technique has yet to reach an actual fuel cell system and a stack level. Heat generation of PEMFC is not uniform inside a fuel cell and it complicatedly changes depending on operating condition [14,15]. Therefore further study considering actual PEMFC system is required to demonstrate the cooling effect and fuel cell performance under various operating condition.

The purpose of this study is to investigate the influence of cooling methods on temperature distribution inside PEMFC with two-phase HFE-7100 cooling method as comparison to conventional single-phase water cooling method. Fig. 1 provides a simple schematic of the two different cooling methods. Fig. 1(a) describes single-phase water cooling method. The temperature of liquid water rises by heat absorption from a fuel cell. There exists quite large temperature difference between inlet water and outlet water. Fig. 1(b) simply shows two-phase HFE-7100 cooling method. Liquid-phase HFE-7100 flows into a fuel cell and boiling starts after subcooled region. The bubble begins to grow along the cooling channels and during the boiling the temperature of HFE-7100 barely changes. As mentioned above, cooling method with phase change, especially boiling cooling system, is attracting an increasing interest. The numerical and experimental research of boiling cooling system associated with PEMFC, however, are both quite insufficient. Before its application, a wide range of studies need to be carried out. In this paper, a steady state and one-dimensional PEMFC model has been developed. The mass transfer and heat transfer model coupled with electrochemical reaction model have been developed in the whole single cell. The comparisons between single-phase water cooling method and two-phase HFE-7100 cooling method under various load conditions are conducted. In order to understand characteristics of two-phase HFE-7100 cooling method, the change of temperature distribution is investigated under various operating conditions such as coolant flow rate, coolant inlet temperature and coolant inlet pressure.

Theoretical model

The model developed in this paper is a steady state, one-dimensional mass and heat transfer model for single fuel cell. A schematic description of single fuel cell is suggested in Fig. 2. Fuel cell has 7 layers; cooling channel, bipolar plate, backing layer for both anode and cathode, and membrane. The model consists of three parts; mass transfer model, electrochemical reaction model and heat transfer model. The result of mass transfer model is used as a boundary condition for electrochemical reaction model. During the calculation of heat transfer model, the results from mass transfer model and electrochemical reaction model are required, and cell temperature data from the heat transfer model has an effect on the mass transfer rate and electrochemical reaction. Therefore, individual models are not independent from one another, but connected deeply. MATLAB is used to calculate the models. The assumptions used in this model are described below. They are commonly used for PEMFC model [16–21].

- The gas mixtures are considered to follow ideal gas law.
- It is steady state process.