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Review

Free air breathing proton exchange membrane fuel cell: Thermal behavior characterization near freezing temperature

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HIGHLIGHTS

- An investigation of the thermal behavior of a free air breathing PEMFC at low temperature.
- A model for estimating the stack internal average temperature using a minimum number of sensors.
- A brief discussion about the effect of hydrogen purge on the fuel cell voltage.

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ABSTRACT

A free air breathing fuel cell thermal model is developed. This proton exchange membrane fuel cell (PEMFC) has been selected as the basis for the study due to its use in automotive applications. The blowers integrated to the stack provide the required air flow for hydrogen oxidation as well as the fluid for the stack thermal regulation. Hence, their controls are a key point for keeping the system to maximum efficiency. Using well-known fuel cell electrochemistry, a dynamic thermal model near freezing temperature, which includes the stack physical parameters, is developed and validated. In addition to these parameters, only the inlet and outlet air temperatures are used to derive the model. Experimental validation with a real 1 kW free air breathing PEMFC has demonstrated that the model can reasonably track the stack internal temperature with a maximum deviation between the observed and the estimated temperatures of 5%. Therefore, the proposed method will allow the development of efficient blower management systems for PEMFC efficiency improvement.

1. Introduction

Electric vehicles are currently the best way to reduce our dependence on fossil fuels and to reduce greenhouse-gas emissions [1]. One of the main research topics is related to on-board energy storage issue. Such vehicles are mostly powered by batteries, which must have a storage capacity for autonomy comparable to gasoline vehicles. Different types of electric vehicles have been developed to meet these constraints: hybrid-electric vehicles (HEV), plugin electric vehicles (PHEVs), and fuel cell electric vehicles (FCEV) [2]. The first two vehicles have an internal-combustion engine with gasoline as fuel whilst the last one uses no fossil energy. Clearly, the FCEV has two interesting advantages (i) the low greenhouse-gas emission; (ii) high-power efficiency compared to internal-combustion engine [3,4].

The fuel cell has also a good power transient behavior. Nowadays, the proton exchange membrane fuel cell (PEMFC) is the most use hydrogen based stack technology for automotive applications. Two different types of PEMFC are being investigated for such applications: the free air breathing PEMFC and the air compressed PEMFC. The free air PEMFC is lighter and more efficient than the compressed air because it does not require a heavy and energy-intensive compressor. However, it cannot operate easily at sub-freezing temperature as the air used for the hydrogen oxidation cannot be used as temperature regulation fluid to heat the stack [5].

This paper main target is to determine a thermal behavior model of a free air breathing PEMFC which can further be used to design an optimal energy management system. So we begin

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Table 1
PEMFC operating conditions.

Room operating conditions	Near freezing operating conditions
Room temperature 24 °C Relative humidity 17% Absolute pressure of hydrogen 0.15 MPa Load current 0–5 A, 0–13 A and 0–20 A	Outside temperature 3.5 °C Relative humidity 38% Absolute pressure of hydrogen 0.15 MPa Load Current 0–5–10 A

the study by developing a transient model by analyzing the stack electrochemical behavior near the water freezing temperature and in a steady-state [6]. This electrochemical model, based on the results presented in Refs. [7–11], has been used in industry [12] as well as in the research community [11,13–15] around the world. In addition, it has been validated experimentally several times in the past. In particular, the model version in Ref. [9] has been investigated in this paper. Indeed, the model parameters are, firstly, estimated through simulation. Secondly, the model with the estimated parameters is compared with a real experimental data obtained by running a 1 kW free air breathing PEMFC. Based on this steady-state model, we derived and validated the stack transient thermal behavior. However, the hydrogen purge at the anode of each cell affects both the electrical characteristics as well as its internal temperature. In addition, a poor anode water management can increase pressure fluctuation and reduce the stack life cycle [16–19]. Indeed, as the stack is producing power, the anode water production increases, reducing the available species diffusion surface [20,21]. Hence, the purge process is mandatory to maintain good condition for reactant diffusion. So, we extend our study in order to better capture the relation between the purge process and temperature. More specifically, the work presented in the paper aims at:

- developing the transient thermal model of a free air breathing fuel cell;
- validating the obtained transient model with a real 1 kW free air breathing fuel cell;
- analyzing and discussing the effect of the hydrogen purge on the free air breathing fuel cell electric and thermal behaviors.

The rest of the paper is organized as follows. Section 2 presents the free air breathing PEMFC thermal behavior whereas the modeling approach is described in Section 3. The experimental setup and the simulation results are presented in Section 4. The purge effects and analysis are discussed in Section 5 and the conclusion is presented in Section 6.

2. Free air breathing PEMFC thermal behavior

A 1 kW free air breathing PEMFC is used for experimentation. The first step towards the development of the PEMFC thermal behavior is to observe its main parameters dynamics under different operating conditions. Two operating conditions have been selected (see Table 1).

The first operating condition is related to the room condition (normal condition) where the temperature and the air relative humidity are set constant and equal to 24 °C and 17%, respectively. During this experiment, three load current profiles are used to evaluate the real thermal behavior. The second operating condition is set in winter (outside the room) where the temperature and the air relative humidity are 3.5 °C and 38%, respectively.

2.1. Temperature sensor positions

Nine temperature sensors are positioned in the front and in the back of the fuel cell in order to capture the stack external surface thermal distribution. Five sensors labeled s_1, s_2, s_3, s_4, and s_5 are located on the front side of the stack and positioned on one main diagonal as shown in Fig. 1 (picture (a)). These sensors will permit to analyze the stack surface temperature distribution. Four additional sensors (s_6, s_7, s_8, s_9) located on one backside main diagonal are shown in Fig. 1 (picture (b)) and will allow to study the outlet air temperature distribution.

2.2. Temperature behavior

The thermal behavior of the free air breathing fuel cell is presented in Section 2.2.1 for the room condition and in Section 2.2.2 for near freezing temperature condition. The sensor distribution over the fuel cell surface allows the partition of the stack into three main zones as shown in Fig. 2(a):

- lowest zone: sensors s_1 (on the stack front side) and s_6 (on the stack backside) are used to monitor the lowest zone thermal gradient;
- middle zone: sensors s_4 (on the stack front side) and s_8 (on the stack backside) are used to monitor the middle zone thermal gradient;
- upper zone: sensors s_5 (on the stack front side) and s_9 (on the stack backside) are used to monitor the upper zone thermal gradient.

Using the infrared thermography technique, the thermal distribution over the PEMFC is shown on Fig. 2(b) for a load current of

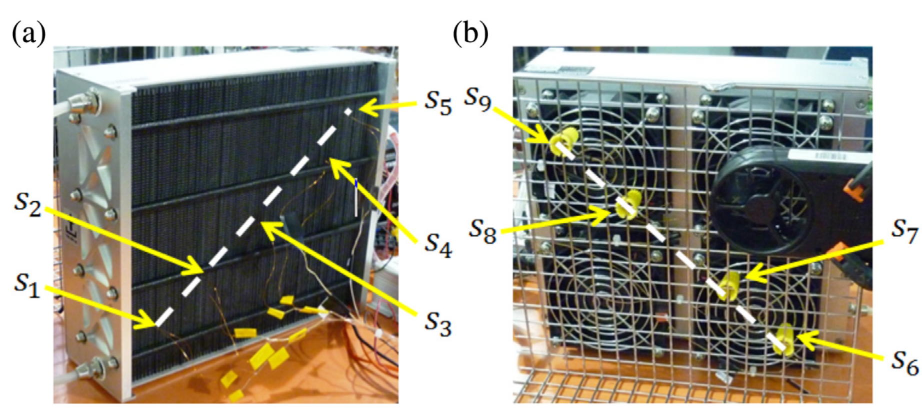

Fig. 1. Temperature sensor positions: (a) front side. (b) Backside.