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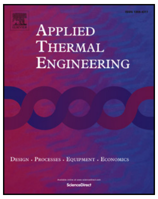

Research Paper

Dynamic behavior study on voltage and temperature of proton exchange membrane fuel cells

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HIGHLIGHTS

- Voltage and temperature transient behavior of PEMFC stack under different step currents was investigated.
- Solenoid valve periodic purge led to periodic oscillation of voltage and temperature.
- Voltage response time and undershoots were related to membrane hydration.
- Gravity affected water and temperature distribution.
- Response time of temperature was longer than that of voltage.

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ABSTRACT

Transient characteristic is one of the important indicators for evaluating the dynamic performance of fuel cells. In this paper, an air-cooled proton exchange membrane fuel cell stack with a dead-end anode was experimentally tested to investigate its transient behavior at different step currents. During the experiment, the undershoot phenomenon was observed and the oscillation law of voltage at different stages was found. The possible influencing factors were discussed. Meanwhile, the temperature variations of the different cross-sections and different single cells were also analyzed in detail by the temperature readings of the 30 thermocouples embedded in the cathode flow channels. Furthermore, in order to compare the difference in the dynamic performance of the stack under different operating conditions, the related parameters, such as voltage fluctuation rate and temperature fluctuation rate, were introduced. This article helps to better understand the dynamic response mechanism of fuel cells and evaluate its dynamic performance.

1. Introduction

Proton exchange membrane fuel cell (PEMFC) has attracted extensive attention due to its advantages of low operating temperature, high energy density, pollution-free [1–3] and has been successfully applied in the transportation field. For automotive PEMFC, it often experiences various complicated operating conditions, such as sudden start-up, idle speed, acceleration, and shut-down [4]. These transient loads not only impose higher requirements on the dynamic response of the fuel cells to meet the normal power demands of the vehicle but also have an important impact on the performance and service life of the fuel cells. Therefore, the study of dynamic behavior and mechanism under different operating conditions is helpful to optimize the structural design and system control strategy of PEMFC [5,6].

A considerable amount of literature has been published on dynamic characteristics of fuel cells. These studies mainly focus on two aspects: numerical simulation and experimental study. In terms of simulation, Chen et al. [7] developed an unsteady mathematical model of PEMFC, and proved that the dynamic performance of the cell was related to the mass transport of water in the membrane. Kim et al. [8] established a simplified model which can well characterize the transient behavior of the output voltage and temperature of the PEMFC stack in the case of the current step change. Wu et al. [9] introduced a non-isothermal transient model that considered species transport, membrane hydration and electric double layer and revealed that heat transfer had an important effect on the dynamic performance of fuel cells. Loo et al. [10] set up a one-dimensional two-phase flow PEMFC model to investigate the transient phenomenon of voltage, overpotential, oxygen concentration, and water content of the membrane under various operating conditions. Li et al. [11,12] simulated the influence of flow field design on the overshoot and undershoot of the current density and the transient response time by a three-dimensional CFD model. Shan and Choe

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Nomenclature

R_d	nominal dynamic internal resistance (Ω)
V_i	transient voltage (V)
V_s	steady-state voltage (V)
T_i	transient temperature (°C)
T_s	steady-state temperature (°C)
ΔI	amplitude of the current step change (A)
$V_{i(\min)}$	minimum transient voltage (V)
$\Delta V_{\max}$	maximum voltage regulation (V)

Greek letters

ε_T	temperature fluctuation rate
ε_V	voltage fluctuation rate
τ_T	temperature response time (s)
τ_V	voltage response time (s)
α_V	voltage response rate (V/s)

Subscripts

d	dynamic
i	transient moment i
max	maximum
min	minimum
s	steady-state
T	temperature
V	voltage

[13] put forward a model that considered temperature effects and revealed that membrane hydration varied dynamically with temperature and strongly affected the output performance of the stack. Raga et al. [14,15] proposed a black-box model that can capture the dynamic response process of the fuel cell only need to obtain the relationship between step current and time, and the fitting error did not exceed 4%. Hou et al. [16] built an improved semi-empirical dynamic model that can predict the voltage undershoot and overshoot of a PEMFC stack under current step change. In another study [17], they also studied the transient effects of hydrogen purge on actual hydrogen consumption. Soltani and Mohammad Taghi Bathaee [18] modeled a PEMFC module to investigate its steady-state and transient performance. The simulation results indicated that the stack temperature significantly affected the dynamic characteristics of fuel cells.

In terms of experimental research, Kim et al. [19–21] systematically explored the effects of stoichiometry, flow field designs and fuel dilution on the dynamic characteristics of the fuel cells. The overshoot/undershoot phenomena, the vacuum effect and reservoir effect were observed and explained in detail. Cho et al. [22] investigated the influence of operating parameters such as stoichiometric ratio, temperature and relative humidity on the dynamic response of the voltage when the current step changed. They also found that flooding seriously affected the dynamic response time of the voltage. Moçotéguy et al. [23] reported that transient voltage behavior of the individual cell varied depending on its location in the stack. Specifically, the cell close to the reaction gas inlet had better dynamic performance than that of the last one. Tang et al. [24] observed that when the load suddenly rose or dropped, the voltage of the PEMFC stack would exhibit a significant undershoot or overshoot. They explained that these phenomena in the transient response process were closely associated with the mass transfer of water and gas. Jia et al. [25] focused on the phenomenon of current overshoot during the start-up process of PEMFC. By measuring the local current density and high-frequency resistance, they found that humidification was a very important factor affecting the transient behavior of the current. Jian et al. [26] conducted an experimental study on the dynamic characteristics of a 2 kW PEMFC stack under different operating conditions. They pointed out that the activated stack had a more stable transient voltage and a shorter response time. In addition, anode periodic purge would cause regular oscillations in voltage and hydrogen pressure. Jang et al. [27] experimentally tested an air-cooled PEMFC stack with the dead-end anode. They confirmed that purge can cause voltage fluctuations, and this effect was more significant at high current densities. The results of Chen et al. [28] showed that unreasonable purge period can easily lead to water flooding inside the PEMFC, thus significantly deteriorating the stability of transient voltage. Zhang et al. [29] compared the transient voltage variation curves of a high-temperature PEMFC. Experimental results showed that the transient performance of the voltage was strongly dependent on the load current and the purge interval.

The above documents mainly focus on the transient behavior of the current and voltage, however, rarely discuss that of the temperature. It is well known that temperature plays an important role in fuel cell performance. Therefore, the study of the temperature response behavior is also a very important way to better understand the dynamic characteristics of fuel cells. Furthermore, in most of the current literature, few people systematically propose relevant indicators to compare the differences in dynamic performance. In this paper, the voltage and temperature response characteristics under different load currents will be investigated and discussed in detail. Besides, the related performance parameters will be introduced to evaluate the dynamic response process of the stack. The results will also provide an experimental basis for subsequent modeling and simulation work.

2. Experimental system and setup

2.1. PEMFC test system

In our presented research, an air-cooled PEMFC stack (Junji Energy Technology Co., Ltd., Zhejiang, China provided) consisting of 10 single cells was tested as shown in Fig. 1. The electrocatalysts of both cathode and anode are Pt, and the loadings are 0.64 mg/cm^2 and 0.12 mg/cm^2, respectively. Proton exchange membrane and carbon papers coated with catalyst are hot-pressed to form a membrane electrode assembly (MEA) with the effective reaction area of 68.5 cm^2. The bipolar plates are made of graphite materials, and parallel rectangular flow channels are engraved on both sides. The specific structural parameters of the bipolar plates are given in Table 1.

Fig. 2a displays the schematic diagram of the test system. Hydrogen (purity 99.999%) came out from a high-pressure tank and its pressure can be adjusted by a pressure relief valve. The hydrogen flow rate was regulated by a flowmeter. Due to a dead-end anode, there was a normally open type solenoid valve in the hydrogen outlet pipeline. It continuously purged for 0.44 s in each action cycle of 18.3 s. Air, in the study, not only provided an oxide for the electrochemical reaction but also provided cooling for the stack. The air flow rate can be adjusted by changing the power of an axial fan. An electronic load (JT6344A, Jartul Electronics Co., Ltd, China) was used to simulate different operating conditions and its current and voltage sampling frequency were both 10 Hz. As shown in Figs. 1 and 2b, there were 5 tested single cells, each of which was attached with 6 K-type thermocouples (accuracy is $\pm 0.004|t|$) on the surface of the gas diffusion layer from the cathode flow channels. For the sake of distinction, these 30 probe points were numbered from CH0001 to CH0030. A data logger (SmartDAC GM, Yokogawa Electric Corp., Japan) was used to receive temperature signals of thermocouples. Finally, real-time monitoring and storage of voltage, current and temperature could be achieved on a computer through related software.