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Study on voltage clamping and self-humidification effects of pem fuel cell system with dual recirculation based on orthogonal test method

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ABSTRACT

Durability and reliability are still major challenges of vehicular polymer electrolyte membrane fuel cell (PEMFC) systems. With exhaust gas recirculation on both the anode and cathode sides, two important functions can be achieved: the voltage clamping in low current density, and the self-humidification without any external humidifiers. The former restrains catalyst decay in small load working conditions, and the latter is beneficial for improving the cold-start ability. In this study, dynamic performances and stable characteristics of a fuel cell system with dual exhaust gas recirculation are firstly experimentally studied using an orthogonal test method. System parameters, including humidification temperature of cathode external humidifier, fresh air stoichiometric ratio (SR), current density, cathode and anode recirculation pump speeds, are regarded as key factors in the experiments based on the testing conditions of the test-bench. Two four-factor and three-level orthogonal tables are designed, and the effects of key factors on system performance indices (average cell voltage, relative humidity (RH) at cathode inlet, high frequency resistance (HFR), oxygen concentrations at cathode inlet and outlet, and the concentration difference between these two positions) are investigated. Results show that: (1) with the cathode recirculation, the cell voltage can be reduced in low current densities by coordinately adjusting the recycled gas flow and reducing fresh air SR; (2) with the dual recirculation, the fuel cell membrane can be well hydrated, and system performance only shows 3% reduction compared with a system with an external humidifier; (3) the difference between the oxygen molar concentration at the inlet and outlet of cathode gas channels becomes small using dual recirculation.

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Introduction

With more restricted regulations on vehicle emission in recent years, developing zero-emission vehicles becomes a common view for governments and automobile companies [1–3]. Fuel cell vehicles, as one kind of promising zero-emission vehicles, have achieved a great progress in past decades, but durability and reliability are still bottlenecks for its large-scale commercialization [4, 5].

Durability of fuel cell vehicles is one big challenge for vehicular applications. Among factors that influence durability of PEMFC, high potential during low current densities is considered to be a key issue. The reason for that is due to significant platinum agglomeration and oxidation in this case, and the electrocatalyst surface area (ECSA) is greatly lost [6]. Experiments [7] showed that, a PEMFC losses around 40% of the ECSA after 1500 potential cycles from 0.1 to 1.0 V, and Pt particle size grows more rapidly during cycling to high potentials, and carbon corrosion also increases with increasing potential. Liu et al. [8] also found that electrochemical active area of anode shows sharp drop after 20-h running test with cycled potentials from 0 V to 1.2 V by 3-electrode system. Noto et al. [9] pointed out that, Pt dissolves at high potential in the repetitious cycle, and it is supposed to suppress the degradation by lowering the upper limit potential. Tests with this countermeasure showed that, with potential cycle of 0.6–0.85 V, a fuel cell shows 20% performance degradation after 6000 h, while with potential cycle of 0.65 V to open circuit voltage, the fuel cell shows the same degradation after only 900 h. Thus, reducing the high potentials of the fuel cell stack in idle or low loads appears to be an effective method to prolong its durability.

Humidification of inlet gases is crucial for high efficiency and good performance of a PEMFC system [10]. Humidification methods can be categorized into external- and self-humidification. For an external humidification method, humidifiers such as membrane humidifiers are installed. This method increases system volume and complexity, and it also makes a fuel cell system take a long time to get heated from a cold environment. Considering requirements on vehicular fuel cell system of small volume and short cold-start time, self-humidification without external humidifiers is attractive.

Bao et al. [11] developed a dynamic model of fuel cell systems including an injection pump for anode recirculation to study the mixed effects of gas flow, pressure and humidify and self-humidification. Migliardini et al. [12] compared the system efficiency, uniform distribution of cell voltages and voltage degradation in two hydrogen feeding method: flow-through and anode recirculation. Toyota has developed first external humidifier-less system with anode recirculation in its fuel cell vehicle Mirai [13]. By innovative stack structure design and anode recirculation, the water generated at the cathode can be migrated to the anode and uniformly distributed onto the surface of the anode membrane electrode assembly (MEA), thus the self-humidification could be achieved.

Kim et al. [14] summarized two cathode recirculation components layouts, and humidification performance by exhaust gas recirculation is validated in comparison with an external humidifier by theoretical model and experiments. Hu et al. [15] designed cathode recirculation control strategies on stack internal water content under membrane drying and flooding conditions. Hydrogenics companies [16] proposed to use cathode recirculation system to adjust the polar curve of fuel cell stack in order to adjust the cell output voltage. Cheng et al. [17] investigated performances of designed control strategies based on cathode recirculation when the fuel cell stack under the low current density and surge conditions, and simulation results show the cell voltage can be maintained under 0.8 V at these conditions.

Many methods have been introduced into fuel cell test area to reduce its time and cost [18]. Orthogonal experiment design is a kind of statistics method to study many factors and their levels simultaneously in a single set of experiments with much fewer experiments units [19]. It can reduce test times, shorten test cycles and has been successfully applied to many fields. Xia et al. [20] applied this method to fuel cell system experiments to investigate the operation parameters on the performance of PEMFC, and this study shows orthogonal experiment method is feasible and efficient in the multi-parameter fuel cell system.

However, these studies mostly focus on one of the recirculation systems, and lack experimental validations. Further, most studies only consider one of the two effects: voltage clamping or self-humidification. Experimental studies on the dual recirculation system considering both voltage clamping and self-humidification are firstly studied in this paper, and both the system performances influenced by the operation parameters and function validation of voltage clamping and self-humidification are also studied.

In a previous paper of our research group by Jiang et al. [21], several dynamic tests have been analyzed and they prove that the humidification performance with dual recirculation is similar to an external humidifier, and voltage clamping also can be achieved. In this study, experimental results of two dynamic tests and especially orthogonal experiments are conducted to investigate the characteristics of the fuel cell system on voltage clamping and self-humidification.

This paper is organized as follows: Section Experiment introduces the system structure of the test bench, orthogonal experiment design and range analysis method; in Section Results and discussion, results of dynamic tests and orthogonal experiments for voltage clamping and self-humidification are analyzed, respectively; conclusions are drawn in the Section Conclusion.

Experiment

System structure

The schematic of the fuel cell system test bench in our lab are shown in Fig. 1. The system in the blue dotted box is the HS-10kW from Hephas Energy, which includes an air supply system, a hydrogen supply system, a cooling system, a Cell Voltage Monitor (CVM) and an electric load. As in vehicular applications [22], a well controlled cooling system for stack temperature is developed. In this study, the cooling system can maintains the stack temperature within 60±1°C. The