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A method to study the intake consistency of the dual-stack polymer electrolyte membrane fuel cell system under dynamic operating conditions

Huicui Chen[a], Yuxiang He[a], Xinfeng Zhang[b,*], Xin Zhao[a], Tong Zhang[a], Pucheng Pei[c]

[a] *School of Automotive Studies, Tongji University, Shanghai 201804, China*
[b] *Technology Center, Dongfeng Motor Coperation, 430056, Wuhan, China*
[c] *State Key Lab of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China*

HIGHLIGHTS

- Intake gas uniformity of the dual-stack PEM fuel cell system was studied.
- Porous media model was proposed to replace fuel cell stack pressure drop model.
- The model was proved to be reasonable by mechanism.
- Several features of intake gas was found through simulation.

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ABSTRACT

The Polymer Electrolyte Membrane Fuel Cell (PEMFC) system is considered as one of the most potential power plant on vehicle. However, the efficiency of the high power fuel cell stack has restricted the high power system which is developed for the full power fuel cell vehicle. The multi-stack system integrated by several fuel cell stacks is a solution aimed for high power level system. However, the inconsistency of the stacks flow distribution restricts the performance uniformity of each stacks and the efficiency of the multi-stack fuel cell system. In this paper, a dual-stack polymer electrolyte membrane fuel cell system was setup, and its intake manifold was established. A porous medium was applied to replace the complex flow field structure inside the fuel cells to simulate the pressure drop of the gas through the stack. According to the operating conditions of the vehicle, variable conditions are designed to carry out simulation experiments for the first time. The results show that there is not a significant effect of the changing load's range on the instantaneous uniformity. However, the initial value of the changing load has a great influence on the instantaneous uniformity. In addition, the settling time of the loading process is much shorter than that of the load shedding process. The equivalent model of porous media proposed provides a new method to model the fuel cell stack, which is very useful in the fuel cell pipe system design and system dynamic response analysis. The uniformity simulation result provides the directions for the fuel cell control strategy design and optimization, and the references for gas intake manifold design.

1. Introduction

Low-emission, high-efficiency fuel cells are often considered as an superior alternative to traditional power source [1,2]. However, there are 4 major technical and scientific barriers preventing the large-scale promotion of fuel cells into the transportation market: (i) with an electrical efficiency lower than 60%; (ii) reliability cannot match the current automotive engines [3]; (iii) durability of approximately 2500 h achieved today on transportation profiles [4]; and (iv) high cost of the entire system.

The performance of the fuel cell system depends on its power level and the system architecture. Multi-stack fuel cell systems could provide an improvement in performance over usual fuel cell systems [5,6]. Moreover, the multi-stack solution allows a modular design of the whole fuel cell system, fuel cells can be separately replaced because it is installed in parallel. Another advantage to use a multi-stack system could be the operating mode of the cells. Indeed, the average power demand differs a lot according to variable road conditions and the average power demand, as a result of which, different fuel cell applications requiring different fuel cell power can be designed based on an

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* Corresponding author.
E-mail address: 13817829495@139.com (X. Zhang).

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elementary fuel cell system. The total power is only dependent on the number of modules. If one module fails, the system loses only its partial power, improving the global system reliability [7]. When the system has more than one stack, there are different power distribution possibilities allowing to reach better efficiencies for varying loads (a multi-stack system offers several optimal power points). Moreover, a multi-stack FC system consists of smaller modules is easier to physically integrate into the whole application [8].

Multi-stack fuel cell systems have already been used by the industry for different applications, such as the air-independent propulsion for submarines or power supplies for space exploration vehicles [5]. Several high power applications, such as Ballard's ClearGen Multi-MW System and Hydrogenics' HyPM Rack, are based on multi-stack technologies. The transportation industry has also incorporated this technology in their applications, e.g., the fuel cell powered bus from Mercedes and the auxiliary power unit of Ballard [9].

The gas intake consistency in the multi-stack system is one of the most important factors that affects the overall performance, and the flow distribution also affects the performance of the system [10]. Some scholars have conducted studies on the flow distribution of the single stack. Joon-Ho Koh et al. [11] analyzed the overall pressure change and flow distribution inside the stack, and found that the pressure loss was mainly concentrated in the manifold and the joint of single cell compared to the friction loss of the manifold wall. The pressure loss is also linked to the size and shape of the manifold. Wang et al. [12] studied the flow distribution of the T-type manifold and the C-type manifold. They found that the resistance of the single cell channel plays a major role in the flow distribution. Xu et al. [13] proposes a nonlinear dynamic mechanism model for the fuel cells system that can describe the dynamic voltage drop during water flooding with a large current density. Wu et al. [14] find out a better protrusive GDL arrangement to enhance cell performance with a numerical model. In addition, many scholars have conducted a series of studies on the flow distribution of single-stack system [15–20], which have used 2D models [15] or 3D models [16] to analyze. These studies show that factors such as intake pressure, intake air flow, concentration and stoichiometry factor [17,18], operating temperature, water transport [19] and manifold structure [20] affect the uniformity of fuel cells intake flow. However, there are few literatures and researches focus on the flow distribution of the stacks in a multi-stack system. On the other hand, it is complicated to carry out the experimental measurement on the flow distribution problem in the multi- stack fuel cell system during dynamic condition.

In this paper, a dual-stack fuel cell system is designed, and a simplified fluid model is developed to analysis the intake flow consistency under both static and dynamic operation conditions.

2. A dual-stack fuel cell system

2.1. System configuration

In our project, a high power level fuel cell system for specific vehicle was under integration and thus a dual-stack PEMFC system was proposed. The schematic diagram of the dual-stack PEMFC system is shown in Fig. 1. Two 40 kW PEM fuel cell stacks were placed side by side, served by one suite of the auxiliary system. As a common automotive application, the auxiliary system was composed of a hydrogen supply sub-system, an air supply sub-system, a cooling sub-system and a humidification sub-system. Hydrogen from the tank went through the release valve to the anode, while the air was delivered to the cathode by one compressor. In addition, the coolant was circulated by one pump.

Compared with the single-stack system, the dual-stack system needs to separate the cathode air supply, anode gas and coolant into two stacks. In such configuration, the uniformity of flow distribution is particularly important, because it has great effect on flow distribution of the dual-stack system, which affects the performance, efficiency as well as the service life of the stack [21,22].

2.2. The shunt structure geometry

Three-dimensional structure of the dual-stack fuel cell intake system is shown in Fig. 2(a). The stacks were placed side by side. After reaching the shunt structure, the air, hydrogen and coolant were all divided into two flows, which were separately connected to each sub-stack.

The inlet and outlet ports were connected to a shunt structure by piping. The cross-section of shunt structure is shown in Fig. 2(b).

3. Simplified fluid model development

3.1. Model assumptions

In addition to the boundary conditions and model parameters, some assumptions were written as follows,

(1) All the solutions use double-precision, pressure-based solver, and use the SIMPLE algorithm, where the pressure, kinetic energy items are taken to the second-order accuracy.
(2) The energy equation has been taken into account in the algorithm.
(3) The gas is a compressible gas and is turbulent within the stack.
(4) Water is only in the form of water vapor throughout the flow field, i.e. only the case of single-phase flow.
(5) Regardless of the electrochemical reaction and diffusion of wet hydrogen during the process of flowing through the stack, i.e. the composition of the mixed gas in the entire flow field remains unchanged.
(6) The flow field pipe is a thermal insulator, the influence of the external temperature change on the gas flow was ignored.

3.2. Fuel cell stack pressure drop model

The physical dimension inside the fuel cell stack distributes from mm in the flow channel, μm in the gas diffusion layer and nm in the catalytic layer. The flow inside the fuel cell stack is very complicated. Three-dimensional modeling the fluid of the entire fuel cell stack requires a huge amount of computation, which will encounter insufficient computer performance in grid rendering and simulation calculations. It is necessary to simplify the fuel cell stack pressure drop model.

(1) The pressure drop of a fuel cell stack has been proposed by Pucheng Pei et al. [23],

$$\Delta P = 1.15 \times 10^{-11}\frac{L}{nAD_h^2}\frac{R_m T^{1.6392}}{p_{in} - \Phi \cdot p_{sat}}Q_v + 2.768 \times 10^{-13}\frac{\zeta}{A_{in}^2}\frac{R_m T(29p_{in} - 11\Phi \cdot p_{sat})}{(p_{in} - \Phi \cdot p_{sat})^2}Q_v^2 \quad (1)$$

where L is the length of the flow field channel, R_m is the gas constant, T is the gas temperature, n is the number of channels, A is the cross-sectional area of the flow channel, D_h is the hydraulic diameter of the flow channel, ζ is the local pressure drop loss factor, p_{in} is the pressure of the fuel cell inlet, Φ is the relative humidity of anode or cathode, P_{sat} is the saturated vapor pressure, Q_v is the volume flow.

The relation between the inlet volume flow and the inlet velocity is as follows,

$$Q_v = Av \quad (2)$$

Here, v is the velocity of the flow.

From Eqs. (1) and (2), the Eq. (3) can be obtained,

$$\Delta P = 1.15 \times 10^{-11}\frac{L}{nAD_h^2}\frac{R_m T^{1.6392}}{p_{in} - \Phi \cdot p_{sat}}Av + 2.768 \times 10^{-13}\frac{\zeta}{A_{in}^2}\frac{R_m T(29p_{in} - 11\Phi \cdot p_{sat})}{(p_{in} - \Phi \cdot p_{sat})^2}A^2v^2 \quad (3)$$

If