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Study on the operating pressure effect on the performance of a proton exchange membrane fuel cell power system

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ABSTRACT

Proton exchange membrane fuel cell is a promising clean energy conversion device. Proton exchange membrane fuel cell power system has great potential in the automotive applications. A fuel cell stack and an air compressor are two important components in a fuel cell power system and it is meaningful to study their properties for better system performance. The aim of this study is to enhance the performance of a 20 kW vehicular proton exchange membrane fuel cell power system incorporating a fuel cell stack and an air compressor, through the cathode operating pressure optimization. The fuel cell stack is investigated numerically and the air compressor characteristics are obtained experimentally. The fuel cell stack and the air compressor are matched properly, and then the operating pressure optimization for the power system is carried out. The results of this study show that the fuel cell stack power generation is increased with the system operating pressure. The compressor power consumption is also increased with the system operating pressure, but it can be reduced by using a two-speed compressor operation mode. The optimum system operating pressure is found to be 1.2 atm. The optimum system operating pressure is influenced by the compressor efficiency and is increased with the compressor efficiency.

1. Introduction

Due to the growing concerns over the air pollution from internal combustion engines (ICE) and the depletion of fossil fuel reserves, the proton exchange membrane (PEM) fuel cell (PEMFC), which is an environmentally-friendly energy conversion device that uses hydrogen as fuel, has drawn considerable attention recently. PEMFC has high energy efficiency, high power density and zero emission features, making it a promising candidate in automotive applications [1].

Hydrogen-oxygen PEMFCs can be generally divided into two sorts in terms of the operating temperature, i.e. low temperature PEMFC (LT-PEMFC) and high temperature PEMFC (HT-PEMFC). The PEMFC operating temperature is mainly controlled or limited by the thermostability and activity of the electrolyte. LT-PEMFC using Nafion membrane as electrolyte is operated below 90 °C, while HT-PEMFC using polybenzimidazole doped polymeric membranes with phosphoric acid (PBI/H3PO4) as electrolyte is operated above 120 °C [2]. HT-PEMFC has several advantages over LT-PEMFC [3]. HT-PEMFC shows good tolerance of fuel impurity and can use an on-board fuel reforming system, whereas LT-PEMFC must use very pure hydrogen as fuel. HT-PEMFC can use alternative catalysts (Fe, Co) as substitutes for the noble Pt catalyst in the electrode, lowering the cost. HT-PEMFC can also avoid the external gas humidification and the complicated water management system which are crucial parts of LT-PEMFC [4], and the relatively large temperature difference from the environment can further simplify the cooling system [5]. However, HT-PEMFC technique is not as mature as LT-PEMFC at the current stage [2]. The electrolyte and catalyst stability and durability of HT-PEMFC are still limited [5]. Comparing with LT-PEMFC, HT-PEMFC power density is several times smaller and the life time is much shortened. In addition, the high operating temperature greatly elongates the power system start-up time, which can be up to 40 min, further confining its utilization in automotive applications [2]. Due to continuous research and development in the past decades, LT-PEMFC technique has become much maturer, with its cost and life time even comparable with the ICE, and it has been commercialized in many mobile or stationary applications [6]. In the current study, the PEMFC used in the power system is LT-PEMFC, and "PEMFC" only stands for "LT-PEMFC", if not stated specifically.

The maximum output voltage of a PEMFC is determined by thermodynamic law and is limited; hence, in order to satisfy the power demand of a vehicle, PEMFCs must be connected in series to form a fuel cell stack which serves as the key component of a

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Nomenclature

C	concentration, mol m^{-3}
E	voltage, V
F	Faraday constant, C mol^{-1}
G	Gibbs free energy, J mol^{-1}
l	degree of water flooding
m	mass flow rate, kg s^{-1}
M	molar weight, kg mol^{-1}
n	compressor speed, rpm
P	pressure, Pa
R	universal gas constant, J mol^{-1} K^{-1}
S	entropy, J mol^{-1} K^{-1}
T	temperature, K
V	overpotential, V
W	power generation or consumption, kW

Greek letters

η	isentropic efficiency
κ	isentropic exponent

Subscripts

1, 2, i	indexes
act	activation
air	air
comp	compressor
conc	concentration
FC	fuel cell
H_2	hydrogen
H_2O	water
in	inlet
O_2	oxygen
ohm	ohmic
out	outlet
r	required
ref	reference condition
s	isentropic process

Superscripts

ref	reference condition

fuel cell system. In a fuel cell stack environment, the reactant gas and pressure distributions may vary from cell to cell due to the complexity of the flow network, leading to difficulties in the water and thermal management and stack performance degradation. Therefore, the PEMFC stack design and operating parameters need to be optimized for better stack performance.

The design and operating parameters of a PEMFC stack are usually investigated by modeling, since fuel cell stack optimization by experiments is time-consuming and expensive. Baschuk and Li [7] established a PEMFC stack model based on a hydraulic network approach in which the mass and pressure distributions in the fuel cell stack were determined by the hydraulic network analysis. They found that the performance degradation of the cells in a stack was induced by the nonuniform mass flow rate distributions among the cells, and the stack performance was improved through the design strategies of obtaining uniform mass flow rate distributions among the cells, such as increasing the size of the manifold and decreasing the number of channels per bipolar plate. Karimi et al. [8] proposed a fuel cell stack design with a symmetric double-inlet, single-outlet topology which promoted the uniform mass distributions among the cells and improved the stack performance significantly. The temperature distributions among the cells in a stack were predicted by Park and Li [9], and the cooling water flow rate on the temperature distributions and the stack performance were also investigated. The above studies on PEMFC stack modeling and optimization indicate that the uniformity of the mass, pressure and temperature distributions are achievable through the optimization of the design and operating parameters of the PEMFC stack.

The design and operating parameters of PEMFC are also crucial for the performance of a PEMFC system. Most of the design and operating parameters have been investigated extensively, and they are usually investigated based on single fuel cell [10]. Qin et al. [11] developed novel flow channels to improve the product water removal in PEMFC. Heidary et al. [12] improved the PEMFC performance through adding blocks in the flow channel. Ghanbarian [13] enhanced the PEMFC performance by flow channel indentation. Fukuhara et al. [14] prepared PEM with nanomatrix channel to increase the proton conductivity in the electrolyte. Zhang et al. [15] investigated the operating temperature range for a HT-PEMFC, considering its effect on the fuel cell performance, CO tolerance and degradation. Santarelli et al. [16] investigated the stoichiometric ratio on the performance of a PEMFC system. Afshari et al. [17] investigated a membrane humidification system for PEMFC. Yin et al. [18] analysed an ejector for the anode reactant recycling of PEMFC. However, the effect of the operating pressure on PEMFC performance is not sufficiently investigated in literature. This is possibly because the lab-use PEMFC size is small, and it is usually operating in ambient pressure assisted by a fan or blower.

Besides the fuel cell stack, a vehicular PEMFC system should also include the air system, hydrogen system, cooling system, start-up system, DC/DC converter, etc. In the anode hydrogen system, hydrogen is usually provided by a high pressure hydrogen tank and the anode operating pressure is controlled by a pressure regulator; however, in the cathode system, oxygen is usually taken from the ambient air and an air compressor or blower must be used to obtain the required pressure and reactant mass flow rate. An air compressor is more commonly employed in a vehicular fuel cell system due to the limited pressure or pressure ratio of a blower.

The design and analysis of vehicular PEMFC power system have been extensively investigated. Evangelisti et al. [19] assessed the life cycle of a PEMFC system for passenger vehicles. Hong et al. [20] proposed a nonlinear control strategy for fuel delivery in PEMFC system. Ezzat et al. [21] analysed a hybrid PEMFC-solar photovoltaic system thermodynamically based on the energy and exergy efficiencies. However, only a few studies have been focused on the air compressor of the fuel cell system and the air compressor-fuel cell stack matching. Santarelli et al. [16] showed that an air fan was not sufficient to feed the cathode and an air compressor had to be used for the air supply at large PEMFC operating stoichiometry, and the compressor power consumption was increased with the air stoichiometry. Han et al. [22] found that the air blower or compressor showed a large contribution to the system power consumption. Thus, regulating the air compressor operating conditions to reduce the power consumption is an effective way to enhance the system efficiency. Zhao et al. [23] theoretically and experimentally studied a scroll compressor in an automotive fuel cell system and they found that the compressor power consumption and isothermal efficiency both decreased with the compressor rotation speed. Pei et al. [24] numerically investi-