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Research Paper

Evaluation of performance enhancement by condensing the anode moisture in a proton exchange membrane fuel cell stack

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HIGHLIGHTS

- Anode Moisture condensing is introduced into a PEMFC stack.
- Performance improves at high current density and high stack temperature after AMC.
- MEA is dehydrated and poor performance occurs at low current density during AMC.

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ABSTRACT

Water management is an important issue for proton exchange membrane fuel cells. Back-diffusion of water from cathode to anode often occurs due to the differences in concentration and pressure during operation of fuel cell, resulting in the flooding and severe carbon corrosion in the cathode. Herein, we report a novel method of anode moisture condensing (AMC) in which a condenser is set at the outlet of the anode to cool down the anode moisture. With the help of AMC, liquid water is condensed from the moisture due to the variation of the saturated pressure of water vapor, which can accelerate the evaporating of the liquid water inside the anode and mitigate the probability of water flooding. A ten-cell stack with a condenser at the outlet of the anode is fabricated to systematically investigate the effects of the stack temperature and flow rate on the stack performance. The result shows that the PEMFC performance can be greatly improved at high current density and high operation temperature under the condition of AMC. The stack exhibits very similar performance before and after application of AMC below 500 mA cm^{-2}, whereas the output power increases from 405 W to 436 W at 600 mA cm^{-2} at 65 °C. With further increase in operation temperature to 80 °C, the average voltage increases from 0.598 V to 0.641 V even at 500 mA cm^{-2}. Moreover, the application of AMC can speed up the water evaporation, leading to the dehydration of the membrane and thus poor performance of PEMFC at low current density.
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1. Introduction

The proton exchange membrane fuel cell (PEMFC) is an energy conversion device which can convert the chemical energy stored in the hydrogen into the electric energy directly. It has been recognized as the most promising power source due to its high energy density, great efficiency and environment friendliness [1,2]. Water management is an important issue for fuel cell [3]. Water flooding occurs when the water removal rate does not keep up with the generation rate, resulting in the severe performance degradation and carbon corrosion [4,5]. Numerous works have been done for anti-cathode flooding during the past years [6–11]. However, anode flooding can also occur due to the back diffusion of the water generated in the cathode [12,13]. Anode flooding will not only accelerate the carbon corrosion in the cathode, but also result in the carbon corrosion in the anode itself [14]. The reasons for anode flooding can be summarized as back diffusion, hydrogen flow velocity, operation temperature, current density and materials of membrane electrode assembly (MEA) as well. (1) Back diffusion. Janssen et al. [15] and Lee et al. [16] pointed out that although

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water in PEMFC generated at the cathode, whereas in pursuit of high performance, the thickness of the membrane has been reduced to several micrometers at present, so that the back diffusion from the cathode to the anode is greatly enhanced. Nguyen et al. [17] found that the back diffusion could cause the anode to flood when the hydration was low. At low current densities, the hydration of membrane is not strong enough, the back diffusion of water can exceed the effect of the electro-osmotic force, thus anode tends to be flooded in this situation. McKay et al. [18] built a two-phase flow model to investigate the performances of proton exchange membrane fuel cell under different working conditions. It was found that the reverse flow of the liquid water from the cathode to the anode would lead to the flooding of the anode when the current density was lower than 0.5 A cm^2 with un-humidified hydrogen at about 60 °C. Moreover, the accumulation of liquid water in the anode flow path and the gas diffusion layer directly resulted in the decrease of the cell voltage. (2) Hydrogen flow velocity. In the anode, nearly all the hydrogen was consumed during the reaction at a low stoichiometry and the flow generated in the channel was not strong enough to blow the liquid water out of the fuel cell, thus anode was easily got flooding during the operation [19–21]. Choi et al. [22] and Hussaini et al. [23] observed the accumulation of large amount of liquid water in the flow channel using a transparent fuel cell, causing clogging of the flow channel. This phenomenon was more severe in a fuel cell with dead-ended anode [24], resulting in fuel starvation and consequently a significant decrease in the performance. Lee et al. [25] developed a fuel cell with transparent anode and cathode to investigate the flooding characteristics in the single-serpentine flow channel. It was found that water flooding in the anode was more serious than that in the cathode, attributed to the low flow velocity in the anode. Zhan et al. [26] found that the liquid water in the flow channel corner was difficult to be removed out of the fuel cell with the gas flow velocity less than 4 m s^{-1} in a visualization experiment. The droplets in the corner could be crashed and flow smoothly out of the fuel cell if the gas flow velocity was over 4 m s^{-1}. (3) Operation temperature. The oxygen reduction reaction in the cathode is exothermic, whereas hydrogen oxidation reaction in the anode is endothermic. Hence, the water vapor was more easily to be condensed into liquid, resulting in more severe water flooding in the anode [25]. Wang et al. [27] developed a transparent PEMFC to study liquid water formation behavior in the anode. It was found that the condensation of water vapor in the flow channel was the main reason for the formation of liquid water and the increase of the operation temperature could effectively constrain the water vapor condensation in the flow channel, mitigating the flooding behavior in the anode. Cho et al. [28] condensed the water vapor in the flow channel of the anode, thus liquid water generated and flooding occurred. The results showed that the performance of the proton exchange membrane fuel cell was greatly reduced. After a long-term experiment, the thickness of the anode became thinner, and the ratio of Pt to carbon was increased indicating the severe carbon corrosion under anode flooding condition. In general, anode was easily flooded at low operation temperature. Increasing the operation temperature, especially the anode temperature, could not only increase the rate of liquid water evaporation, but also effectively avoid the condensation of water vapor in the flow channel, thereby reducing the anode flooding. (4) Current density. McKay et al. [18] pointed out that the anode flooding was easy to occur in the case of low current density. Ge et al. [27] found that liquid water generated in the anode side only in the low current density (200 mA cm^{-2}). Liquid water was not observed in the anode under high current density because the evaluated electro-osmotic force can bring more water from the anode to the cathode and reduce the water content in the anode. Pasaogullari et al. [29] found that anode flooding phenomenon could be often observed under the low current density, especially in the low hydrogen flow rate and low temperature. Water content in the entrance of the anode maintain in a low value due to the effect of electro-osmosis. On the contrary, high water content and even droplet could be observed near the anode outlet because the current density was lower than that in the entrance. Lee et al. [25] also pointed out that flooding phenomenon could occur more easily at low current density due to the less heat generated during the electrochemical reaction. (5) MEA materials. Hydration of the membrane plays an important role in proton conductivity and water transport across the membrane [30]. The most widely used membrane in PEMFCs was the perfluorosulfonic acid (PFSA) membrane. Although many studies have focused on modified or composite PFSA membranes [31,32], few other commercial membranes have met the strict requirements of the water transport and balance in the membrane. Hydrophobic material, such as Polytetrafluoroethylene (PTFE), was added to the Pt/C catalyst layer or gas diffusion layer to realize the purpose of anti-water flooding [33,34].

Several techniques, such as special flow channel design [35], gravity [36] has been applied to help the water removal in the anode. However, there are few literatures about the effect of the anode moisture management on the PEMFC performance. In this paper, a novel method of anode moisture condensing (AMC) was applied to a 10-cell PEMFC stack to improve the water management in the anode. The effects of the operation temperature, current density and the hydrogen flow rate on the PEMFC performance were investigated in detail.

2. Experimental

2.1. Preparation of PEM fuel cell stack

The PEM fuel cell stack was assembled by connecting ten individual cells in series with a 200 cm^2 active area. Geometrical properties of PEM fuel cell stack are listed in Table 1. Each single cell was composed of the bi-polar plate, the MEA and the silicone seal. The bi-polar plate was made by the graphite plate with straight channel for the reaction gas flow. The cooling channel was located on the back of each plate to allow the deionized water at a pre-set temperature as the circulated coolant. MEA was fabricated with the Pt/C catalyst coasted on the Nafion® XL membrane. The catalyst loading on the cathode and anode is 0.4 mg cm^{-2} and 0.4 mg cm^{-2}, respectively. Toray carbon paper was used as the gas diffusion layer (GDL). Two gold-plated copper plates were selected as electrodes. The end plates of the stack are made by the stainless steel.

2.2. AMC system and the test station

The exhaust gas at the cathode of the PEM fuel cell stack ejected directly into the atmosphere, however the exhaust gas at the anode was supplied into the AMC system. The AMC system, which was shown in Fig. 1(a) was composed of a buffer located at the anode outlet of the stack and aluminum (Al-based) condenser. The effective radiation area for the condenser was 4.5 m^2. There was a radiation fan on the condenser. The specification of the electrical fan was shown in Table 2. The manometer and the thermocouple were assembled at the inlet and the outlet of the buffer, respectively. The inlet pressure of the gas moisture was measured with the FCX-AII pressure transmitter which was supplied by Fuji Electric Global [37] with the accuracy of ±0.1%. The gas temperature was measured with the TT-T-36-SLE thermocouple, supplied by OMEGA Engineering [38] with the accuracy of ±0.2%. Both the pressure and the temperature data were recorded with Keithlet-2700 data collector.

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