Journal of Power Sources 382 (2018) 1–12

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Experimental and analytical analysis of polarization and water transport behaviors of hydrogen alkaline membrane fuel cell

Sen Huo[a,1], Jiaxun Zhou[a,1], Tianyou Wang[a], Rui Chen[a,b], Kui Jiao[a,*]

[a] State Key Laboratory of Engines, Tianjin University, 135 Yaguan Rd, Tianjin, 300350, China
[b] Department of Aeronautical and Automotive Engineering, Loughborough University, Leicestershire LE11 3TU, UK

HIGHLIGHTS

- Experimental tests are carried out to study the operational behavior of AEMFC.
- Analytical model is conducted to further reveal the transport behavior in AEMFC.
- Performance is enhanced by maintaining pressure gradient from anode to cathode.
- Pressure gradient mainly affects the electrochemical kinetics of anode and cathode.
- Possible reversion of water back diffusion through the membrane is analyzed.

ARTICLE INFO

Keywords:
Alkaline electrolyte membrane fuel cell
Experimental test
Analytical model
Water transport

ABSTRACT

Experimental test and analytical modeling are conducted to investigate the operating behavior of an alkaline electrolyte membrane (AEM) fuel cell fed by H_2/air (or O_2) and explore the effect of various operating pressures on the water transfer mechanism. According to the experimental test, the cell performance is greatly improved through increasing the operating pressure gradient from anode to cathode which leads to significant liquid water permeation through the membrane. The high frequency resistance of the A901 alkaline membrane is observed to be relatively stable as the operating pressure varies based on the electrochemical impedance spectroscopy (EIS) method. Correspondingly, based on the modeling prediction, the averaged water content in the membrane electrode assembly (MEA) does not change too much which leads to the weak variation of membrane ohmic resistance. This reveals that the performance enhancement should give the credit to better electro-chemical reaction kinetics for both the anode and cathode, also prone by the EIS results. The reversion of water back diffusion direction across the membrane is also observed through analytical solution.

1. Introduction

Fuel cells have been touted as a popular alternative clean energy conversion device due to its high power density, low emission, fast startup and high thermal efficiency, acquiring increased interests from commercial, governmental, military and academic organizations [1–4]. Alkaline electrolyte membrane (AEM) fuel cell offers potential superiority over the conventional proton exchange membrane (PEM) fuel cell, most dramatically to surmount the precious catalyst dependence which greatly encumbers the commercial implementation. AEM fuel cell is considered to generate from alkaline fuel cell (AFC) which seriously suffers from the carbon dioxide (CO_2) poisoning problem. The fast commercialization of AEM makes it possible for the AFC to overcome to the poisoning problem [5,6].

Recently, many experimental studies on the AEM fuel cell have been carried out to investigate the operating behavior with various cell designs and different operational conditions [7–19]. Compared to the well-developed PEM fuel cell, the researches on AEM fuel cell are still at early stage. A novel membrane electrode assembly (MEA) based on the porous silver electrode has been designed by Kucernak et al. [7] and an enhanced performance of 60 mW cm^{-2} at 0.6 V has been obtained. The effect of the electrode design parameters, including the ionomer content, thickness of catalyst layer (CL) and membrane and aminating agent of the membrane, on the performance of AEM fuel cell has been investigated by Mamlouk et al. [8]. The experimental tests were also carried out by Yang et al. [9] to optimize the design parameters of the

* Corresponding author.
E-mail address: kjiao@tju.edu.cn (K. Jiao).
[1] Equal contribution.

https://doi.org/10.1016/j.jpowsour.2018.02.020
Received 5 December 2017; Received in revised form 1 February 2018; Accepted 5 February 2018

gas diffusion layer (GDL), PTFE content and catalyst loading, and a peak power density of 213 mW cm^{-2} was achieved at 50 °C. In addition, high performance AEMs and non-precious catalysts have been prepared to enhance the MEA performance [5,6,10–14]. With the design of AEM fuel cell getting improved, a series of experimental researches on the performance test, control strategy and water management are emerging in the literature. The importance of dynamic water balance between membrane and electrode water uptake was demonstrated by Omasta et al. for the performance enhancement [15]. Anode flooding issue has been also declared by Oshiba et al. [16] and efficient water management strategies by changing the membrane thickness and anode flow rate has been proposed. The critical relation between the electrochemical stability and water content inside the electrode was addressed based on the experimental work and molecular dynamics modeling [17]. The overall cell performance under various operating conditions has been tested using an AEM fuel cell containing A201 alkaline membrane as the solid electrolyte [18]. Early researches on the fuel cell design and operating performance has deeply facilitated the development of AEM fuel cell technology. However, the experimental investigation on the hydrogen AEM fuel cell is still scarce and immature, and the operating characteristics, especially the water transport behavior and management strategy still need to be further explored [19].

Water balance should be recognized as a critically pivotal issue for AEM fuel cell with increasing rigor. Several water transport approaches should be addressed inside the cell, covering the water back diffusion, electro-osmotic drag effect and liquid permeation though the alkaline membrane. Considering the complexity and difficulty of the visualization research on fuel cell, modeling study is viewed to be a more effective and low-cost approach to gain a deep insight into the water transport in the porous electrodes and alkaline membrane. Modeling study has been proposed and demonstrated by Raya et al. [20] and the coupling of the membrane conductivity with the water absorption and temperature has been emphasized. Dekel et al. [21] presented a new model for hydrogen AEM fuel cell and the critical dependence of cell performance on the cathode hydration was stated. Sommer et al. [22] also developed a transient model for AEM fuel cell to predict the cell response with respect to the physical properties and operation/design parameters. A series of multi-dimensional multiphase modeling work has been conducted for hydrogen AEM fuel cell in the last several years [23–29], pointing out the importance of water management in AEM fuel cell. However, in these early modeling studies on AEM fuel cell, the water transport mechanism is still not impeccable and needs to be further developed. One important issue is that the models for AEM fuel cell need to be validated more comprehensively to reveal the transport mechanism precisely.

In this present work, experimental and modeling work is conducted to further explore the operating behavior of AEM fuel cell, as well as the water transport inside the electrode. The polarization losses are obtained using in-situ electrochemical impedance spectroscopy (EIS) method. An analytical model is also developed to simulate the transport characteristics inside the cell based on the experimental data and promotes understanding of the operating behavior under different operating conditions. It should be noted that the liquid permeation through the membrane is also taken into consideration which was often neglected in previous studies and its significant influence on the cell performance and mass transport is also discussed. The detailed experimental setup and analytical modeling formulation is introduced in the second and third sections, respectively. The experimental and analytical results are presented in the fourth section, followed by the conclusion in the last section.

2. Experiment

2.1. Experimental setup and procedures

The schematic of experimental setup is shown in Fig. 1, composed of the testing AEM fuel cell, fuel cell test station, environment chamber, electrochemical station and data processing system. The fuel cell test station is used for controlling and monitoring the operating parameters for the fuel cell tests, such as the humidification condition, stoichiometry ratio, flow rate, operational current or voltage, feed gases species and back pressures. The deionized water is utilized for humidifying the feed gases based on bubbling humidification. The environment chamber is applied for heating up (or cooling down) and maintaining the fuel cell and operating environment at a specific operating temperature. The in-situ polarization losses, as well as the high frequency impedance of the testing fuel cell can be captured and estimated via the EIS method utilizing the electrochemical station. The equivalent circuit for the EIS data is also presented in Fig. 1. The measurement of back pressure is implemented at both anode and cathode outlets. Meanwhile, the data are constantly collected by the data processing system during the fuel cell tests.

2.2. Fuel cell design and MEA fabrication

The testing AEM fuel cell consists of end plates (aluminum alloy), electrical collectors (gold coated aluminum alloy), graphite flow fields with flow channel and catalyst coated membrane (CCM). The testing AEM fuel cell has a serpentine flow channel with a cross section area of 0.8 mm by 1.0 mm and active area of 2.5 cm by 2.5 cm. A commercial A901 alkaline membrane from Tokuyama Corporation is selected as the solid alkaline electrolyte. The catalyst loading of Pt is set as 0.5 mg cm^{-2} for both electrodes. The MEA is prepared by sandwiching the GDLs with micro-porous, carbon-based layer (MPL) and the CCM. The GDL used in the test is H23C6 from Freudenberg Group which contains a macro-porous superstructure (carbon fiber paper) and MPL. The thickness of GDL is around 250 μm with consideration of the MPL. The weight ratio between Pt/C and ionomer in the CL is set as 3:1 to maintain effective electrochemical kinetics and ionic conductivity inside CL. The scanning electron microscope (SEM) images of the CL surface are also given in Fig. 1. The basic information and physical properties of AEM fuel cell are listed in Table 1.

As for the preparation of the CCM, the Pt/C (Pt 56.6% wt.) is calculated as 5.52 mg in terms of the Pt loading of 0.5 mg cm^{-2} and the active area of 6.25 cm^2. Pt/C should be firstly infiltrated by the deionized water of 50 mg and then mixed with the normal propyl alcohol solution (1 mL) due to the fact that the direct contact between dry Pt/C and normal propyl alcohol solution possibly leads to fire risk. According to the weight ratio between Pt/C and ionomer in the CL (3:1), the required amount of the ionomer solution (alkaline electrolyte 5% wt.) is 36.81 mg. The catalyst-ionomer ink is prepared by mixing the ready-made catalyst ink with the ionomer solution. Sonication is implemented on the catalyst-ionomer ink for 90 min for better mixture. At last, the CCM is fabricated via spraying the catalyst-ionomer ink onto the A901 alkaline membrane under infrared spotlight. In order to facilitate the solidification of Pt/C and the volatilization of normal propyl alcohol, vacuum heating is employed and the heating temperature is set as 50 °C.

2.3. Experimental test

The polarization test is conducted in constant-voltage mode, which is separated into two cases by feeding H_2/air and H_2/O_2 for the testing AEM fuel cell. The flow rates at anode and cathode inlets are 0.5 and 1.0 slpm, respectively. Since the gas supply is conducted based on the inlet flow rate via the fuel cell test station, the actual stoichiometry ratio varies with the operating current density. The normal operating temperature of AEM fuel cell is set at around 50 °C which is slightly lower than the conventional PEM fuel cell in order to achieve both the effective membrane performance and operational durability. Through setting the dew point temperature at 50 °C, fully humidified hydrogen and air or O_2 are supplied.