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Development and performance evaluation of a high temperature proton exchange membrane fuel cell with stamped 304 stainless steel bipolar plates

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ABSTRACT

In this work, a high temperature proton exchange membrane fuel cell (HT-PEMFC) with stamped SS304 bipolar plates is successfully developed. Its performance was evaluated under two types of gaskets at different assembly torques and air stoichiometric ratios. The rates of pressure loss at a torque of 7 N-m with 50 Shore A hardness gaskets was 2.0×10^{-3} MPa min^{-1}, which is acceptable. The best performance of the developed HT-PEMFC with stamped SS304 bipolar plates was 228.33 mW cm^{-2}, which approaches the performance of HT-PEMFCs with graphite bipolar plates. The optimal air stoichiometric ratio for the HT-PEMFC with stamped SS304 bipolar plates was 4.0, which is higher than that for proton exchange membrane fuel cells with CNC milled graphite bipolar plates. This is probably because of the deformation of the flow channels under the assembly compression force, which causes an elevated gas-diffusion drag in the flow channels. After the test, it was observed that some products of corrosion reaction formed on the surface of the SS304 bipolar plate. This phenomenon may lead to a decrease in the operating life of the HT-PEMFC.

Introduction

Over the past few centuries, human requirements for energy have been met by burning fossil fuels. However, exploiting this resource has led to global warming and innumerable environmental issues, such as air pollution and oil spills. Nevertheless, increasing human mobility and economic development has increased the demands for energy. Thus, finding solutions to the growing demands for energy and simultaneously avoiding environmental damage has recently been driving the development of low-carbon and even zero-carbon energy sources. Some mainstream renewable energy technologies, including wind power and solar energy, have the problem of unstable power output due to unpredictable weather conditions. To overcome this problem, a reliable and efficient energy storage sub-system is required in future distributed-power systems. Among energy storage technologies, fuel cell systems with hydrogen storage are a promising option [1–4]. Additionally, fuel cell power generation systems also have the advantages including no production of polluting emissions during operation, high energy conversion

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efficiency, and low noise. Consequently, this technology is expected to play an important role in future renewable energy systems.

Based on the different types of electrolytes, fuel cells can be divided into different categories. Among the various types of fuel cells, the proton exchange membrane fuel cell (PEMFC) has the advantages of rapid start, reliable output, high practicability, and a wide range of applications; accordingly, it may be a suitable power source for future clean transportation or portable energy demands. Nevertheless, some challenges still need to be overcome before PEMFCs can become fully commercialized. Two of the most critical problems are hydrogen delivery and storage [5,6], and the cost, in particular, the costs related to the catalyst and graphite bipolar plates (BPs) [7–9]. The most common approach to solving the problem of hydrogen delivery and storage is to integrate a PEMFC with a hydrogen reformer, which reforms natural gas, liquefied petroleum gas, methanol, ethanol or bio-mass fuels into hydrogen-rich reformate gases. Nevertheless, the drawback is that carbon monoxide produced from a reforming system degrades the performance of PEMFCs because CO binds more strongly to Pt than H_2 [10]. However, increasing the operating temperature has been shown to improve the CO tolerance [11,12], which has led to high temperature proton exchange membrane fuel cells (HT-PEMFCs) attracting increased attention from researchers.

To solve the second critical problem, namely the cost of PEMFCs, one practical method is to reduce the cost of the bipolar plates, which constitutes a large proportion of the overall cost of the PEMFC stacks. Traditional computer numerical control (CNC) milled graphite bipolar plates are expensive due to both the material itself and the CNC-milling fabrication process, which is time consuming and increases the cost during the mass-production phase. Thus, using thin metallic bipolar plates in PEMFCs is regarded as a good alternative to the high cost of bipolar plates [13]. In addition, using thin bipolar plates reduces the volume and weight of the stack, leading to an increase in the specific power of the PEMFC stack [7,8]. Another advantage of metallic bipolar plates is that they can be manufactured via alternative fabrication methods [14], including stamping [15–21], hot pressing [22], rubber pad forming [23–26], hydroforming [15,27–30], vacuum die casting [31,32] and semisolid forging [33]. These fabrication methods are faster than CMC milling and therefore are able to reduce the fabrication cost of such plates. Among these alternative fabrication methods, stamping is currently one of the most common, and is therefore selected as the method by which to fabricate the HT-PEMFC bipolar plates discussed in this work.

In 2005, Hermann et al. [34] reported that the primary substrate materials for metallic bipolar plates include stainless steel, aluminum alloy, titanium, and nickel. Although the mechanical stability, electrical conductivity, thermal conductivity, gas impermeability, and formability of the above metals are good and thus make them suitable for bipolar plates, they tend to corrode and dissolve due to the operating environments having a pH of 2–3 and temperatures of up to 80 °C [35]. Wang et al., in 2006 [36], Xu et al., in 2016 [37] and Asri et al., in 2017 [38] studied titanium-based bipolar plates for PEMFCs. In contrast, aluminum-based bipolar plates are up to 65% lighter compared to stainless steel and are able to meet the U.S. DOE targets for conductivity, flexural strength, and cathodic corrosion resistance for fuel cell bipolar plates [39]. Thus, aluminum bipolar plates have also been studied by several researchers, including Lin and Tsai in 2012 [40], Mawdsley et al., in 2013 [39] and Li et al., in 2014 [41]. Nevertheless, among all the materials studied in the previous literature, stainless steel is still considered the most common material for metallic bipolar plates, as exemplified in works reported by Wang et al., in 2007 [42], Sun et al., in 2013 [43], Bi et al., in 2015 [44], Rajasekar et al., in 2015 [45], Sanmugham et al., in 2015 [46], and Alishahi et al., in 2016 [47].

Presently, although there have been numerous studies of metallic bipolar plates for PEMFCs, most of these works have focused on their ex-situ properties. Some published papers have reported the experimental performance of PEMFCs with metallic bipolar plates. However, most of the bipolar plates in these works were fabricated using traditional CNC milling [38,48,49]. Moreover, HT-PEMFCs are currently equipped primarily with graphite bipolar plates; by contrast, HT-PEMFCs with metallic bipolar plates have only been tested in-situ and discussed in recent years. In 2011, Hartnig et al. [50] conducted a performance degradation test of an HT-PEMFC with different types of bipolar plates, including gold-coated stainless steel bipolar plates. Their results showed that the gold-coating treatment led to negligible water uptake on the bipolar plate surface. In 2015, Alnegren et al. [51] studied the possibility of applying 316L stainless steel bipolar plates in an HT-PEMFC. They obtained the performance degradation rate of the HT-PEMFC and observed some corrosion products on the SS316L bipolar plate surface. In 2016, Tseng et al. [52] proposed an HT-PEMFC with a metal-foam flow field and found that this approach improved the cell performance by 20% compared with a graphite-serpentine flow field.

Among the above studies into PEMFCs and HT-PEMFCs, a few works concerning PEMFCs with stamped metallic bipolar plates can also be found in the literature, such as those by Ren et al., in 2012 [53], Jin et al., in 2014 [54], Jung et al., in 2015 [55] and Haase et al., in2016 [56]. However, to the best of the author's knowledge, reports targeting in-situ testing of HT-PEMFCs are lacking. In response, this work focuses on the development and performance evaluation of an HT-PEMFC with stamped 304 stainless steel bipolar plates, the focal parameters of which include the gasket hardness, assembly torque, and air stoichiometric ratio. Additionally, a preliminary study of the corrosion phenomenon on the bipolar plate in the HT-PEMFC is also focused.

Experimental setup

In this study, an HT-PEMFC with stamped SS304 bipolar plates was fabricated, and its performance was evaluated. The rate of pressure loss, polarization curves, electrochemical impedance spectroscopy (EIS), and a surface element content analysis were used to evaluate the performance of the HT-PEMFC. As aforementioned, the studied parameters included gasket hardness, assembly torque and air stoichiometric ratio. The fuel cell, experimental setup, and facilities are introduced in the following section.

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