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Experimental investigation on PEM fuel cell cold start behavior containing porous metal foam as cathode flow distributor

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HIGHLIGHTS

- PEM fuel cell cold start tests compare metal foam (MF) and parallel flow fields.
- MF produces higher max power than parallel considering pumping loss.
- MF produces slightly lower power than parallel at low current operation.
- Galvanostatic MF cold start is better due to improved ice storage and gas flow.
- Ice blockage occurs in both MF and parallel channel in potentiostatic mode.

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ABSTRACT

Metal foam has been regarded as one of the most important replacement for the conventional flow distributor of commercial fuel cells in recent years. One critical issue for the commercialization of proton exchange membrane (PEM) fuel cell is the successful startup from subzero temperatures. In this study, experimental tests on a PEM fuel cell using nickel metal foam as the cathode flow distributor are carried out to investigate the cold start performance. The cold start performance is also compared to a PEM fuel cell with parallel flow channels. Both galvanostatic and potentiostatic control are considered. The results show that under normal operating conditions the metal foam PEM fuel cell exhibits higher maximum net power density than the cell with parallel flow channels, whereas the parallel channel case exhibits slightly better performance at lower current densities. For cold start tests, metal foam is superior to the conventional parallel flow channel under galvanostatic control, due to its extremely porous structure, uniform mass and heat distribution. It is more difficult for PEM fuel cell under potentiostatic control to successfully start up due to possible ice blockage at the outlet.

1. Introduction

Proton exchange membrane (PEM) fuel cells have been regarded as one of the most efficient energy conversion engines due to their low to zero emissions, high power density, fast startup, system robustness and high energy conversion efficiency (depending on the fuel types) [1–4]. For widespread commercial adoption, the operational performance under various environmental conditions must be reliable. The cold start issue of PEM fuel cells has drawn increasing attention in recent years. Under freezing temperatures, the startup potential, operating performance and cell durability have been proven to be significantly reduced due to the supercooled water, ice formation, and blockage of reaction sites, which may also result in irreversible damage to the cell components. As PEM fuel cells are known to be widely used in automotive, portable power, aerospace applications, it is almost inevitable for the fuel cell to need to start up and operate in freezing environments [5,6]. Therefore, understanding the cold start behavior and ice formation mechanism is a critical issue for PEM fuel cell commercialization [7,8].

Considerable efforts have been made in both the numerical and experimental aspects to study the startup capability of PEM fuel cells and the performance degeneration during the cold start thermal process [9–20]. Various startup conditions, including startup temperature, startup current density, and initial water content in the membrane, were investigated to study the cold start behaviors of PEM fuel cell [9]. In order to successfully start up from freezing temperatures, Guo et al. developed a numerical multiphase model for PEM fuel cell cold start, and the results showed that adoption of

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hydrogen-oxygen catalytic reaction assisted method significantly enhances the startup capability [10]. Santamaria et al. proposed a new type of flow field design, which can be switched between parallel and interdigitated, to improve the startup performance from subzero temperatures [11]. Ko et al. implemented several numerical simulations to investigate the effects of cell design parameters, including the ionomer fraction and platinum (Pt) loading in the catalyst layer (CL), and physical properties of the micro-porous layer (MPL), on the unassisted cold start behaviors of PEM fuel cells. The results indicated that the ice formation and water absorption mechanisms in the CL could be improved by controlling these parameters [12,13]. Miao et al. mixed nanoscale SiO_2 into the CL, which dramatically enhances the water storage ability of the CL, as well as the cold start capability of the PEM fuel cell [14]. Although much progress has been made in the cold start of PEM fuel cell, the relevant study on the new design of flow distributor and optimization for the traditional flow channels is still lacking, which should be regarded as an important factor affecting the cold start ability of PEM fuel cell.

With the rapid development of PEM fuel cell technology in the last few decades, a series of flow channel configurations have been presented and applied for the gas flow distributor, such as the parallel, serpentine, multiple serpentine, interdigitated, and fractional flow channels [21–23]. However, there exist critical issues related to the conventional flow channel types [24]. Because of the existence of ribs in the channel structure, the reactants flow, the heat generation, as well as the electrochemical reaction are not evenly distributed in the CL, resulting in ineffective catalyst utilization. Liquid water tends to accumulate under the rib and is difficult to remove from the fuel cell, contributing to gas feed interruption, water flooding and ice blockage. Therefore, the designs of traditional flow distributors for PEM fuel cell need to be improved urgently [11,25].

In recent years, the porous metal foams are well developed for various fields mainly because of their distinctive thermal and physical properties, such as the extremely high porosity, large surface area and controllable mechanical strength [26–29]. For structural performance and weight saving, a novel flow distributor - commercial metal foam material - was proposed as a replacement for the conventional flow channels in the fuel cell [30–34]. In this kind of fuel cell, the MEA is sandwiched between two pieces of compressed metal foams with Teflon coatings, which leads to strong corrosion-resistance and hydrophobicity. Compared to conventional flow fields, metal foam offers several benefits during the normal and cold start operation, including:

(i) The most distinct characteristic is its extremely porous structure (around 95% porosity), resulting in uniform distribution of reactants, enhanced catalyst utilization and liquid/ice storage capability.
(ii) Metal foam maintains tortuous and uniform pathways for reactant and charge transport.
(iii) Better gravity independence due to the porous property.
(iv) Metal foam has the potential to offer a reasonably high pressure drop, which may lead to enhanced normal and cold start performance [34].

One possible disadvantage of metal foam flow field is associated with its corrosion resistance. Therefore, metal foams materials should have the ability to withstand the acid and alkaline corrosion in a fuel cell. Specific coatings (PTFE, graphite and precious metals) for the metal foam are considered as one effective method to improve the corrosion problem [26,35].

As mentioned previously, cold start is an important issue for the commercialization of PEM fuel cells. The application of metal foam distributor should be considered as an effective way to improve the performance. However, the related experimental and numerical work in the literature for the cold start of metal foam PEM fuel cells is scarce, which should be viewed as an important supplement to the current published cold start studies in the literature. In this study, a series of experimental tests on the cold start of a PEM fuel cell containing metal foam as the cathode flow field are implemented to investigate the startup performance, which is then compared to a PEM fuel cell with conventional parallel flow channels. The experimental setup and procedures are presented in Section 2. The operating conditions and cold start results are discussed in Section 3.

2. Experimental setup and data analysis

The schematic of experimental setup is shown in Fig. 1. Arbin Instruments fuel cell test station (FCTS) is utilized for setting, capturing and collecting the fuel cell operating parameters, including cell temperature, feed reactants, fuel cell humidification, stoichiometry ratio, inlet flow rate, operating current and voltage. Bubbling humidification is applied to both the anode and cathode using deionized water, where dew point temperature is set for controlling the inlet gas humidity. The data sampling frequencies of fuel cell voltage and current are set as 10 Hz. Four cartridge heaters from the test station and an environment chamber (ESPEC®) are used for heating up or cooling down the fuel cell and the operating environment to a desired temperature. A K-type thermo-couple is plugged into the middle of the cathode bipolar plate with a depth of 4 mm close to the channel walls to capture the cell temperature evolution. Fuel cell temperature and inlet gas temperature data are monitored by the fuel cell test station with a collecting frequency of 1 Hz. Pressure measurement is conducted at the cathode inlet.

2.1. Fuel cell design and cell conditioning

The design of testing PEM fuel cell is shown in Fig. 1. The flow channel plates are separated from the bipolar plate superstructure, not directly machined or sheet-metal formed on it, to allow for easy and rapid flow field switching for direct comparison. There are seven parallel aligned channels on the parallel flow channel plate. The cross-section area of a single channel or a rib is 1 mm × 1 mm. Compared to the square-shape flow field, the long and narrow strip-shape flow distributor has less channels in parallel, leading to more evenly distributed reactants and products in the overall flow field, which is possible to handle the fuel starvation and remove the produced water quickly in high current density condition. The reaction area of the testing fuel cell is 1.5 cm × 20 cm. The GDL used in the experiment is the Sigracet 10BC from SGL Group®, and is composed of a macro-porous backing material (carbon fiber paper) and micro-porous, carbon-based layer (MPL). The wettability and physical structure of GDL will dramatically affect water transport through the liquid pressure-concentration correlation. A commercial Nafion 112 proton exchange membrane from DuPont® is selected as the electrolyte and the catalyst loading (Platinum) is approximately 0.4 mg cm^{-2} for both sides. The testing MEA is prepared via hot pressing by sandwiching the catalyst coated membrane (CCM) with GDLs at 7 MPa and 140 °C for 25 min.

Two different cathode flow field designs are constructed for the PEM fuel cell in this study. One is a PEM fuel cell containing nickel metal foam (3 mm originally, Grade 5, from Sumitomo Electric Company) as the cathode flow field and a parallel flow channel as anode flow field. The other is a PEM fuel cell using conventional parallel flow channels as both anode and cathode flow fields. Due to the water production in the cathode CL and worse electrochemical kinetics for the cathode semi-reaction, namely, cathode perfor-