Applied Energy 107 (2013) 264–270

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Vacuum-assisted drying of polymer electrolyte membrane fuel cell

Hong-Yue Tang, Anthony D. Santamaria, John Bachman, Jae Wan Park *

Department of Mechanical and Aerospace Engineering, University of California, Davis, CA 95616, United States

HIGHLIGHTS

- Vacuum pressure was applied to a PEMFC to dry the membrane.
- The vacuum-drying performance was compared to dry N2 purging method.
- Electrochemical impedance spectroscopy was used to monitor the drying process.
- An equivalent circuit model was used to analyze the membrane resistance and anode charge-transfer resistance.
- Experimental results show vacuum-assisted drying methods provide a higher water removal rate than dry N2 purging.

ARTICLE INFO

Article history:
Received 28 August 2012
Received in revised form 11 January 2013
Accepted 16 January 2013
Available online 16 March 2013

Keywords:
PEM fuel cell
Vacuum-assisted drying
Purging
Membrane

ABSTRACT

Purging a polymer electrolyte membrane fuel cell (PEMFC) with dry N_2 to remove water in the catalyst layer and the membrane during shutdown is necessary for ensuring successful startup and avoiding damages from the freeze/thaw cycling during cold-start. However, carrying N_2 onboard may be impractical for mobile applications. Vacuum-assisted drying can accelerate and aid in water removal by reducing the boiling point of water, thus enhancing the evaporation and diffusion rate. This method is applied to a single cell PEMFC and compared to purging using dry N_2. The drying process was monitored using electrochemical impedance spectroscopy (EIS), and the results were fitted to an equivalent circuit model. Our experimental results show the vacuum-assisted drying method may provide faster and more thorough water removal than N_2 purging.

1. Introduction

Polymer electrolyte membrane fuel cells (PEMFCs) convert hydrogen and oxygen into electricity, producing heat and water as byproducts. Water is produced during the reaction within the cathode catalyst layer (CL) and leads to variable saturation of the membrane, CL, gas diffusion layer (GDL), and channel regions. Some water collection may also be a result of condensation from humidified gases [1–3] and water redistribution after cooling [4,5]. This may be beneficial during operation as the membrane must be hydrated in order to effectively conduct protons [6,7]. However, excess liquid water build-up leads to blockages of critical reaction sites as well as gas re-routing [8]. Additionally, water remaining in a cell under sub-zero conditions may lead to membrane degradation and failed start-up [9–11]. Investigation of advanced cell drying techniques during shut down has important implications on the cell operation and life.

Numerous groups have studied purging and reported its effect on water removal [12–16]. Critical testing parameters include purge time, gas velocity, relative humidity, and surface treatment of bipolar plates as these are coupling factor that impact a cells condition and performance [4,5,17,18]. After a fuel cell shuts down, water is present in both gas and liquid phase. As the purging gas flows over the GDL surface, a complex interaction between the purging gas and water occurs [4], and water can be drawn out from the membrane into the flow field by concentration and pressure gradients. Purging is effective in removing water from a cell if it is in the form of slugs [19]. However, it can be wasteful to purge with an inert gas such as N_2 for an extended period of time when high gas velocities are required to remove unconnected droplets in the GDL, and dry the CL and the membrane [4,17], especially in automotive applications. Additionally, short duration purging (60–120 s) is less effective at small scale water removal [20]. Although alternative purging methods are available such as actively purging the cell during and after operation [21–23], many of these are still energy intensive processes. Additionally, as cell temperature decreases after shutdown, the falling saturation pressure and the increase of the GDL thermal conductivity may cause

* Corresponding author. Tel.: +1 530 752 5559.
E-mail address: jwpark@ucdavis.edu (J.W. Park).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.01.053

the remaining water to condense out from the GDL after purging had taken place [24–26], thus a second purge is required. Vacuum-assisted drying methods may compliment short duration purging techniques and improve system performance.

In the food industry, vacuum drying is a common method and is used to extract water from various products such as meats and vegetables. Vacuum-assisted drying processes reduce energy consumption by allowing products to be dried at lower temperatures thus preserving the nutrients in the final product [27]. Producing a vacuum lowers the boiling point of water; enhancing evaporation rates and effectively reducing drying times. After the surface water evaporates first, it creates a concentration gradient which draws moisture towards the surface. General Motors studied freeze-protection using vacuum drying have been carried out under various temperatures and fuel types in PEMFCs to find the optimal conditions for successful start-up [28]. Lee et al. [15] also used vacuum based techniques for determining the amount of water remaining in their PEMFC during a purging study. However, both of these works did not study the dynamic of the dehydration process when using the vacuum. With a PEMFC usually operating around 80–100 °C, close to water's boiling point at atmospheric pressure, vacuum-assisted drying may be more effective than purging alone.

This work primary focuses on the dynamics of the vacuum-assisted drying process. We investigated a vacuum based method for drying a PEMFC and compare it with purging using N_2 gas. We use high frequency resistance (HRF) measurements via electrochemical impedance spectroscopy (EIS) to measure the degree of membrane hydration over time under both vacuum and gas purging scenarios. EIS is a non-invasive technique and has been used by several groups [29–36] to investigate the cell properties. The results from each case are compared and show vacuum-assisted drying performs better than purging when utilized for the same length of time. The cell performance has not shown any degradation during the limited number of vacuum-assisted drying cycles. Optimal vacuum pressure can be determined by a number of factors including the state of water in the cell and cell temperature [24,25].

2. Experimental setup

A test cell with an active area of 8 mm × 15 cm and three parallel channels with 1 mm × 1 mm cross sections ware used for the experiment. The cell requires four 150 W heating elements for maintaining cell temperature during the test. The GDL is a SGL 10 BC carbon GDL and the membrane is a Nafion 112 with a platinum loading of 0.4 mg cm^{-2} on both sides. An Arbin Instruments fuel cell test station was used to control the cell operation and provide temperature and humidity control of the fuel and air inputs. After the break-in cycle, a conditioning cycle was performed at 80 °C. The conditioning consists of five cycles at 0.6 V and 0.3 V for 15 min each. This procedure is modified from the break-in cycle detailed by the U.S. Fuel Cell Council (USFCC). Both the anode and cathode were fed with 100% relative humidity gases at a stoichiometry of 2 in order to maximize the liquid water formation in the cell. A GAST vacuum pump, model: 0823-V131Q-SG608X, provided a vacuum source at −96.5 kPa measured by a Grainger vacuum gauge: 4FLP6.

Fig. 1 shows the schematic for the vacuum-drying setup. The vacuum source is connected to the fuel cell via a 3-way valve. On the other end of the 3-way valve is an 80 °C heated line filled with dry N_2 for refilling the cell. Both the cathode and anode are tied together in order to have the same vacuum pressure applied to both sides of the membrane to avoid membrane rupture. Fig. 2 shows the test setup, excluding the temperature regulator for the N_2 purge line and the vacuum pump.

Fig. 3 shows a plot of boiling temperature of water versus pressure. The boiling temperature lowers as the pressure decreases and it allows evaporation to take place at a lower temperature. Therefore, by decreasing the pressure in the channels, the liquid water remaining in the cell will evaporate until the water vapor is saturated. Fig. 4 compares the experimental procedure of the vacuum-assisted drying and nitrogen gas purging, and the conditions sequence are shown in Table 2. The total duration of each of the methods is 25 min. After conditioning of the cell water accumulation is left in the fuel line, manifolds and channels. In both tests, using low velocity (<0.2 m/s) dry N_2 to remove water slugs is useful in providing a similar initial condition for comparing the two methods. This step is also necessary for protecting the vacuum pump. In principle, a water trap combined with a vacuum pump can provide the same result as purging with N_2 gas to remove water slugs prior to the drying process, thus simplifying the overall design for vehicle application. Fig. 5 is a series of neutron images of the cell being purged by low velocity N_2 gas. Water slugs are gradually removed from the flow channels and manifolds, leaving the MEA in a humidified state. In the vacuum-assisted drying experiment, the cell is first filled with dry N_2 at 80 °C and then the vacuum is applied to both sides of the MEA. The same cycle was repeated four times and the cell impedance has been measured using EIS at the end of

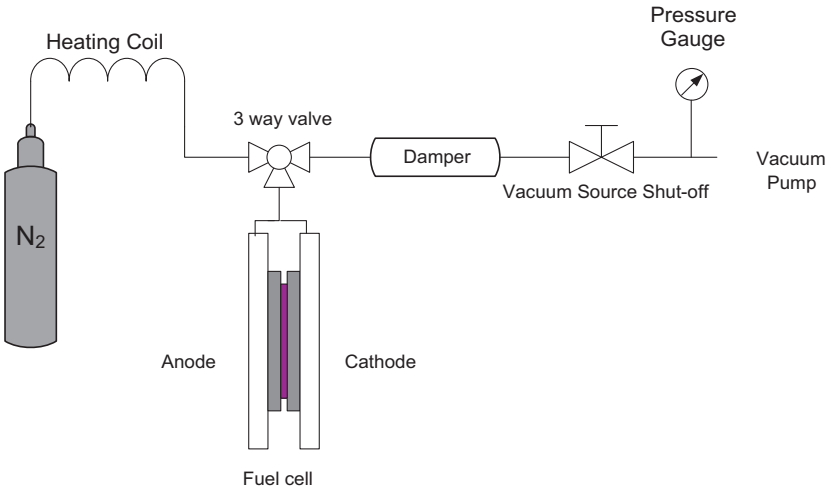

Fig. 1. Schematic of the vacuum-assisted drying experiment.