Journal of Power Sources 195 (2010) 1177–1181

Contents lists available at ScienceDirect

Journal of Power Sources

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

Short communication

Dominant frequency of pressure drop signal as a novel diagnostic tool for the water removal in proton exchange membrane fuel cell flow channel

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ARTICLE INFO

Article history:
Received 17 July 2009
Received in revised form 2 September 2009
Accepted 2 September 2009
Available online 11 September 2009

Keywords:
PEM fuel cell
Diagnostic tool
Pressure drop
Dominant frequency
FFT
Water removal

ABSTRACT

In this work, a transparent assembly was self-designed and manufactured to perform ex situ experimental study on the liquid water removal characteristics in PEM fuel cell parallel flow channels. It was found that the dominant frequency of the pressure drop across the flow channels may be utilized as an effective diagnostic tool for water removal. Peaks higher than 1 Hz in dominant frequency profile indicated water droplet removals at the outlet, whereas relatively lower peaks (between 0.3 and 0.8 Hz) corresponded to water stream removals. The pressure drop signal, although correlated with the water removal at the outlet, was readily influenced by the two phase flow transport in channel, particularly at high air flow rates. The real-time visualization images were presented to show a typical water droplet removal process. The findings suggest that dominant frequency of pressure drop signal may substitute pressure drop as a more effective and reliable diagnostic tool for water removal in PEM fuel cell flow channels.

1. Introduction

The proton exchange membrane (PEM) fuel cell has been regarded as an ideal power source for a variety of applications due to its significant advantages, *i.e.*, high efficiency, low emission, silence and simplicity [1]. The water management in PEM fuel cell is one of the crucial issues to be fully understood and optimized before further advances could be made. Sufficient amount of water is necessary for maintaining the membrane ion conductivity whereas excess water, or water flooding, may block the pores of electrodes and the flow channels, thereby reducing the reactant mass transfer to catalytic sites [2–5]. The capacity to perform effective water removal, therefore, becomes one of the most important specifications for PEM fuel cell flow channels [6]. Since it is highly desired to know the water behavior in both flow channels and porous electrodes, many modeling studies have been conducted [7–10]. Several advanced considerations including two phase flow in channels and electrodes, wettability of gas diffusion layer (GDL) and transient processes in fuel cell have been covered in these modeling studies. On the other hand, numerous experimental works concern about the diagnostic tools for the water behavior in PEM fuel cell. Research in such aspect may proceed as a more straightforward and effective way to deal with the water management, since the objective is to sense or predict the flooding/drying accurately before applying corresponding actions. Particularly, transparent fuel cell was designed for direct in situ visualization of water transport and distribution in flow channels [11–13]. Due to the limited view field and water visualization effect, however, transparent fuel cell normally can apply straight parallel channel design only. In addition, the water transport and distribution under the land cannot be revealed under transparent fuel cell configuration. Neutron imaging technique was also utilized to obtain the water distribution profiles in PEM fuel cell [14–16], with a limitation that the precise location of water is difficult to determine due to the overlapping of images. Moreover, magnetic resonance imaging (MRI) technique turned out to be also an effective tool to capture the water behavior both in membrane and flow field [17–19]. Its weakness is principally in the requirement that the materials have to be nonmagnetic, making the water in the catalyst layer and GDL, either nonwoven carbon paper or woven carbon cloth, hard to visualize. A thorough review of these techniques can be found in Ref. [20]. In addition to direct visualization, indirect diagnostic tool usually is to monitor some easy-to-measure engineering parameters. Pressure drop across the flow channel was proposed to be a diagnostic tool for PEM fuel cell flooding by Bosco and Fronk in General Motors [21]; similar findings concerning pressure drop as a diagnostic tool were reported by Barbir et al. [22], Ma et al. [23] and Ito et al. [24]. Although other parameters, such as cell resistance [22] and electrode diffusivity [25], were also used as diagnostic tool, pressure drop as the mainstream one shows significant advantages, namely, the immediate and real-time linkage between the air–water two phase flow behavior and the pressure drop. Normally, a pressure

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doi:10.1016/j.jpowsour.2009.09.003

drop increase is considered a sign of water accumulation or water film build-up in the channel; whereas a sudden decrease indicates a water removal at the outlet. However, pressure drop as a diagnostic tool for the water behavior, particularly water removal, does have shortcomings: first, high frequency oscillation in pressure drop is usually observed, which comes from the unstable two phase flow transport in channel; such oscillation does not indicate any water removal/build-up at the outlet but make a regular increase/decrease pattern in pressure drop profile fairly hard to distinguish; second, considering the relatively low pressure drop (usually <1000 Pa) across fuel cell channels, signal noises from disturbances and measurement errors may contribute considerably to the results, reducing the accuracy and even changing the pattern of the pressure drop profile. Consequently, real-time visualization results are usually used to assist the interpretation of the pressure drop profiles.

Under such circumstance, the author attempted to find a more reliable and effective diagnostic tool for water removal. In performing fast Fourier transform (FFT) upon certain amount of pressure drop data, one can obtain the frequency spectrum determined by the absolute magnitude and phase. The normalized dominant frequency is defined as the weighed average of the three components with largest power magnitudes. Compared with simply using the pressure drop as the diagnostic tool, its dominant frequency provides more accurate and robust insights about the water removal, although the new diagnostic tool essentially comes from applying some special mathematical treatment on the original pressure drop signal.

2. Experimental

2.1. Experimental setup

In this work, an assembly resembling the transparent PEM fuel cell [11] was self-designed and precisely manufactured using CNC machine. It consists of an end plate with two parallel micro-channels built on, a transparent plastic plate for visualization and a window plate to apply even compression to the whole assembly. Porous media (carbon foam) was inserted into the channels to simulate the effect of GDL intrusion in flow channel [26]. Necessary O-rings were placed on site to avoid leakage. The width of the channel is 1.5 mm and the depth 1.2 mm; consistent with typical fuel cell designs. The effective length of the channel is 40 mm, with an entrance region to stabilize the air flow. Since the core frictional pressure drop in the developing (entrance) region of the channel is non-linear and unstable [27], the pressure drop measurement was only performed on the effective length (40 mm) of the channel. Pressure measurement ports were precisely drilled at two ends of the channels. The experimental setup is schematically shown in Fig. 1, with a photo of the transparent assembly attached. The differential pressure across the whole channel was measured by a Setra 230 series transducer; data from the transducers were real-time displayed and recorded using self-developed LabVIEW programs. A CCD camera was attached to the microscope to capture the real-time water removal video at the outlet. Both de-ionized water and compressed air were injected into the channels to simulate the two phase flow in fuel cell. Liquid water was injected into each channel separately using a syringe pump, so that the injection rate can be accurately controlled. The water injection rate was set to 0.01 ml min^{-1} corresponding to liquid superficial velocity (U_l) of 0.093 m s^{-1} in each channel, which was an analogy to the generation rate in real fuel cell operation under a normal current density of 0.6 A cm^{-2} and an effective MEA area of 4 cm^2. Meanwhile, air flow rates were varied from 0.01 to 0.8 l min^{-1} using a mass flow controller, corresponding to stoichiometry ratios up to 10 in fuel cell operation, and gas superficial velocities (U_g) from 0.09 to 3.7 m s^{-1} in each channel.

2.2. Mathematical treatment

In this section, the author would like to present the method to obtain the dominant frequency from the pressure drop signal. Signals are converted from time domain to frequency domain through the Fourier transform. It converts the signal information to the magnitude and phase component of each frequency. Customarily the Fourier transform is further processed to obtain the power spectrum, which is the magnitude of each frequency component squared. The spectrum can be then studied to obtain information about which frequencies are present in the input signal and/or which are significant component in terms of the magnitude of power.

FFT is an efficient algorithm to compute the discrete Fourier transform (DFT). Let $x_0, \ldots x_{N-1}$ be complex numbers, the DFT is defined by [28]:

$$X_k = \sum_{n=0}^{N-1} x_n e^{(-j2\pi/N)nk} \quad k = 0,\ \ldots,\ k-1$$

Obviously, this algorithm is complicated to work out as it involves many additions and multiplications of complex numbers. FFT is another method for calculating the DFT. While it produces the same result, it is incredibly more efficient, often reducing the

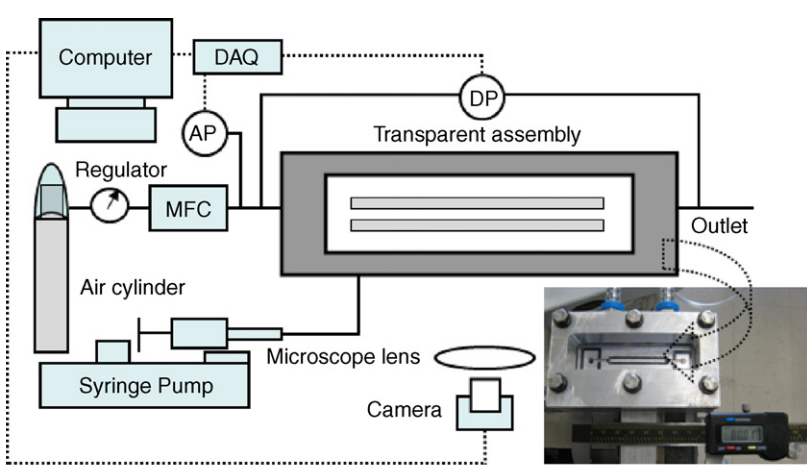

Fig. 1. Schematic of the experimental setup.