

Employing Hot Wire Anemometry to Directly Measure the Water Balance of a Commercial Proton Exchange Membrane Fuel Cell Stack

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ABSTRACT

Proton exchange membrane fuel cells (PEMFC's) are currently being commercialized for various applications ranging from automotive (e.g. the Toyota Mirai) to stationary such as powering telecom backup units. In PEMFC's, oxygen from air is internally combined with hydrogen to form water and produce electricity and waste heat. One critical technical problem of these fuel cells is still the water management: the proton exchange membrane in the center of these fuel cells has to be hydrated in order to stay proton-conductive while on the other hand excessive liquid water can lead to cell flooding and increased degradation rates. Clearly, a fundamental understanding of all aspects of water management in PEMFC is imperative. This includes the fuel cell water balance, i.e. which fraction of the product water leaves the fuel cell via the anode channels versus the cathode channel. Our research group is currently developing a novel technique to obtain an ad-hoc and real time electrical signal of the fuel cell water balance by employing hot wire anemometry. In this work, the hot wire sensor is placed in the anode outlet of a commercial air-cooled fuel cell stack by Ballard Power Systems, and the voltage signal received gives valuable insight into heat and mass transfer phenomena in a PEMFC.

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INTRODUCTION

An air-cooled proton exchange membrane fuel cell (PEMFC) stack was originally designed by Ballard Power Systems for supporting telecom backup power capability in the event of electrical grid failure and material handling equipment. It is usually operated on dry hydrogen and air. Dry hydrogen is fed to the anode electrode where it is split up into protons and electrons while air is provided to the cathode electrode through the open air channels where the oxygen is recombined with the protons and electrons to form water. The amount of air supplied is much larger compared to the oxygen that is consumed because the air is also used as coolant to remove the waste heat. Typical stoichiometric flow ratios at the cathode are 40-60, while at the anode it is imperative to not waste hydrogen and therefore operate at a low stoichiometric flow ratio.

Water management inside the stack is a crucial issue to attain a higher stack performance, durability, reliability, and lower cost [1]. The fuel cell water balance can be measured using a dew point technique by measuring the dew points of both hydrogen and air at the entrance and the exit of the PEMFC which allows for the calculation of the water balance [2]. However, this technique is complicated, costly, and might not be accurate enough since the dew point has to be measured at four different locations in the PEMFC. Also, humidity sensors can be used in the same way for water balance measurements. However, the cost and size of existing sensors for monitoring humidity are prohibitive for online measurements [3]. The most commonly used technique to measure the fuel cell water balance is the water trap

technique which entails condensing and weighing the amount of water in the exhaust of the PEMFC for an extended period of time [4,5,6]. This technique is time consuming and can not be used for ad-hoc such as automotive applications. Our group recently suggested applying hot wire anemometry to measure the anode outlet velocity which can be converted into the water balance almost in real-time [7]. This method can be easily integrated in the ad-hoc fuel cell system with lower cost. As demonstrated in our previous work, a hot wire anemometer can be used at PEMFC anode outlet to measure an accurate and real-time water balance [8, 9]. Also, the demonstrated method can be used to measure the water balance even at low current densities.

In this work the real-time water balance of an air cooled stack is measured at different current densities, different anode stoichiometric ratios, and different stack temperatures using constant temperature anemometry (CTA) hot wire. The CTA hot wire can measure a direct voltage signal E_w if it is replaced at the stack anode outlet. The voltage signal is proportional to the heat loss from the wire to the humidified residual hydrogen stream exiting the stack. This voltage is then compared to the pre-determined voltage of a dry hydrogen stream where the molar flow of hydrogen corresponds to the fuel cell current and stoichiometry, here called E_{w0} . The measured E_w/E_{w0} at the stack outlet can be used to determine the stack water balance in real time using a pre-determined calibration curve E_w/E_{w0} versus the so-called effective drag coefficient that represents the fuel cell water balance (r_d) [8, 9].

DETERMINING PEMFC WATER BALANCE USING CTA VOLTAGE

The incoming hydrogen in the air-cooled fuel cell stack is always dry. In this case, the effective drag coefficient r_d can be determined from the measurement of the molar water stream leaving the anode via:

$$r_d = -\frac{\dot{n}_{H_2O,out}}{I/F} \quad (1)$$

Where I is the total cell current in [A], F is Faraday's constant (96485 C/mole), and $\dot{n}_{H_2O,out}$ is the molar water stream leaving the anode. Consequently, r_d is a dimensionless property that can only be negative for a dry hydrogen inlet stream. According to this definition, a value of $r_d = -0.5$ means that all the product water ends up at the anode.

The output signal of the hot wire is the voltage E_w , and because the wire dimensions and its resistance R_w are constant, the relationship between the wire voltage E_w and the heat transfer coefficient h can be simplified to [8]:

$$E_w/E_{w0} = \sqrt{h/h_0} \quad (2)$$

E_{w0} is the voltage response of a dry hydrogen stream at the anode outlet temperature as function of the molar flow rate of hydrogen. In that way, E_{w0} depends only on the stack current density and the anode side stoichiometric flow ratio, both of which are usually known. E_w on the other hand is the hot wire voltage at the stack anode outlet where humidified hydrogen leaves the cell. Water vapour has a much lower thermal conductivity compared to hydrogen, and therefore the heat transfer rate from the hot wire sensor is reduced and E_w is always smaller compared to E_{w0} . If the right side of Equation 2 is determined in advance, the PEMFC stack water balance can be directly determined by placing the hot wire in the anode outlet pipe.

EXPERIMENTAL DETAILS

Experimental Set-Up

The experimental set-up is shown in Figure 1.

A Ballard air-cooled fuel cell stack 1020ACS (Ballard Power systems, Canada) which has a total of 28 cells, connected in series with a cell surface area of 200 cm² was used for this test. The anode side of the stack was connected to an automated fuel cell testing station (FCATS G60, Greenlight Innovation, Canada) to supply the dry hydrogen. The hot wire from Dantec Dynamics A/S (Dantec Dynamic, Denmark) was inserted in the stack anode outlet. Air was supplied to the cathode open channels at room temperature by a fan (Sunon 120X120X38 mm, 48 VDC, Taiwan) that was placed behind the stack and sucked the air through. The nominal stack temperature is measured by inserting a T-type thermocouple in an air channel in the centre of the stack as recommended by the manufacturer and shown in Figure 1. The stack temperature is then controlled by the fan speed.

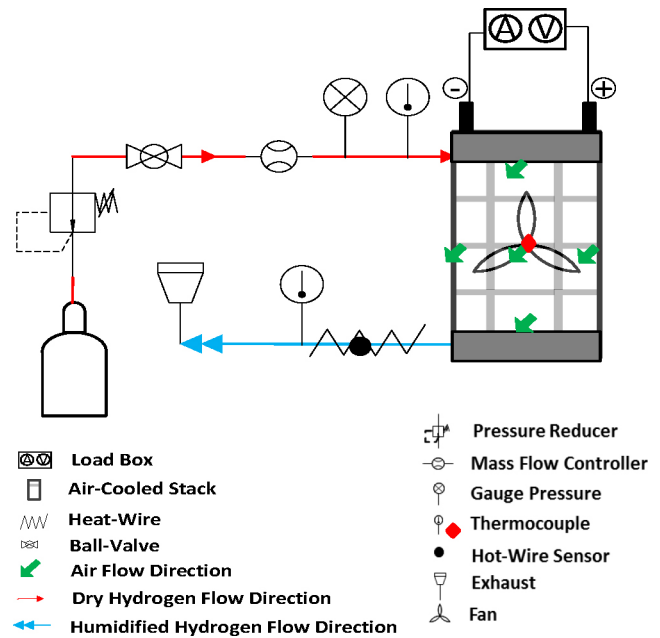


Figure 1. Schematic of Ballard air-cooled stack testing system set-up.

The hot wire was placed at the anode outlet in a 4 mm pipe. To keep the temperature of the hydrogen gas around the hot wire constant, the heat wire with a T-type thermocouple was installed to control the hydrogen gas temperature using Temparton PID 330 temperature controller with auto tune (Temparton, Essex, UK).

Test Procedures

Dry hydrogen is supplied to the anode side and the air is supplied to the cathode channels of the stack. After that, the load was applied on the stack at a specific current density. The fan speed is modified to keep the stack temperature constant. The water-balance measurements were recorded using the hot wire method for one hour after the stack had reached steady state. All the data were measured and recorded using DAQ system for hot wire and a FCATS G60 fuel cell test station. All the data were saved and processed using Lab View software for the FCATS G60 and Basic Stream Ware for the hot wire data.

The calibration curve was measured in an ex-situ experiment following the same experimental procedures explained in previous work [9]. The hot wire and the pipe diameter were the same in the calibration curve measurements and the anode stack outlet measurements.

After connecting the stack and installing the hot wire, the hydrogen leak was tested using leak hydrogen sensor. After making sure that everything was working properly all the experiments were controlled remotely, i.e. they were fully automated.

Experimental Conditions

The air-cooled stack was run according to the experimental conditions described in Table 1. The temperature of hydrogen around the hot wire was set to 85 °C which corresponds to the hydrogen temperature in the calibration curve measurements.