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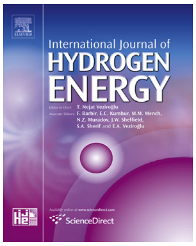

Short Communication

Applying hot-wire anemometry to directly measure the water balance in a proton exchange membrane fuel cell for a pre-humidified hydrogen stream

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ABSTRACT

In a recent publication it has been shown how the water balance in a proton exchange membrane fuel cell can be determined employing hot wire anemometry. The hot wire sensor has to be placed into the anode outlet pipe of the operating fuel cell, and the voltage signal E that is read from the sensor has to be divided by a pre-determined voltage signal E_0 that has been obtained for a stream of dry hydrogen where the molar flow rate corresponds to a total current I of the fuel cell stack and a stoichiometric flow ratio, ξ. Because the last two properties are usually continuously known in fuel cell experiments, E_0 is also continuously known. There is a one-to-one correlation between the relative voltage signal E/E_0 and the fuel cell water balance, and therefore the fuel cell water balance can be a continuous output signal similar to the fuel cell voltage and the high frequency resistance. This method was originally believed to be limited to the fuel cell anode operating on dry hydrogen. In the current work, it is expanded for the case of a pre-humidified hydrogen stream. In addition, useful correlations are derived that link the fuel cell water balance with the anode side inlet and outlet thermodynamic state. Finally, it will be shown how previously developed dew point diagrams for the anode side in a fuel cell can be corrected for a humidified hydrogen inlet stream.

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Introduction

While low temperature proton exchange membrane fuel cells (LT – PEMFC's) are currently entering the commercialization phase, there are still technical hurdles to overcome in order to make this technology more affordable and reliable. Many of the current problems in PEMFC technology are related to water management, and it is highly desirable to develop new methods e.g. in order to better diagnose anode dry-out. Our group has recently suggested employing hot wire anemometry in the anode outlet pipe of a PEMFC that operates on dry

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hydrogen [1,2]. We have shown how the measured wire signal voltage E can be directly converted into the fuel cell water balance by dividing E through the pre-measured voltage signal E_0 for a stream of dry hydrogen where the molar flow rate corresponds to the outlet hydrogen stream of a fuel cell stack that operates at a total current I and an anode stoichiometric flow ratio, ξ. There is a clear one-to-one relationship between the relative voltage E/E_0 which is a continuous signal that is obtained in real-time and the relative humidity of the binary anode outlet stream that contains just hydrogen and water vapour. The relative humidity can then be directly converted into the fuel cell water balance, usually the effective drag coefficient, defined as [3]:

$$r_d = \frac{\dot{n}_{H_2O,in} - \dot{n}_{H_2O,out}}{I/F} \tag{1}$$

Here, the difference in the molar flow rate at the anode inlet and anode outlet (in mole/sec) is non-dimensionalized by the total current drawn from the cell I and Faraday's constant F (96,485 C/mole).

Fig. 1 shows exemplarily the relationship between the relative voltage signal E/E_0 and the fuel cell water balance for an anode stoichiometric flow ratio of $\xi_a = 1.03$ and an anode outlet temperature of 85 °C. The anode inlet stream was dry so that the values for the water balance according to Equation (1) can only be negative.

The derivation of this method was so far limited to the anode operating on dry hydrogen. In the following it will be shown how this method can also be extended to a pre-humidified hydrogen stream. In this case the effective drag coefficient r_d can also become positive up to a certain, limiting value when all the incoming water at the anode side crosses over to the cathode side. This is the maximum possible water balance value. A second limiting case is that the anode outlet stream becomes supersaturated so that liquid water is entrained in the anode outlet stream. In this case the current hot wire sensor can not be expected to provide an exact reading because it is known to only work under non-condensing conditions. The resulting regime between these two limiting values for the water balance is the operating regime for the hot wire sensor, and in the following it will be shown how this regime can be calculated and how it depends on the anode inlet and outlet thermodynamic conditions such as temperature, pressure as well as the stoichiometric flow ratio.

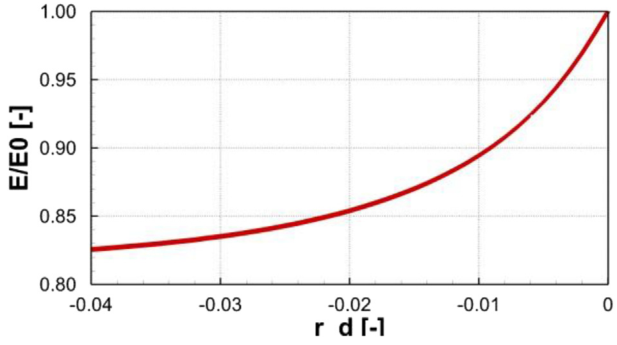

Fig. 1 – Exemplary relationship between the relative voltage signal of the hot wire sensor E/E_0 and the fuel cell water balance r_d.

Determination of the operating regime for the hot wire sensor

Determination of molar inlet and outlet streams at the anode

When the incoming hydrogen at the anode side is pre-humidified, the molar flow rate of water into the anode can be calculated out of the relative humidity according to:

$$RH_{in} = \frac{p_{H_2O,in}}{p_{sat}(T)} = x_{H_2O,in}\frac{p_{g,in}}{p_{sat}(T_{in})} = \frac{\dot{n}_{H_2O,in}}{\dot{n}_{H_2O,in} + \dot{n}_{H_2,in}}\frac{p_{g,in}}{p_{sat}(T_{in})} \tag{2}$$

Here, RH_{in} denotes the inlet relative humidity, x_{H2O} the molar fraction of water vapour, p_g is the gas phase pressure, p_{sat} is the saturation pressure which only depends on the temperature, and $\dot{n}$ denote the molar fluxes (in mol/s). The dependency of the saturation pressure on the temperature can be most conveniently expressed by Antoine's equation:

$$\log_{10} p_{sat} = A - \frac{B}{C + T} \tag{3}$$

Where the constants for water are $A = 8.07131$, $B = 1730.63$, and $C = 233.426$ while T is the temperature in [°C]. The resulting pressure p_{sat} in Antoine's equation is given in [*mmHg*] and has to be multiplied with 133.322 [Pa/mmHg] to be converted into [Pa].

Rearranging Equation (2) and solving for the inlet stream of water vapour as function of the RH value yields:

$$\dot{n}_{H_2O,in} = \dot{n}_{H_2,in} \times RH_{in} \times \left(\frac{p_{g,in}}{p_{sat}(T_{in})} - RH_{in}\right)^{-1} \tag{4}$$

The same equation was derived by Janssen and Overvelde [3]. The ratio between the molar streams of water vapour and hydrogen entering the anode is thus:

$$\frac{\dot{n}_{H_2O,in}}{\dot{n}_{H_2,in}} = RH_{in} \times \left(\frac{p_{g,in}}{p_{sat}(T_{in})} - RH_{in}\right)^{-1} \tag{5}$$

The molar flow rate of hydrogen at the anode inlet is simply:

$$\dot{n}_{H_2,in} = \xi\frac{I}{2F} \tag{6}$$

where ξ is the anode side stoichiometry, I is the total stack current and F is again Faraday's constant. Note that the total stack current is calculated out of the electrical current of a single cell in the stack multiplied with the number of cells in a stack. Therefore, an automotive fuel cell stack with 200 single cells and an active area of around 300 cm^2 the total current for the calculation of the gas flow rates can be as high as:

$$1.5\frac{A}{cm^2} \times 300\frac{cm^2}{cell} \times 200\frac{cell}{stack} = 90.000A \tag{7}$$

Assuming a maximum power density of 1.0 W/cm^2 such a stack would produce 60 kW.

An important observation from Equation (5) is that when the inlet pressure of the anode gas phase $p_{g,in}$ is increased for a constant RH_{in} the molar fraction of water vapour and thereby the molar flow rate of water at the anode inlet actually decrease. Hence, increasing the anode pressure may actually

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