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# Applying hot wire anemometry to directly measure the water balance in a proton exchange membrane fuel cell – Part 1: Theory

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## ABSTRACT

In order to accurately determine the water balance of a proton exchange membrane fuel cell it has recently been suggested to employ constant temperature anemometry (CTA), a frequently used method to measure the velocity of a fluid stream. CTA relies on convective heat transfer around a heated wire at around 200 °C. The heat loss to the fluid stream is balanced by electrical power dissipation, and the required voltage  $E$  is the output signal which is highly sensitive to the heat transfer coefficient of the wire and therefore provides accurate readings. This work explains the theory and summarizes the equations required to calculate the heat transfer coefficient and the resulting voltage signal as function of the fuel cell water balance. The most critical and least understood part is the determination of the Nusselt number to calculate the heat transfer between the wire and the gas stream. Different expressions taken from the literature will be examined in detail, and it will be demonstrated that the power-law approach suggested by Hilpert is the only useful one for the current purposes because in this case the voltage response from the hot-wire sensor  $E/E_0$  shows the same dependency to the water balance for all current densities. Therefore, only one curve-fit equation will be required. The voltage curve  $E_0$  is an arbitrary calibration curve, and this can be conveniently chosen to be the voltage signal for a dry hydrogen stream at a given temperature and various flow rates which can be easily measured.

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## Introduction

In order to fully understand transport phenomena in a proton exchange membrane fuel cell it is desirable to measure the fuel cell water balance with high accuracy and ideally in real-time during fuel cell operation. Various research groups

have previously determined the fuel cell water balance, most of them applying a water trap by running the exhaust gases through a condenser and weighing the amount of water collected after a certain period of time [1–5]. This technique is time consuming and it has to be assumed that the cell behaviour does not change over several hours or even days. It also suffers from minor inaccuracies although the respective

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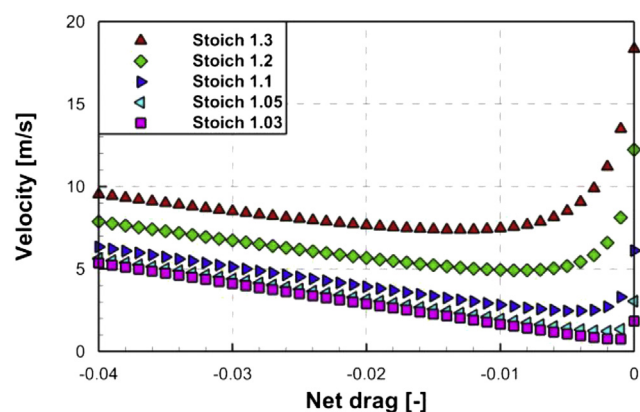
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authors did make an effort to close the water balance in each experiment.

In general, determining the water balance was found to yield important insight. Büchi and Srinivasan found that when operating the fuel cell on dry gases the anode side exhaust gas was close to being 100% humidified [1]. Janssen and Overvelde found that the membrane thickness was the single most important parameter in the fuel cell water balance, and that cathode drying had a much more detrimental effect on the fuel cell performance than anode drying [2]. Karan et al. found that the micro-porous layer has almost no effect on the fuel cell water balance [4], and, finally, Husar et al. found that in contrast to most modelling predictions the fuel cell water balance does frequently favour the anode side, i.e. back transport has been measured [5]. A detailed review on all water management aspects was published by Dai et al. [6].

In order to refine the experimental methods and get accurate and real-time results, a new method to measure the fuel cell water balance by determining the dew point of the anode and cathode outlet gases has been suggested by He et al. [7]. This method as well as the weighing method can be applied even when the incoming gas streams are pre-humidified. The shortcomings of these methods are that they can not be applied *ad hoc*, e.g. in a fuel cell vehicle, and that the latter one is quite complex. A simpler method that can be applied *ad hoc* and that yields a continuous voltage signal which can be converted into the water balance is to employ hot wire anemometry at the anode outlet to measure the anode outlet velocity [8]. If the anode outlet velocity can be determined the water balance can be calculated. The great advantage of this method is that it yields a voltage signal of high frequency and that the water balance can be determined almost in real time, even as a diagnosis tool for fuel cell stacks during operation in vehicles. The main drawback is that it can currently only be used for fuel cells that operate on pure, dry hydrogen, and it appeared to be restricted to relatively low stoichiometric flow ratios (at or below  $\xi_{an} = 1.2$ ) [8]. Both these restrictions are not too severe as it has been suggested that there is no need for external humidification on neither cathode nor anode side when a water uptake layer is included in



**Fig. 1** – Anode outlet velocity as function of the stoichiometric flow ratio (“Stoich”) and water balance (“Net drag”).

the fuel cell catalyst layer [9]. Moreover, operating at low stoichiometric flow ratios is highly desirable as it reduces the cathode side compressor power which is the largest parasitic loss in any fuel cell system [10], and it can eliminate the need for anode side recirculation [11] which is known to be a large cost factor in fuel cell vehicles.

Fig. 1 summarizes calculated anode outlet velocities at different stoichiometric flow ratios for a fuel cell stack current of 8000 A and an inner pipe diameter of the anode outlet of 5 mm [8]. This diagram suggests that if the anode outlet velocity could be accurately measured the fuel cell water balance will be known and consequently it was suggested to employ hot wire anemometry (also called constant temperature anemometry – CTA). This high total current of 8000 A results out of the fact that the gas flow rates have to be calculated out of the total current drawn from a single cell multiplied with all the cells in the fuel cell stack. While the total electrical current drawn from an automotive fuel cell stack with an active cell area of 300 cm<sup>2</sup> might be as high as 450 A, the reactants have to be provided for several hundred single cell, and this has to be accounted for when calculating the overall molar flow rates at the anode inlet and outlet.

The principle of CTA is based on heat transfer where a heated metal wire at around 200 °C is placed into a cooler gas stream. In order to keep the temperature of the wire constant, the heat loss of the wire is equilibrated by the heat that is dissipated in the wire, and the voltage that provides the current can be accurately determined. In this work the underlying equations to calculate and understand the voltage signal of a hot wire anemometer will be given in order to directly measure the fuel cell water balance. It will be seen that a good understanding of the calculation of the convective heat transfer coefficient via the Nusselt number is critical. While various approaches to calculate the heat transfer around a cylinder can be found in the literature, it will be shown that only the power-law equation as suggested by Hilpert should be used in the current case, and this leaves only one adjustable parameter to match the theory with experiments. This parameter is the exponent of the Reynolds number in the calculation of the Nusselt number, “m”, and it depends on the wire diameter and the inner diameter of the anode outlet pipe. Finally, it will be shown that in contrast to the previous statements and to Fig. 1 the stoichiometric flow ratio poses no limitation on this method to work accurately.

## CTA correlations

### Basic principle

A schematic of hot wire anemometry is shown in Fig. 2.

Because the hot wire is at a temperature of 200 °C and the gas stream is at 80–90 °C there is heat transfer between the wire and the gas stream which can be described via Newton's law of cooling:

$$\dot{Q} = A_w h (T_w - T_g) \quad (1)$$

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