

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

Al Shakhshir S. *, Hussain N. **, Berning T. *

*Department of Energy Technology,
Aalborg University,
9220 Aalborg, Denmark,

E-mail: sas@et.aau.dk

**HySA/Catalysis, Department of Chemical Engineering
University of Cape Town
7701 Rondebosch, South Africa

ABSTRACT

Water management in proton exchange membrane fuel cells (PEMFC's) remains a critical problem for their durability, cost, and performance. Because the anode side of this fuel cell has the tendency to become dehydrated, measuring the water balance can be an important diagnosis tool during fuel cell operation. The water balance indicates how much of the product water leaves at the anode side versus the cathode side. Previous methods of determining the fuel cell water balance often relied on condensing the water in the exhaust gas streams and weighing the accumulated mass which is a time consuming process that has limited accuracy. Currently, our group is developing a novel method to accurately determine the water balance in a PEMFC in real time by employing hot-wire anemometry. The amount of heat transferred from the wire to the anode exhaust stream can be translated into a voltage signal which can be directly converted into the fuel cell water balance. In this work, experimental *ex-situ* results are presented and the elegance and usefulness of this method is demonstrated.

INTRODUCTION

The popularity of low emission vehicles has increased remarkably in the recent decade with proton-exchange membrane fuel cell (PEMFC) technology being one of the most promising candidates. A PEMFC is usually operated on hydrogen and air. Hydrogen is fed to the anode electrode where it is split up into protons and electrons while air is provided to the cathode electrode where the oxygen is recombined with the protons and electrons to form water. The only by-product is waste heat. Water management in a PEMFC is a crucial issue which affects PEMFC durability, cost, and performance [1]. Sufficient hydration of the membrane is essential to keep its proton conductivity high and thereby minimize ohmic losses. On the other hand, removal of water generated at the cathode is crucial to avoid flooding of pores in the catalyst layer as well as the pores of the commonly used gas diffusion layers (GDL) and consequently the flow-field plates. This hinders oxygen transport to the active reaction sites resulting in an increased mass transport limitation; therefore it reduces the maximum current that can be drawn from the cell. Furthermore, localized drying of the membrane can occur leading to excessive ohmic heating and, ultimately, to pinhole formation in the membrane [2,3]. A better understanding of the fuel cell water management might be achieved by an accurate and real time detection of the water balance.

NOMENCLATURE

Q'	[W]	Convective heat transfer rate
A_w	[m ²]	Surface area of the hot-wire
h	[W/m ² K]	Convective heat transfer coefficient
k	[W/mK]	Thermal conductivity
T_w	[K]	Hot-wire temperature
T_f	[K]	Fluid temperature
$Q'^{electrical}$	[W]	Electrical energy rate dissipated in the hot-wire
I	[A]	Current passing through hot-wire
R_w	[Ohm]	Hot-wire resistance
D_w	[m]	Hot-wire diameter
L	[m]	Hot-wire length
Nu	[-]	Nusselt number
Re	[-]	Reynolds number
Pr	[-]	Prandtl number
E_b	[V]	Bridge voltage
E_w	[V]	Voltage across the hot-wire
C	[-]	Reynolds number pre-exponent constant
m	[-]	Reynolds number exponent constant
n	[-]	Prandtl number exponent constant = 1/3
RH	[%]	Relative Humidity
\dot{n}	[mol/s]	Molar flow rate
Special characters		
α	[-]	Hot-wire over heat ratio
π	[-]	Is the mathematical constant π
Subscripts		
0		Dry hydrogen measurements
H_2		Hydrogen gas

Previous studies have quantified the water balance in a PEMFC 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 [4]. The dew point 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. Another 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 a certain period of time [5-8]. This technique is time consuming, and it has to be assumed that the cell behaviour does not change over several hours or even days, and this makes it inappropriate for automotive applications. Moreover, this method is often restricted to high current densities to produce a sufficient amount of water. It also requires an extra energy for condensing the water.

In general, measuring the water balance can provide very useful information with respect to fuel cell operation. Abe *et al.* found that the water transport through the membrane is sensitively affected by the temperatures of the cathode side humidifier [4]. Ciureanu and Badita provided a criterion to optimize the fuel cell water balance in order to prevent cathode

flooding and at the same time anode dehydration when running on dry hydrogen. They also found the effective drag coefficient is relatively small compared to the electro-osmotic drag coefficient [5]. Büchi and Srinivasan found that the product water inside a PEMFC is sufficient to cover the humidity requirements of both reactant gases internally without using external humidification for low current densities [6]. Janssen and Overvelde found that the cell performance was sensitive to the humidity of the inlet gases and the cathode dry-out phenomena had a more pronounced effect on cell performance than anode dry-out. Furthermore, the severity of the drying-out depended strongly on the cathode electrode material [7]. Karan *et al.* found that the micro-porous layer has almost no effect on the fuel cell water balance [8]. Husar *et al.* found in their experiments that in contrast to most modeling predictions the fuel cell water balance frequently favours the anode side [9].

During the previous years, Berning *et al.* have developed a multi-phase model of a PEMFC based on computational fluid dynamics and found in a modelling study that a fuel cell might be operated even at high current densities without external humidification when a water uptake layer inside the fuel cell electrode-membrane assembly was applied [10]. The underlying reasoning was that the fuel cell water balance is determined out of two competing mechanisms inside the catalyst layer: the electro-osmotic drag and the non-equilibrium sorption/desorption of water to/from the membrane. The difference between these two mechanisms is the amount of water that crosses the membrane via diffusion [10]. This implies that it might in fact be anode dry-out that limits the maximum current density that can be drawn from a fuel cell, and therefore an accurate determination of the fuel cell water balance is highly desirable. In order to accurately determine the fuel cell water balance *ad hoc* and in real time, Berning recently suggested applying hot wire anemometry to measure the anode outlet velocity. This method yields a continuous voltage signal of high frequency which can be converted into the water balance almost in real time [11]. The great advantage of this method is that it can be easily integrated in the *ad hoc* fuel cell system, and it is a low cost option as an additional tool for PEMFC testing stations.

In this work it will be shown how hot wire anemometry can be used to receive a direct voltage signal that can be converted into the fuel cell water balance if the hot wire is placed in the anode outlet of the fuel cell. The voltage signal for dry and humidified hydrogen stream with varying flow rates has been measured and will be analysed. It will be shown that the Nusselt number that describes the convective heat transfer from the hot wire has to be described as function of the Reynolds number of the flow and the Prandtl number of the fluid by the power-law approach. The importance in this finding is that this allows for a continuous determination of the fuel cell water balance over all current densities.

HOT-WIRE HEAT TRANSFER FUNDAMENTALS

The underlying principle of hot wire anemometry is to place a heated metal wire at around 200°C into a cooler gas stream. Convective heat transfer from the wire to the gas occurs, and this heat loss is compensated continuously by heat

that is dissipated in the wire via electric current. The wire resistance is a strong function of its temperature, and the resistance can be held constant by a Wheatstone bridge which helps to adjust the voltage and electric current across the wire. Thereby, the hot wire anemometer yields a high frequency voltage signal that is related to the amount of heat transfer. When the hot wire anemometer is operated in constant temperature mode (as opposed to constant current mode) it is also referred to as constant temperature anemometry (CTA). Figure 1 shows schematically the principle of hot wire anemometry. The amount of convective heat transfer to the gas phase is strongly sensitive to the gas phase velocity, and this is why CTA is frequently used to measure the multi-component velocity of a gas stream.

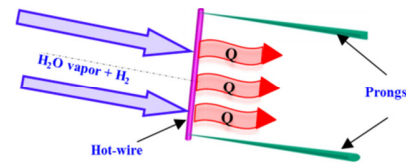


Figure 1 Schematic of hot-wire sensor connected to the prongs in the flow field. Q is the convective heat transferred from the wire to the fluid.

Because the hot wire is usually at 200 °C and the anode outlet temperature is typically between 75 °C and 85 °C, convective cooling of the wire occurs that can be described by Newton's law of cooling [12]:

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

This assumes that radiation is negligible which is usually the case [13]. In above equation, \dot{Q} is the convective heat transfer rate, A_w is the area of the wire [m^2], h is the convection coefficient in [W/m^2K] and $(T_w - T_f)$ is the temperature difference between the heated wire and the fluid stream. A CTA involves one part of a Wheatstone bridge to keep the wire resistance constant. This requires keeping the hot-wire temperature constant by continuous electrical power dissipation $\dot{Q}_{electrical}$ through the wire, given by:

$$\dot{Q}_{electrical} = I^2 R_w \quad (2)$$

where I is the electric current and R_w is the wire resistance at temperature T_w . For steady-state operation, the rate of electric power dissipation equals the rate of convective heat transfer which yields [12]:

$$I^2 R_w = \pi D_w L h (T_w - T_f) \quad (3)$$

where D_w is the diameter and L is its length of the wire. The convective heat transfer coefficient h can be expressed by dimensionless Nusselt Nu number:

$$Nu = h D_w / k \quad (4)$$

where k is the thermal conductivity of the surrounding fluid in [W/mK].

Combining equations (3) and (4) results in:

$$I^2 R_w = \pi L k (T_w - T_f) Nu \quad (5)$$

Introducing Ohm's law to express the electrical voltage E_w across the wire, equation (5) can be re-written as:

$$E_w^2 / R_w = \pi D_w L h (T_w - T_f) = \pi L k (T_w - T_f) Nu \quad (6)$$

A central question in hot wire anemometry is how to express the Nusselt number. In this work, it is calculated employing the power-law expression suggested by Hilpert [14]:

$$Nu = C Re^m Pr^n \quad (7)$$

where Re is the Reynolds number and Pr is the Prandtl number. The Reynolds number depends on the gas stream velocity u , its density ρ and its dynamic viscosity μ as well as the hot-wire diameter D_w , according to:

$$Re = u \rho D_w / \mu \quad (8)$$

The Prandtl number depends on the gas specific heat capacity c_p , its dynamic viscosity μ , and its thermal conductivity k :

$$Pr = \mu c_p / k \quad (9)$$

Where the fluid properties have to be evaluated at the film temperature, defined by:

$$T_{film} = 0.5 \times (T_w + T_f) \quad (10)$$

In equation (7) the exponent to the Pr number n is a constant which is usually taken to be $(1/3)$. The constants C and m usually depend on the Reynolds number, and they will be experimentally determined in this work. An accurate determination of the gas properties is very important, and the calculation details for the binary mixture of hydrogen and water vapor are described separately [15].

The output signal of 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 [15]:

$$E_w / E_{w0} = \sqrt{h / h_0} \quad (11)$$

where E_{w0} represents an arbitrary calibration point. As is pointed out elsewhere, a very convenient choice for E_{w0} is the voltage response of a dry hydrogen stream at the anode outlet temperature as function of the molar hydrogen flow rate [15]. In that way, E_{w0} depends on the fuel cell current and the anode side stoichiometric flow ratio, both of which are usually known. E_w on the other hand will be the hot wire voltage at the PEMFC anode outlet. If the right side of equation (11) is determined in advance, the hot wire can be placed directly in the anode outlet pipe, and the fuel cell water balance can be directly determined. The following sections will describe how the wire voltage E_{w0} for dry hydrogen was measured first, and then the wire voltage for a humidified hydrogen stream at varying flow rates and different relative humidities (RH) ratios (0-100) % RH was recorded.

EXPERIMENTAL

Experimental techniques and apparatus

The measuring system used in this work was purchased from Dantec Dynamics A/S (Dantec Dynamic, Skovlunde, Denmark), and it consists of a hot-wire sensor with its probe support connected to the 54T42 anemometer unit with a screened cable using Bayonet Neill-Concelman (BNC) connectors as illustrated in Figure 2.

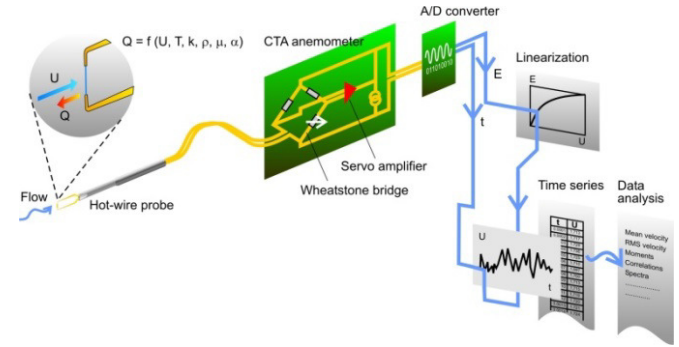


Figure 2 Schematic of hot-wire anemometry (courtesy of Dantec A/S).

The analog output signal is directly proportional to the fluid velocity and provides continuous voltage time series which is digitized in the analog-digital convertor (ADC). Then the signal is transmitted to the computer RAM which can be processed by Stream Ware Basic v5.10 software.

For the purpose of determining the fuel cell water balance, however, it is not required to determine the anode outlet velocity. Instead, we will make direct use of the sensor voltage E_w as will be described below.

The experiments with dry hydrogen were performed using a hydrogen cylinder connected to a mass flow controller (Bürkert 8712, Bürkert FLUID CONTROL SYSTEMS, Germany), a 1000mm stainless steel pipe including a 250mm testing section length with an inner diameter of 7.5mm. The hot-wire sensor was placed at the end the testing section, and a heating wire connected to a Temparton PID 330 temperature controller with auto tune (Temparton, Essex, UK) was added to control the hydrogen temperature as illustrated in Figure 3.

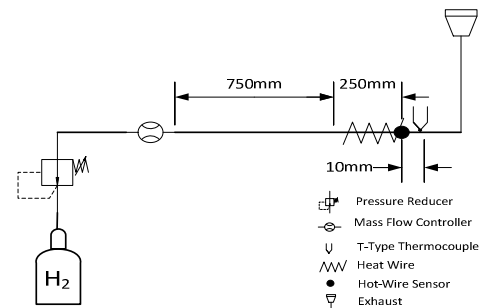


Figure 3 Schematic of the dry hydrogen testing set-up.

A K-type thermocouple with 3mm diameter was used to measure the gas temperature. The hot-wire sensor was positioned between the hydrogen inlet and the thermocouple as shown in Figure 3.

The experiments with humidified hydrogen were performed by connecting the 250 mm testing section to the anode side outlet of an automated FuelCon Evaluator C 50 LT test station (FuelCon, Germany). An extra thermocouple was placed at the inlet of the testing section to control the temperature as required in order to avoid condensation in the testing section.

Test procedures

The hot-wire temperature is set based on the overheat ratio ($\alpha = 0.8$), defined by the manufacturer as [16]:

$$\alpha = (R_w - R_0) / R_0 \quad (12)$$

where R_w is the sensor resistance at operating temperature T_w and R_0 is its resistance at ambient (reference) temperature $T_0 = 20^\circ\text{C}$. The sensor that was used for this analysis was a 70 microns diameter Nickel sensor with quartz coating. The electrical resistance at ambient reference temperature R_0 was given to be 5.17Ω so that the wire resistance at the operating temperature was $R_w = 1.8 \times 5.17 \Omega = 9.3 \Omega$ where the factor of 1.8 is due to the overheat ratio. The dependency of the electrical wire resistance on the temperature was given by the manufacturer as $0.4\%/K$, resulting in a wire temperature of 197°C .

The direct signal that is obtained from the CTA is the bridge voltage which includes the ohmic losses of the hot wire sensor, the probe holder (R_l), and the cables resistance (R_c) [13]. The resistances of the latter two were given as 1.14Ω and 20Ω , respectively. Therefore, the conversion between the wire voltage E_w and the measured bridge voltage E_b is given by:

$$E_w = R_w / (R_w + R_l + R_c) \times E_b = 1/3.272 \times E_b \quad (13)$$

Experimental conditions

The experimental conditions for which E_w and E_{w0} were measured are tabulated in Table 1. While the main temperature of interest was the typical anode outlet temperature of 85°C , it was still deemed important to understand the effect of the hydrogen temperature on the recorded sensor voltage, and therefore experiments were conducted for three different temperatures.

Table 1: Experimental conditions of the dry H_2 measurements

Description	Value
Hydrogen Inlet temperature (T_{H_2}) ($^\circ\text{C}$)	20, 55, 85
Working Pressure (atm)	1
Hydrogen molar flow rate (mol/s)	0 - 0,0035
Relative humidity of the hydrogen stream (%)	0 - 100
Hot-wire over heat ratio (α)	0.8
Hot-wire diameter	70 microns
Hot-wire length	1,25 mm

Uncertainty analysis

In carefully controlled experiments, CTA has a high voltage signal accuracy of (0.1 - 0.2) %. However, in many practical applications 1% accuracy is more likely to be achieved [13]. On the other hand, the voltage signal accuracy depends on the accuracy of the system input parameters such as temperature, flow rate and %RH as mentioned above in the experimental conditions.

The accuracy of a FuelCon Evaluator C 50 LT dew point control is $\pm 1^\circ\text{C}$ in steady state conditions and $\pm 2^\circ\text{C}$ under extreme conditions. This corresponds to $\pm 4\%RH$, and $\pm 8\%RH$, respectively at 85°C and $100\%RH$ according to the testing station saturator equations. All the humidified hydrogen measurements are carried out at 85°C which simulates the anode outlet of PEMFC. In addition, the mass flow controller accuracy is 0.8 % of the actual value. These inaccuracies are directly reflected on the measured experimental data as it will be shown below.

RESULTS AND DISCUSSION

Results for a dry hydrogen stream

The dry hydrogen test shows that the CTA hot-wire can measure a very clear voltage signal E_{b0} even for very small molar flow rate of H_2 as shown in Figure 4. The voltage signal shown here is the bridge voltage which is the direct output of the hot wire device, and the relationship between the bridge voltage and the hot wire sensor voltage was given in equation (13).

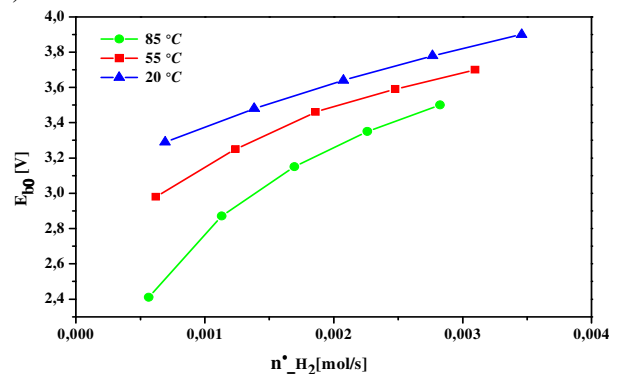


Figure 4 Measured bridge voltage E_{b0} at different dry hydrogen molar flow rates and different temperatures.

Increasing the molar flow rate of dry hydrogen at the same temperature increases the measured E_{b0} . This can be attributed to the increments in the amount of convective heat loss from the wire to the hydrogen gas at higher flow rates. Increasing the flow rate of H_2 increases Re which can be translated into increments in Nu and consequently h increases as described in equations (4) and (7). On the other hand, increasing the temperature at the same flow rate of hydrogen leads to a decreased voltage signal and this agrees with equation (6).

The recorded bridge voltage can now be converted into the wire voltage which can then be translated into the measured Nu number according to equation (6). It is the goal of this work to extract the pre-exponential coefficient C and the Re exponent m from equation (7) out of the experimental data. Therefore, it is

instructive to plot the measured Nu numbers divided by $Pr^{0.333}$ on the y-axis against the Re number of the hydrogen stream (x-axis). The missing parameters C and m from equation (7) can then be easily obtained from a power-fit of the general form $Y = CX^m$ as shown in Figure 5. The resulting curve-fit coefficients are listed in Table 2.

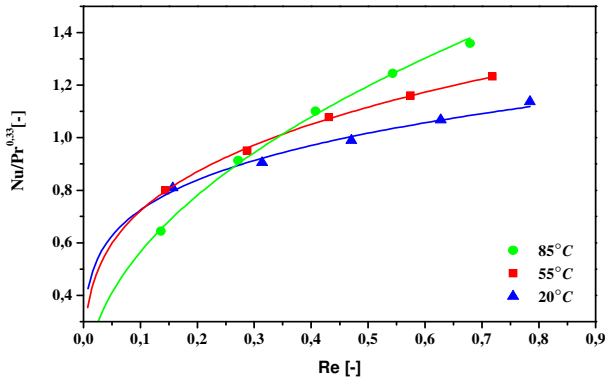


Figure 5 Power-law fits of the form $Y=CX^m$ for the experimental data. The symbols represent the results from the measured voltage and the lines represent the curve-fitting.

Table 2: Curve-fit parameters C and m for equation (7).

T [°C]	C	m	R ²
85	1.7251	0.4661	0.9974
55	1.4067	0.2716	0.9989
20	1.2279	0.2104	0.9853

As noticed from Table 2, both the values for m and C increase with increasing temperature of the dry hydrogen flow. This refers to the increments in the heat transfer coefficient h and consequently the Nusselt number as concluded in many previous studies [17].

The Reynolds number range investigated here depends on the wire diameter and the inner pipe diameter, and it is limited by the flow range that can be adjusted in the test station. The wire diameter of 70 microns in this study is rather large. A second wire of only 5 microns is available as well, and results will be published, soon. The obtained values of C and m from Figure 6 for dry hydrogen are within the range of the obtained results for other researchers for air as tabulated in Table 3. Also, it must be kept in mind that the hydrogen flow rates of interest correspond to the depleted gas stream at the anode outlet.

Table 3: Comparison the C and m values determined in this work with previous studies.

Re	C	m	Reference
[0–1]	1.23-1.72	0.210-0.466	This work
[0.09–1]	0.8	0.28	Morgan [17]
[0.4–4]	0.981	0.33	Hilpert [14]
[1–35]	0.795	0.384	Morgan [17]
[4–40]	0.911	0.385	Hilpert [14]

The importance of using a power-law equation to calculate the Nu number is summarized in reference [15]. Examples for

other, frequently employed equations to calculate the Nu number in CTA are the Churchill-Bernstein equation [18] which is often used for air, or the Kramer equation [19] which was designed for different types of fluids. It is important to understand that with the Nu number the mathematical problem is completely described and the voltage signal can be calculated. Figure 6 shows a comparison of the resulting theoretical bridge voltages when using different approaches for the calculation of the Nu number. For the current set of experiments the agreement with either the Churchill-Bernstein equation or the Kramer equation is surprisingly quite poor, especially for low molar flow rates, and only a power-law fit as used by Hilpert yields a good agreement between theory and experiments. A major difference between the power-law approach and both the Churchill-Bernstein and the Kramer equation lies in the fact that for the former the Nu number (and hence the voltage) approaches zero when the Re number (and hence the molar flow rate) approaches zero. This can be nicely seen in Figure 5. For both the Churchill-Bernstein equation and the Kramer equation the Nu values for a Re number of zero are non-zero which essentially captures the effect of natural convection.

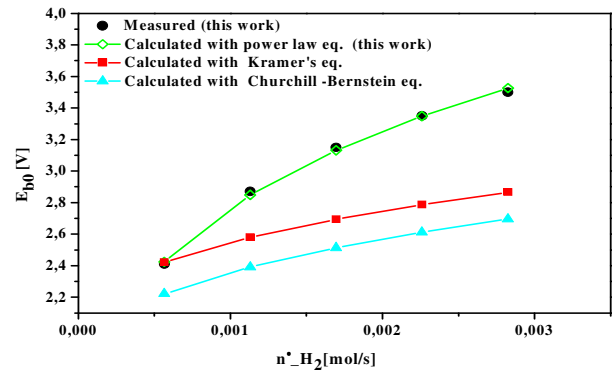


Figure 6 A comparison between the calculated E_{b0} at 85°C using various approaches to calculate the Nu number.

Results for a humidified hydrogen stream

After the $E_{w,0}$ -curve has been determined, the general voltage response E_w for a stream of dry and humidified hydrogen from a fuel cell test station was measured. Figure 7 shows the measured wire voltage E_w for five different flow rates of dry hydrogen with an increasing relative humidity.

Despite the fact that data has been obtained in 10% RH steps, for easier readability only the 20% RH steps are shown. It is noted that the detected voltage and therefore the amount of convective heat transfer decreases with increasing RH, despite the fact that the overall mass flow (and hence the velocity) must increase. This is attributed to the thermal conductivity of the binary mixture of water vapour and hydrogen. The thermal conductivity of hydrogen is one order of magnitude higher than that of water vapour. This makes the water vapour acting as an insulator and consequently reducing the convective heat loss. Thus, increasing the humidity ratio at the same dry hydrogen flow rate reduces the heat loss from the wire resulting in lower measured E_w . In other words, the effect of the material

properties on the heat loss from the wire to the surrounding gas dominates over the effect of increasing the gas velocity.

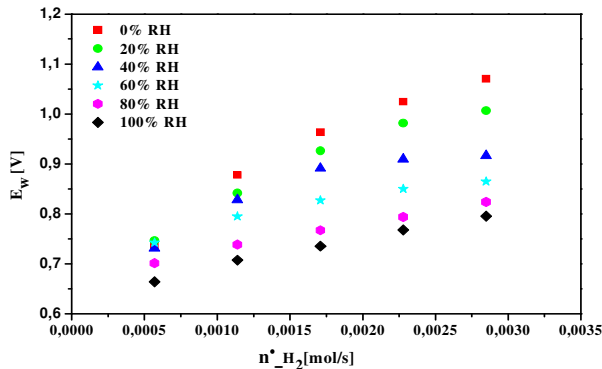


Figure 7 Measured E_w vs. hydrogen flow rates at 85°C and at different %RH.

The general trend of the measured E_w is very clear even for a fully saturated hydrogen stream. This is particularly important because it is known that CTA only works for non-condensing gas streams. While the experimental results shown in Figure 7 appear to be very clear, problems become apparent when calculating the desired E_w/E_{w0} curve by dividing the voltage response E_w for the humidified cases by the voltage response for the dry hydrogen case as received from the test station. It can be fundamentally shown that if the Nu number in these experiments depends on the Re and Pr number in a power-law form, then the voltage response curves E_w/E_{w0} have to coincide for all hydrogen flow rates [15]. While it was shown in the previous section that the power-law applies to the dry hydrogen case, intuition suggests that it also applies for the humidified hydrogen cases because the above mentioned approaches such as the Churchill-Bernstein equation and the Kramer equation are based on curve-fitting experimental data, while for some cases such as laminar flow over a flat plate the power-law equation can be fundamentally derived. For the direct determination for the fuel cell water balance it would be very important that all the E_w/E_{w0} curves fall together, as this would mean that the same curve-fit can be used to convert the wire signal E_w into the fuel cell water balance for all current densities.

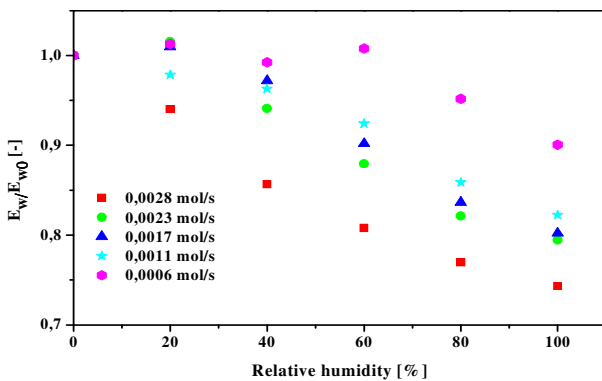


Figure 8. Comparison of the measured E_w/E_{w0} vs. relative humidity at 85°C .

The underlying reason why the curves in Figure 8 show such a large spread was found in the design of the fuel cell test station that was used to provide the gases. Even the supposedly dry hydrogen was led through the top of the bubbler section so that it did pick up some water. Therefore, “dry” hydrogen was not fully dry, and consequently the E_{w0} curve was slightly faulty in these experiments. Clearly, if the E_{w0} signal is wrong than all the resulting E_w/E_{w0} curves are slightly wrong, and this can be seen in Figure 8. On the other hand it is encouraging that the E_w/E_{w0} curve changes by as much as 25 % with increasing RH, demonstrating how sensitive the hot wire voltage is to the fuel cell water balance.

Nevertheless, it was deemed important to find out whether the Nu number can in fact be described via the power-law equation even for the humidified cases, and therefore similar calculations as for the dry hydrogen case were conducted with the data from Figure 7. As before, the measured voltages at 85°C were converted into the Nu number using equation (6) and divided by $Pr^{0.333}$ which now varies with the gas composition. The same holds true for the calculated Re number, and therefore there is some conversion inaccuracies in the data shown in Figure 9. However, clear trends can be observed, and the resulting constants m and C of the Hilpert equation (7) can again be determined for humidified hydrogen. The calculation of the physical properties of humidified hydrogen and the dimensionless numbers such as Nu , Re and Pr is explained in detail elsewhere [15]. For accurate curve-fittings all the measured data are used which were measured in 10 %RH steps.

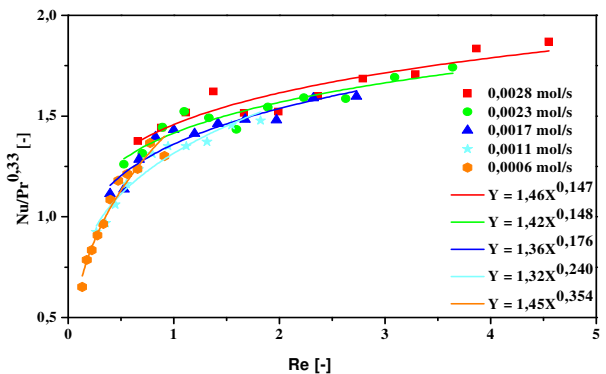


Figure 9. Calculated C and m using power-law curve fitting at different hydrogen molar flow rates and %RH.

It is obvious from Figure 9 that C and m depend on the Reynolds numbers of the humidified hydrogen. m increases with decreasing Re and C increases with increasing Re . The only exception is for the value of C at 0.0006 mol/s dry hydrogen flow rate. This is attributed to higher error at low Re as explained earlier.

In general, the resulting Nu number as function of the Re number and Pr number should not depend on the mixture composition (this is the main motivation to use dimensionless numbers). Moreover, it appears from Figure 9 that in fact all the measured data might be captured by a single curve, and this is shown in Figure 10.

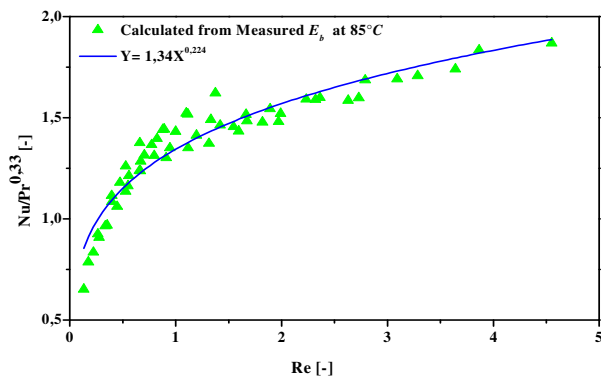


Figure 10. Calculated C and m using power curve fitting for the calculated data points from the measured E_b .

The resulting C is equal to 1.34 and the Re exponent m over the entire range is 0.224. If the power-law equation is used to calculate the Nu number, m will be the only parameter that affects the E_w/E_{w0} signal as function of the fuel cell water balance [15]. It is, however, noted that the dry hydrogen flow rates applied here were high considering the fact that the hot wire will eventually be placed in the anode outlet of the operating fuel cell where only the depleted hydrogen stream is left. More work is needed to better detect the signal at much lower hydrogen flow rates.

CONCLUSION

A voltage signal was measured in the dry and humidified hydrogen stream using a CTA hot-wire. The voltage increases with increasing molar flow rate of dry hydrogen due to the increase in the convection rate. When using humidified hydrogen the voltage signal decreases with increasing RH at a constant hydrogen flow. This is due to the thermal conductivity difference between hydrogen and water vapor, where the value for hydrogen is one order of magnitude larger.

A central question in CTA is the calculation of the Nu number as function of the Re number and the Pr number, and this study has shown that the power-law equation as used by Hilpert was the approach that best fits the experiments. Using the experimental data, the missing coefficient C and m in the power-law equation could be accurately determined, and they were in good agreement with values from the literature. The voltage response E_w/E_{w0} for the humidified hydrogen case showed a strong dependency on the RH which will help to accurately determine the fuel cell water balance *in situ*.

Overall, the usefulness of applying CTA to directly measure the fuel cell water balance has been demonstrated, but more work is needed especially at low hydrogen flow rates and with different sensors.

ACKNOWLEDGEMENTS

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