INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (2016) 14917–14926

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Applying hot-wire anemometry to directly measure the water balance in a proton exchange membrane fuel cell – Part 2: Experimental

Saher Al Shakhshir[*], *Søren Juhl Andreasen*, *Torsten Berning*

Department of Energy Technology, Aalborg University, Pontoppidanstr. 111, 9220 Aalborg, Denmark

ARTICLE INFO

Article history:
Received 30 March 2016
Received in revised form
12 May 2016
Accepted 12 May 2016
Available online 16 June 2016

Keywords:
Proton exchange membrane fuel cells
Water balance
Hot-wire anemometry
Convection heat transfer around a cylinder
Fuel cell diagnosis
Power law

ABSTRACT

In order to better understand and more accurately measure the water balance in a proton exchange membrane fuel cell our group has recently proposed to apply hot wire anemometry in the fuel cell's anode outlet. It was theoretically shown that the electrical signal obtained from the hot wire sensor can be directly converted into the fuel cell water balance. In this work an *ex-situ* experimental investigation is performed to examine the effect of the wire diameter and the outlet pipe diameter on the voltage signal. For a laboratory fuel cell where the mass flow rate the anode outlet is small, it is found important to use a small output pipe diameter to obtain a sufficiently strong convection effect and hence clear voltage readings. Depending on the hot wire diameter and the inner pipe diameter, the resulting values for the exponent of the Reynolds number *Re* in the determination of the Nusselt number *Nu* range between $m = 0.267$ and $m = 0.329$. In general, it is shown that applying hot wire anemometry yields in fact very clear voltage readings with high frequency, and it can be used as a diagnosis tool in various fuel cell applications.

Introduction

Proton exchange membrane fuel cells (PEMFC's) are currently being commercialized for various applications ranging from hydrogen powered electric vehicles to telecom back-up systems in remote areas. These fuel cells internally combine oxygen from air with hydrogen to form water and generate electricity with waste heat as a by-product. While the general technical progress over the past decades have resulted in a substantial price drop of this technology, there are still technical hurdles to overcome to make fuel cells more reliable and affordable. Many of the technical problems are related to the water management in the PEMFC: the fuel cell membrane has to be sufficiently hydrated to secure proton conductivity while on the other hand an excess of water in the cell leads to "flooding" of the fuel cell channels and porous media. It was recently shown that these flooding phenomena can be better understood and potentially avoided when optimizing the fuel cell operating conditions using dew point diagrams [1]. These diagrams allow for the identification of fuel cell operating conditions such that both the anode and cathode outlet streams are exactly saturated with water vapour while the inlet streams can be completely dry, thereby avoiding external

* *Corresponding author*. Tel.: +45 9940 9289.
E-mail address: sas@et.aau.dk (S. Al Shakhshir).
http://dx.doi.org/10.1016/j.ijhydene.2016.05.110

Nomenclature

$\dot{Q}$	Convective heat transfer rate, W
A_w	Surface area of the hot-wire, m^2
h	Convective heat transfer coefficient, W/m^2K
K	Thermal conductivity, W/mK
T_0	Hot wire temperature at ambient conditions, K
T_w	Hot wire operating temperature, K
T_g	Gas temperature, K
$\dot{Q}_{electrical}$	Electrical energy rate dissipated in the hot-wire, W
I	Current passing through hot-wire, A
R_0	Hot wire resistance at ambient temperature, Ohm
R_1	Anemometer bridge internal resistance, Ohm
R_L	Cable and sensor holder resistance., Ohm
R_w	Hot wire resistance at operating temperature, Ohm
D_w	Hot wire diameter, m
L	Hot wire length, m
Nu	Nusselt number, –
Re	Reynolds number, –
Pr	Prandtl number, –
E	Bridge voltage, V
E_w	Voltage across the hot-wire, V
C	Reynolds number pre-exponent constant, –
$e_2 - e_1$	Bridge voltage error, V
m	Reynolds number exponent constant, –
n	Prandtl number exponent constant = 1/3, –
RH	Relative Humidity, %
$\dot{n}$	Molar flow rate, mol/s
V_g	Gas velocity, m/s
c_p	Specific Heat, J/kg-K

Special characters

A	Hot wire over heat ratio, –
α_0	Temperature coefficient resistance (TCR) at 20 °C, –
Π	Is the mathematical constant π, –
σ	Stefan–Boltzmann constant, W/m^2K^4
ε	Emissivity, –
ρ	Gas Density, kg/m^3
μ	Dynamic Viscosity, kg/m.s

Subscripts

0	Dry hydrogen measurements
H_2	Hydrogen gas

humidifiers which are complex and expensive. Three different such operating conditions are listed in Table 1 [2]. It can be seen that in all these cases anode and cathode have to be arranged in counter-flow mode and the coolant runs in co-flow to the anode gas stream. The coolant flow rate can then be automatically determined out of the amount of waste heat and the desired temperature increase. Clearly, both gas streams leave the fuel cell exactly saturated for exactly one value of the fuel cell water balance. In this work, the definition of the fuel cell water balance has been adopted from. Janssen and Overvelde [3]:

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

Where r_d is the net drag coefficient, $\dot{n}_{H2O}$ is the molar water stream entering/leaving the anode (mol/s), I is the total cell current in (A), and F is Faraday's constant (96,485 C/mole).

Therefore, it is very important to understand and accurately measure the fuel cell water balance [4,5]. Several earlier methods of determining the fuel cell water balance [6–12] and the resulting findings have been summarized in detail in the first part of this work [13]. However, these previous methods suffer from inaccuracies and in any case are not suitable for *ad-hoc* applications.

Our group has recently proposed to employ hot wire anemometry, a technology that yields a continuous voltage signal of high frequency which can even be digitized and directly fed into the control board of fuel cell test stations or vehicles. We have shown that there is a one-to-one correlation between the relative voltage signal of the hot wire sensor E/E_0 versus the fuel cell water balance, where E is the voltage reading of the hot wire sensor and E_0 is a pre-determined sensor response curve for a dry hydrogen stream. The amount of hydrogen that is leaving the fuel cell anode side can be calculated out of:

$$\dot{n}_{H_2,out} = (1 - \xi_{an})\frac{I}{2F} \quad (2)$$

Where I is the total current drawn from the stack in (A), ξ_{an} is the anode side stoichiometric flow ratio and F is Faraday's constant (96,485 C/mole). Because both the fuel cell current and the anode stoichiometry are constantly known, E_0 can also be treated as continuously known. Therefore, we only need to pre-determine the dependency between the E/E_0 curve and the fuel cell water balance as exemplarily shown in Fig. 1.

In our previous work, we have also shown that the identical dependency holds for all current densities in the case that the heat transfer rate of the hot wire, characterized by the Nusselt number Nu, can be described as a function of the Reynolds number Re of the flow and the Prandtl number Pr of the binary hydrogen and water vapour mixture at the anode outlet according to a general power–law equation [14]:

$$Nu = CRe^m Pr^n \quad (3)$$

Where the Nusselt number is defined as:

$$Nu = \frac{hD_w}{k}, \quad (4)$$

the Reynolds number is given by:

$$Re = \frac{\rho V_g D_w}{\mu}, \quad (5)$$

And the definition of the Prandtl number Pr is:

$$Pr = \frac{c_p \mu}{k} \quad (6)$$

The exponent to the Prandtl number in Equation (3) is usually taken to be $n = 1/3$. Our previous work has revealed that there is only one experimental parameter to be determined in order to understand the correlation between the relative voltage signal E/E_0 and the fuel cell water balance, and