Journal of Power Sources 297 (2015) 315–322

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Combined current and temperature mapping in an air-cooled, open-cathode polymer electrolyte fuel cell under steady-state and dynamic conditions

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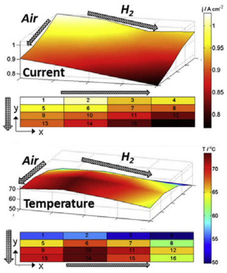
HIGHLIGHTS

- Combined current and temperature mapping as a novel performance metric.
- Large current and temperature gradients form in dead-ended mode.
- Localised extreme temperatures can change the current density gradients.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 10 June 2015
Received in revised form
15 July 2015
Accepted 22 July 2015
Available online 13 August 2015

Keywords:
Current mapping
Temperature mapping
Air-breathing fuel cell
Performance optimisation
Spatiotemporal electro-thermal analysis

ABSTRACT

In situ diagnostic techniques provide a means of understanding the internal workings of fuel cells so that improved designs and operating regimes can be identified. Here, for the first time, a combined current density and temperature distributed measurement system is used to generate an electro-thermal performance map of an air-cooled, air-breathing polymer electrolyte fuel cell stack operating in an air/hydrogen cross-flow configuration. Analysis is performed in low- and high-current regimes and a complex relationship between localised current density, temperature and reactant supply is identified that describes the way in which the system enters limiting performance conditions. Spatiotemporal analysis was carried out to characterise transient operations in dead-ended anode/purge mode which revealed extensive current density and temperature gradients.

1. Introduction

Polymer electrolyte fuel cells (PEFCs) are complex devices, due to the variety of operational strategies (liquid/air cooled, humidified/dry gases), designs (closed/open cathode, through-flow/dead-ended) and materials. Understanding of the *in-situ* behaviour and more specifically of the complex interaction between localised

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http://dx.doi.org/10.1016/j.jpowsour.2015.07.069

current and temperature is crucial for the development of improved systems.

Current mapping was first introduced by Cleghorn and Derouin [1] and Brett et al. [2,3], using printed circuit board (PCB) technology to produce segmented current collector plates, along with Stumper et al. [4], using segmented membranes. This technique shows that significant current density gradients can be generated as a result of fuel and oxidant depletion. Other techniques have proven the value of localised current measurements, including segmented PCBs [1,3,5–9], segmented current collector plates [10–12], shunt resistors [13–15] and Hall effect sensors [16–21]. Measurements have also been performed at sub-millimetre resolution [22,23], investigating the gradients across the land and channel areas. Most studies highlighted uneven performance under high current density, uneven fuel consumptions [2,5,6,14], the crucial influence of the operating conditions [3,13,19], stoichiometric ratios [8,11,12,20], fuel orientations [6,13], water management [10], CO electro-oxidation [7] and CO poisoning [24,25] distribution.

Temperature distribution has also been extensively studied, identifying areas of higher electrochemical activity, hot spot formation and fuel depletion. Thermocouples can provide a crude measure of temperature inside fuel cells [16,17,26,27] but have accuracy limited to ±1 °C and cannot provide high spatial resolution. Moreover, thermocouples need to be inserted inside the fuel cell, which often requires design modifications. In contrast, infrared thermal imaging can provide very high spatial and temperature resolution [28–34], yet it typically requires use of specially designed fuel cells with a window transparent to infrared radiation, or is otherwise confined to measurement of the outer surface of a cell or stack.

Although current density and temperature have been separately investigated, little has been reported on the combined current and temperature mapping of PEFCs. Studies have used micro-thermocouples arrays inserted within a cell [17,35] and infrared transparent windows [15,30] for temperature measurement; current density measurements performed using PCB segment plates. In the case of the thermocouple insertion method [17,35], they have to be positioned between the cathode flow field and the membrane electrode assembly (MEA) to provide accurate reading, which could affect the flow of reactants and access to the electrodes; similarly, the introduction of the window [15,30] might alter the water condensation, and overall thermal management aspects of cell performance.

Comprehensive understanding of temperature and current density distribution is essential for effective design of PEFCs to assess steady-state operation over a range of operating conditions/modes. For air-cooled open-cathode systems, in which a stream of air generated by external fans concurrently services both the cooling requirement of the stack and supply of oxygen to the cathode, the need to understand the link between electrochemical and thermal performance is particularly important. The electro-thermal performance of such systems has been investigated previously at a whole-stack level [36], but methods of spatiotemporal electro-thermal analysis are required.

Knowledge of the temperature and current density distribution is also essential for understanding transient processes occurring in PEFCs operated in dead-ended mode. During the voltage decay observed in dead-ended mode [37–41], multiple processes are have been identified to play a part, including water accumulation (highlighted using neutron imaging [37,38]) and nitrogen accumulation (measured via off-gas analysis [37,42,43]).

Meyer et al. [37] reported an increase of the overall temperature and ohmic resistance in dead-ended mode. Eventually, local current density could be much higher than the average, and the overall effect could be a local drying of the membrane due to the enhanced reaction heat. Therefore, understanding of the spatiotemporal evolution of the electro-thermal map at constant load but in dead-ended mode would be useful to investigate these claims.

Here, we present the results obtained using a PCB sensor plate device that incorporates both current collection and temperature measurement in close registration with each other. The technique is applied to an air-cooled PEFC where the plate is inserted at the middle of a 5-cell stack. Both steady-state and dynamic operation are investigated.

2. Experimental

Fuel cell testing – A 5-cell (60 cm^2 active area) air-cooled fuel cell stack was used for testing (Intelligent Energy Ltd., UK). The membrane electrode assembly was composed of commercially available gas diffusion layers and commercially available state-of-the art membrane with Pt loading of 0.1 and 0.4 mg cm^{-2} on the anode and cathode, respectively.

The fuel cell test station supplied dry, non-heated, hydrogen (with a purity of 99.995%) into the anodes and air was blown by three fans (SanAce 36, Sanyo Denki) to the open-cathode channels. The exhaust hydrogen flow rate in through-flow mode was measured using a thermal mass flow meter (MassVIEW, Bronkhorst) to be 4.7 SLPM (standard litres per minute) when no load was applied. The fans, which provide cooling and air supply to the cathode, were controlled by a programmable power supply (3649A Agilent). The current drawn from the PEFC was controlled by an electronic load (6060B, Agilent) in galvanostatic mode. An in-house computer controlled system coordinates the air, hydrogen, cooling and electrical valves (LabVIEW, National Instruments) as well as recording and presenting data using a data acquisition card (PCI 6221, National Instruments). Ambient temperature, pressure (absolute) and relative humidity (RH) were measured, being of around 25 °C, 1.02 bar (Abs) and 40% RH respectively, during all tests. The operation of this fuel cell in terms of cathode design, cooling and active channels [36], temperature uncertainty [44] and water management in dead-ended anode mode [37] has been described in previous work.

Surface temperature mapping: Thermal imaging was performed using a 640 × 512 focal plane array camera (SC5600MB FLIR, UK). The images were recorded using commercially available software (ResearchIR, FLIR ATC, Croissy-Beaubourg, France). The camera has an extended wavelength detector allowing detection of infrared light within the range 2.5 μm–7 μm. The cavity nature of the cooling and active channels approximate to quasi-blackbody emitters, with an emissivity of 1. The thermal camera used during the experiments has a noise equivalent temperature difference (NETD), a measure of the signal-to-noise ratio, of approximately 19 mK which is within the range of calibration required for the accurate measurement of absolute temperatures. The geometry of the systems imaged resulted in a pixel resolution of approximately 27 μm across the image.

Combined current and temperature mapping: A device for the measurement of the current and temperature distribution, based on PCB technology, was developed by S++ (S++ Simulation Services, Germany). The device is shown in Fig. 2. The temperature measurement is made with copper 'meanders'. Copper has a temperature coefficient of resistance of 3.9×10^{-3} K^{-1}. The copper wires are supplied with a constant current of 2 mA and the voltage drop across each wire is measured, with its changes proportional to the temperature variations. Current measurement is made with integrated shunt resistors, using a special alloy with a much lower temperature coefficient than copper, therefore relatively insensitive to temperature changes. The resistance of an individual shunt