INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 38 (2013) 5348–5356

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Thermal and electrical experimental characterisation of a 1 kW PEM fuel cell stack

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ARTICLE INFO

Article history:
Received 25 May 2012
Received in revised form
18 December 2012
Accepted 5 February 2013
Available online 15 March 2013

Keywords:
Proton exchange membrane fuel cell
Stack
Experimental characterisation
Hydrogen
Performance test
Thermal characterisation

ABSTRACT

The present work describes the experimental characterisation of a self-humidified 1 kW PEM fuel stack with 24 cells. A test bench was prepared and used to operate a PEMFC stack, and several parameters, such as the temperature, pressure, stoichiometry, current and voltage of each cell, were monitored with a LabView platform to obtain a complete thermal and electrical characterisation. The stack was operated in the constant resistance load regime, in dead-end mode (with periodic releases of hydrogen), with 30% relative humidity air and with temperature control from a cooling water circuit. The need to operate the stack for significant periods of time to achieve repeatable performance behaviour was observed, as was the advantage of using some recuperation techniques to improve electrical energy production. At low temperatures, the individual cell voltage measurements show lower values for the cells nearer to the cooling channels. The performance of the fuel cell stack decreases at operating temperatures above 40 °C. The stack showed the best performance and stability at 30 °C, with 300 mbar of hydrogen and 500 mbar of air pressure. The optimised hydrogen purge interval was 15 s, and the most favourable air stoichiometry was 2. Between 15 A and 32 A, the maximum electrical efficiency was 40%, and the thermal energy recovery in the cooling system was 40.8%; these values are based on the HHV. Electrical efficiencies above 40% were obtained between 10 and 55 A. The variation in the electrical efficiency is explained by the variation in the following independently measured factors: the fuel utilisation coefficient and the faradic and voltage efficiencies. The deviation between the product of the factors and the measured electrical efficiency is below 0.5%. Measurements were taken to identify all the losses from the fuel cell stack; namely, the energy balance to the cooling water, which is the main portion. The other quantified losses by order of importance are the purged hydrogen and the latent and sensible heat losses from the cathode exhaust. The heat losses to the environment were also estimated based on the measured stack surface temperature. The sum of all the losses and the electrical output has a closure error below 2% except at the highest and lowest loads.

1. Introduction

Among the various fuel cell stacks available today, the proton-exchange membrane fuel cell (PEMFC) seems to be a promising source for use in residences and small-scale distributed generation systems. These uses require the response of the fuel cell over a large range of operating conditions; therefore, it is important to characterise the thermal and electrical behaviour

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0360-3199/$ – see front matter
http://dx.doi.org/10.1016/j.ijhydene.2013.02.025

under different operating conditions to achieve the optimal operating point. Johnson et al. [1] presented measurements of the electrical output and energy balance of a 3 kW fuel cell stack using humidified air. In that work, the losses associated with the hydrogen purge were calculated from the flow rate and the energy loss to the ambient was estimated from the measured surface temperature. The values were presented for the maximum power with a closure error of 1%, and for three other loads, the authors claim errors below 2.6%. Bao et al. [2] modelled the entire PEM stack system and key components of the water and thermal management system, namely, the fuel cell stack (64 kW, active cell area of 128 cm^2), the radiator, the condenser and the membrane humidifier. They analysed the influence of pressure and air stoichiometry on the thermal loads in the different components and on the losses of the global system. For the stack, they found a performance improvement by increasing the pressure and the stoichiometry from 1.1 to 3. Pandiyan et al. [3] evaluated the ohmic and the global electrical resistances, determined respectively from the polarisation curve and the cooling heat output. The experimental results were obtained in a PEM fuel cell stack using humidified air with only four membrane electrode assemblies with electrode areas of 153 cm^2. The study addressed the evaluation of the thermal output that could be used for cogeneration in the residential sector. Eckl et al. [4] analysed the influence of the temperature, the stoichiometry and the water management on the performance of a 300 W PEMFC consisting of 20 water-cooled cells, each with an active area of 49 cm^2. They also analysed the membrane hydration/dehydration, which had significant effects on the stack performance. They realised that in the low power range, elevated temperatures have a large effect on membrane dehydration. Bradley et al. [5] developed an aircraft powered by a 500 W PEMFC similar to the one used in the present work, and they presented typical tests and parameters for the fuel cell characterisation. The stack had a 32-cell, self-humidified PEM with an active area of 64 cm^2, which is 4 times smaller than the active area of the stack characterised in the present work. Rodatz et al. [6] identified the typical problems in fuel cell stacks that do not occur in individual fuel cells because individual cells do not have a complex thermal regulation system or distribution of reactants. They suggested monitoring all the cells and presented results for a 6 kW stack with 100 cells with a cell area of 204 cm^2. Rodatz et al. also presented techniques to recover and improve the fuel cell performance. They showed that in thin membranes (such as Nafion 112), water flux due to back-diffusion to the anode can effectively compensate for the flux due to the electro-osmotic drag, thus producing a more uniform distribution of water. In the current work, a Nafion 212 membrane was used; the 212 membrane has an identical thickness to the Nafion 112; therefore, it should have a similar capacity for self-humidification. Williams et al. [7] presented a step-by-step technique to evaluate six sources of polarisation, and this technique was used to identify the main sources of loss in a single cell MEA. The technique was used to show that several sources of loss are present simultaneously for high temperature/low relative humidity operation.

In most studies of fuel cell PEM stacks, the electrical characterisation is presented based on the polarisation curves. In the present work, the voltage in the individual cells is measured as well as the polarisation curves. The stability with time and the influence of the location of the cooling channels are discussed. The effects of the temperature, stoichiometry and pressure difference between the anode and cathode on the polarisation curves are analysed. A semi-empirical model representing the activation losses and ohmic losses is presented for the optimal conditions. The present work also describes the variation in the measured factors that affect the electrical efficiency, namely: the faradic and voltage efficiency and the fuel utilisation coefficient.

The thermal characterisation of the PEMFC stack in most studies is limited to the energy balance of the cooling fluid and the estimated heat loss to the ambient. In the present work, the losses associated with the hydrogen purge, and the cathode exhaust's sensible heat loss and latent heat loss are assessed. The sum of all the energy outputs, including an uncertainty analysis, is presented to show the consistency of the data.

In the following section, the experimental set-up that was prepared to characterise a 1 kW PEM fuel cell stack is presented. This section also includes a description of the tests performed and the data interpretation method. The next section presents the experimental results, starting with the cell voltage distribution in the stack and the stability tests and followed by analyses of the polarisation curve and the influence of the operating conditions. For the optimal conditions, an interpretation, including a model for the polarisation curve and an analysis of the factors affecting the electrical efficiency, is presented. In the results, the energy outputs are quantified and compared to the energy inputs. The final section of the paper summarises the conclusions.

2. Experimental

2.1. *Test bench*

Fig. 1 shows a schematic representation of the test bench and the installed instrumentation. The 1 kW PEMFC stack was built by BCS Fuel Cells, Texas, USA. The stack has 24 cells with 4 cooling plates positioned in intermediate positions. The MEA specifications are as follows: membrane size: 21 × 21 cm^2, electrode area: 250 cm^2, membrane type: Nafion® 212, and catalyst [8]. The fuel cell uses membranes from De Nora Inc. (Somerset, NJ) and a proprietary membrane electrode assembly production method. Each bipolar plate provides four parallel channels that are 2 mm wide, 2 mm deep, and separated by 2 mm wide ridges. The channels for the anode and cathode are arranged in serpentine fashion with eleven sections in series for a total length of 154 cm between the inlet and the outlet.

The single cell and stack voltages were monitored and acquired by a NI 9205 module. The stack current and all the temperature values measured by K thermocouples were acquired by a NI 9201 module. All the thermocouple probes have a diameter of 0.5 mm, with the exception of the one located at the cathode exhaust; this thermocouple was provided by BCS and has a diameter of 3.7 mm. The hydrogen and air flows were acquired with Omega FMA flow meters, the pressure was