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Stack Cooling Profile of an Air-Cooled 3-Cell Polymer Electrolyte Membrane Fuel Cell Stack

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Abstract. A locally designed, 3-cell closed cathode PEM fuel cell stack was developed as a platform for thermal engineering studies. Stack polarization behavior is combined with thermal behavior analysis to identify the cooling profiles of an air-cooled fuel cell stack under variable load and cooling settings. The objective of the study is to identify the bulk thermal effects of the stack under cooling for further consideration in fuel cell system control development. The stack is designed with 40 cooling channels and tests were conducted with airflows in the range between 200 and 400 Reynolds number. Different fan settings are applied to analyze the response of the design to negative and positive pressure airflows. The temperature measurements are translated into an averaged stack temperature and a subsequent second order thermal analysis showed that an exponential cooling trend is obtained. Analytical evaluation on the dynamic cooling rates relative to response time and cooling trend is also performed and reported.

Introduction

Polymer Electrolyte Membrane Fuel Cells (PEMFC) is normally applied for small to medium scale applications. The magnitude of thermal energy released, a product of entropic heat of reactions and the irreversibility of the electrochemical reactions, is associated with the cell conversion efficiency which is a function of polarization behavior. The heat generated increases exponentially below the 50% efficiency [1] and membrane dehydration that limits the charge transport is the major concern of this phenomena.

Fuel cell thermal engineering serves to maintain temperature profile uniformity in the gas diffusion layer [2] by applying suitable cooling techniques to control the stack temperature. PEMFC stacks with outputs less than 3 kW is popular where the applications include for backup power systems and small-scale or demonstration vehicles. Closed cathode designs, where the reactant air and cooling air are separate entities, require effective active cooling assistance. Current commercial practice is the application of air cooling for less than 2 kW power and using water cooling for higher outputs. However, using air as a cooling medium is only suitable for small stacks due to the low heat capacity and small temperature differences between the stack and environment.

The geometrical aspect of cooling channels is a viable approach in improving the capability of air-cooled stacks [3]. Matian et al. [4] provided a useful technical study based on computational and experimental evaluation of cooling channel designs of air-cooled PEMFC which is rare in open literature. They noted that temperature variations within a stack can be minimized with wider cooling channels. However, second order thermal analysis was not covered in their work where the cooling effect was derived mainly from the direct interpretation of the stack temperature profiles. Also, the fan operation only applied a singular mode of the widely applied suction flow (negative pressure).

In the predictive thermal modeling domain, Zhang et al. [5] summarized that stack thermal models based on electrochemical performance and reactant characteristics are too large for calculation. A lumped thermal mass model was introduced instead, applying the transient stack temperature profiles based on solid-state thermal analysis. In modeling and experimentally validating steady-state and dynamic heat transfers in a portable stack, Graf et al. [6] suggested using temperature profile plots at different load currents and dynamic temperature to electrical power variation as tools for temperature control strategy. A large degree of temperature variation [7] was also experimentally plotted across the cell and stack, and found to be directly linked to the current density and reactant gas humidity. A 900s cooling response time to shift from dynamic to steady-state heat transfer was also defined for the air-cooled NEXA stack.

The common approach in thermal analysis directly relates the physical temperatures to the phenomena under study. While this is a satisfactory approach, the evaluation of heat transfer rates provides more information on the thermal behavior during operation. In experimental design, the fuel cell temperature is continuously monitored in short periods, or time steps. By using the second order thermal analysis approach, the transient temperature plot is converted into transient heat transfer profiles. The transient heat transfer profile indicates the rate of thermal energy change for the measured periodicals; positive values point to stack heating while negative values means a cooling effect occurred.

Fan selection, position and setting is also an important factor in adapting the cooling rate to the power variations of a stack [8]. Thus, the cooling channel geometry and fan operation setting are two aspects capable of further improving the cooling performance of air-cooled PEMFC. The operational relationship of straight channel geometry with a very small aspect ratio to differences in fan settings was investigated. An experimental approach is reported here to complement the previous works based on numerical analysis [9].

Analytical Method

The stack efficiency or conversion efficiency is evaluated based on [10]

$$\eta_{stack} = \frac{V_{stack}}{V_{rev,stack}} \tag{1}$$

where V_{stack} is the measured stack output voltage and $V_{rev,stack}$ is the total reversible open circuit voltage of the stack. The open circuit cell voltage is normally around 1V, or 80% from the reversible voltage of a PEMFC, and the reversible stack voltage is 1.264V per cell multiplied by the number of cells, n_{cell}.

The heat generated can be estimated by using the simplified system operation relations [8] based on the energy balance of the system and depending on the state of water formed. If the water exists as vapor at room temperature, then the heat generated $\dot{Q}_{gen}$,

$$\dot{Q}_{gen} = (1.264 - V_{cell})\, I.n_{cell} \qquad \text{(Watts)} \tag{2}$$

where I is the stack load in Amps.

The transient temperature plots can be converted into transient heat transfer profiles based on

$$\Delta\dot{Q}_{stack} = \frac{m_{cg}C_{cg}\left(T_{i+1} - T_i\right)}{\Delta t} \qquad \text{(Watts)} \tag{3}$$

where $\Delta\dot{Q}_{stack}$ traces the change of stack heat for the duration of the time step (W), m_{cg} is the total mass of carbon graphite plates (kg), C_{cg} the specific heat of carbon graphite (J/kg.K), T_i is the measured temperature at initial time step (K) while T_{i+1} is the temperature at the end of a single time step (K), and finally, Δt is the time step (sec).

Design and Experimental

A fuel cell stack consists of a number of major components. The flow field, or bipolar, plates acts as the reactant carrier into the cells as well as acting as the path for electron flow. In this design, each plate is 5 mm thick and the cooling channels at 1.7 aspect ratio are integrated within the bipolar plates. Fig. 1 displays individual bipolar plate where the cooling channels runs from one side of the plate to the other side and Fig. 2 shows the actual 3-cell stack in assembly perspective. Each cell was designed with an active area of 230 mm^2, a large cell by definition. This allows a comprehensive thermal analysis to be conducted compared with studies using small cell areas.

A new aspect of the experimental is on conducting the tests under variable load and fan settings. Typically, the cooling fans are set at negative pressure (or suction) configuration and positioned horizontally to induce air flow from the bottom to the top of the stack. Cooling effects at positive pressure flows was not found in literature. Here, the fans are positioned vertically and the fan operation in this study includes the single-fan positive pressure (blower) and single-fan negative pressure (suction) settings.

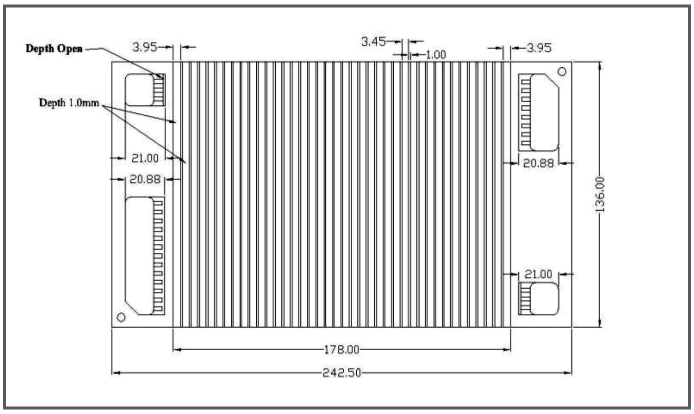

Fig. 1. The bipolar plate and cooling channel design geometry

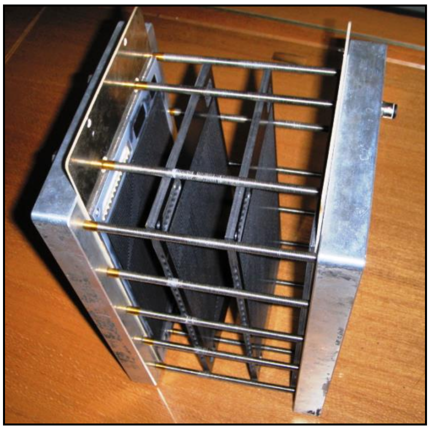
Fig. 2. Stack assembly displaying the integrated cooling channels within the two bipolar plates

The test sets were labeled based on both the load and fan setting. The first letter designates the cooling fan setting and the immediate number identifies the current load setting, as specified in Table 2. The experimental timeframe was limited to 10 minutes and conducted using a fuel cell test station (Fig. 3). The temperature was logged at 5 sec intervals using 8 K-type thermocouple sensors positioned within the cooling channels. All tests were conducted at reactant temperatures near to ambient (max 35^{o}C), and low inlet pressures (max 0.8 bar gauge). The steady flow Reynolds number of the air coolant is between 200 and 400 which is derived from the steady velocity profile of the cooling fans in use. No humidification of the reactants was performed in order to evaluate the thermal effects within the stack without significant influence from the inherent reactant properties.

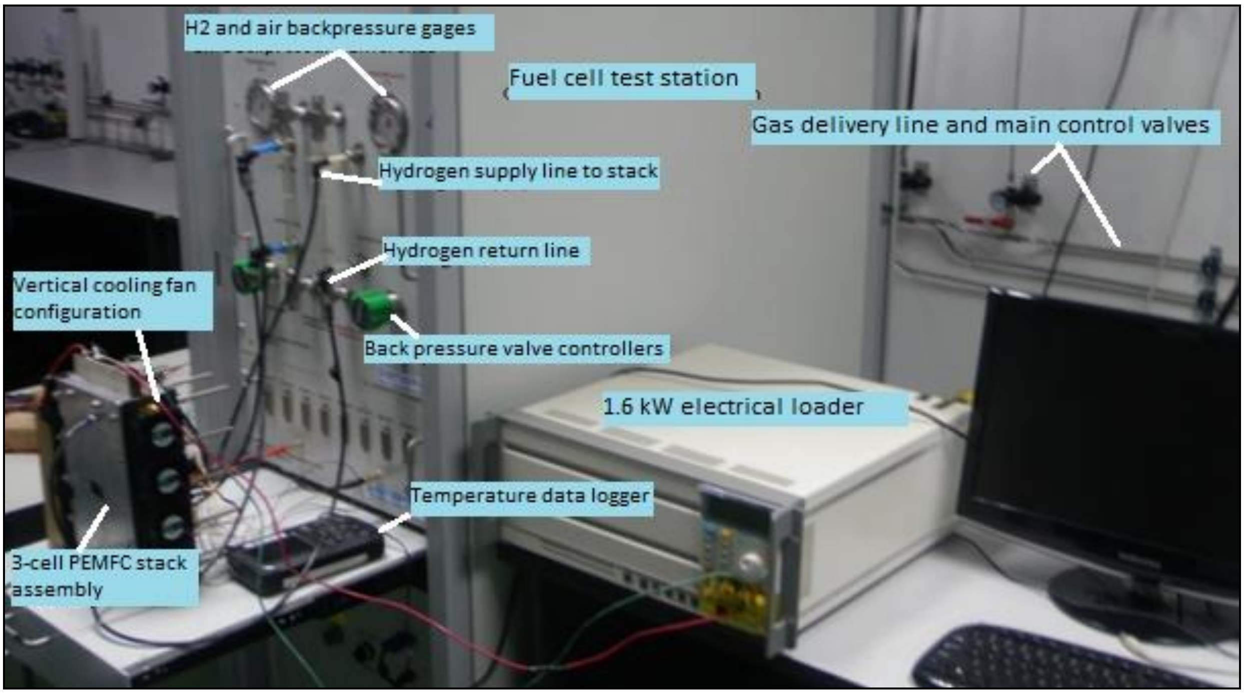

Fig. 3. Hydrogen fuel cell test station setup

Table 2. Designation of test labels

Load (Amp)	Cooling fan setting	
	Blower (B)	Suction (C)
10	B10	C10
20	B20	C20
30	B30	C30

Results and Discussion

The polarization curves using averaged voltage values and the calculated thermal power are presented in Figures 4 and 5. In practice, the reversible fuel cell voltage is 1.26V; therefore, the 3-cell assembly would have a reversible voltage of 3.78V. The highest efficiency is 80% at open voltage, indicating an enormous potential to produce high power densities. However, the selected operating conditions (dry and low temperature/pressure reactants) led to lower power densities than usually reported for industrial stacks as it promotes a significant level of flooding, blocking the flow of reactants. In addition, the performance was based on dry reactant condition where no humidification of the reactants was performed; thus, increasing the charge flow resistance through the membrane.

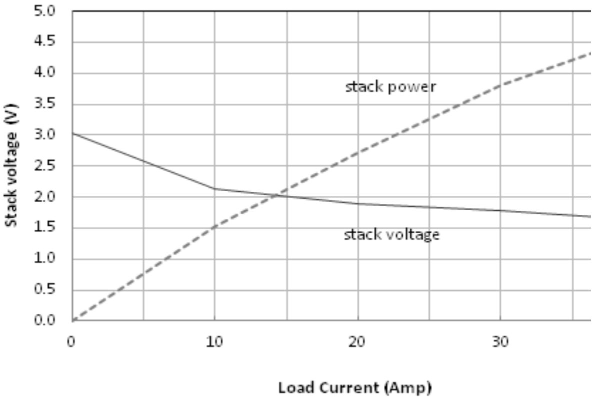

Fig. 4. Polarization curve of stack D1

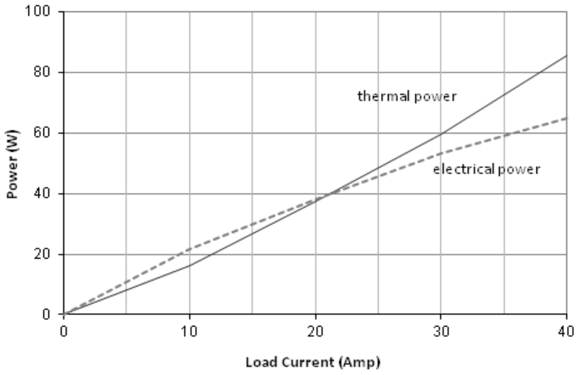

Fig. 5. Relation of electrical power to thermal power generation

The polarization analysis allows the evaluation of thermal energy as the load is varied. Equal electrical and thermal power outputs occurs at 20A corresponding to a conversion efficiency of 50%. From that point onwards, the thermal power increases exponentially. The maximum thermal-to-electrical power ratio at 40A was determined at 1.3 to 1.

Fuel cell voltage is relatively dependant on the energy density of each reactant flowing through the anode and cathode, as well as the conductivity of the components bridging the two reactants. An efficient fuel cell allows a very fast removal and replenishment of the reactants. However, the existence of generated heat and water, and combined with geometrical aspects of the flow channels such as depth and length that influences the mechanics of flow, would have diverse effects on the rate of reactant replenishment into the fuel cell. The most common phenomena during operation to explain voltage drops would be the flooding effect. Operation at low reactant temperature, such as defined for the works here, evidently promoted a high level of flooding within the channels that led to voltage deteriorations.

Stack Temperature. In the experiments, 8 local stack temperatures for each experimental set were obtained. However, these temperatures are individual readings and do not represent the stack temperature as a lumped entity. Therefore, the temperature readings were averaged to represent a single stack temperature as a basis for thermal calculations. The comparative profiles of the averaged stack temperature (Fig. 6) indicates a greater cooling consistency of the negative pressure (suction) fan setting compared to positive pressure (blow) setting due to a better degree of flow control into the channels. Higher inlet resistance are expected from the more energetic and mixed fluid stream of the blower fan setting resulting in erratic flow rates within the cooling channels. At 30A load where the stack thermal energy is generated higher and across a wider area, the blower fan setting has the advantage of stack edge cooling that contributed to enhanced cooling rates.

In terms of cooling response, the suction fan setting has the capability to achieve thermal saturation conditions at a faster response time compared to blower fan setting, especially at low thermal loads. However, a significant increase in generated thermal energy (at 30A) shows that the cooling response deteriorates for the suction fan setting and is approximately similar with the blower fan setting. In general, the controlled induced streamlines of the suction fan setting provides a more stable cooling behavior within the channels.

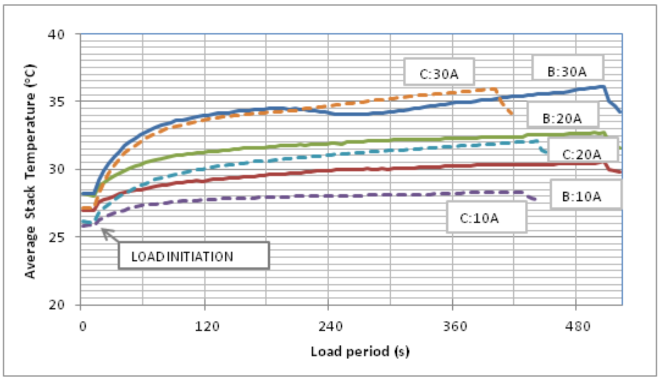

Fig. 6. The averaged stack temperature profiles at different loads for positive (B) and negative (C) cooling fan settings

Cooling Profile. The averaged stack temperature profile is the representative bulk temperature of the stack as it is simultaneously heated and cooled. The analysis on heat transfer of the fuel cell stacks complements the analysis of temperature, allowing a comprehensive evaluation on the cooling performance such as transient energy profile and mean cooling effectiveness. It is useful in improving new designs, operational settings, as well as qualitative evaluation from the perspective of fuel cell thermal engineering.

The relation between the generated stack heat, assumed constant for a specific electrical load, and the stack heat gain profile provided the required dynamic cooling rates of each load and fan setting. Due to the constant thermal power assumption, the projected transient cooling trend resembles the trend of the exponential stack energy gain but with a visible difference in magnitude and flow vector (minus sign indicating stack cooling).

Mathematically,

$$\dot{Q}_{c,transient} = P_{th} - \dot{Q}_{stack,a\exp} \qquad \text{(Watts)} \qquad (4)$$

An effective cooling system is capable of immediately responding to the cooling load that would translate into lower temperature jumps and thus reducing the effect of thermal stresses within the fuel cell. The exponential cooling rate trend should also have a large negative gradient that allows the conduction and convective heat transfer mechanisms to reach an asymptotic level at a faster response time. Fig. 7 compares the cooling profiles of all the experimentations, and it shows a larger gradient is generally achieved by the suction fan setting.

With an assumed constant generate heat, the stack thermal gain was initially higher as the energy is accumulated and reduces exponentially as the internal convection takes effect. By subtracting the stack heat gain from the generated heat, a cooling profile was obtained. The cooling trend line is similar to the stack heat gain trend due to the assumed linear heat generation. Generally, the heat transfer for all the experimental sets is similar in trend with differences in maximum and minimum values, averaged linear rates, and period of stability. The initial jump and its subsequent gradual decrease towards a consistent heating magnitude is governed by two related conditions; firstly, the immediate temperature of the stack, and secondly, the rate at which the heat spreads throughout the stack.

At load initiation, the heat from specific active sites is converged within specific areas of the cell and raises the immediate local temperature significantly; thus, effective cooling occurs only in that particular area. Hence, the initial rapid rise in stack heat as the incoming fluid in that area was overwhelmed by the heat magnitude. Over time, the heat spreads by conduction to the non-active sites, increasing its temperature, and the temperature gradient across the stack is minimized. This promotes a more distributed cooling activity throughout the stack resulting in higher total cooling rates, finally achieving a period where the conductive and convective rates are nearly in equilibrium. This is evident by the negative slope of the stack heating trend during loading, where the stack heating rate approaches a stable behavior upon reaching the thermal balance condition.

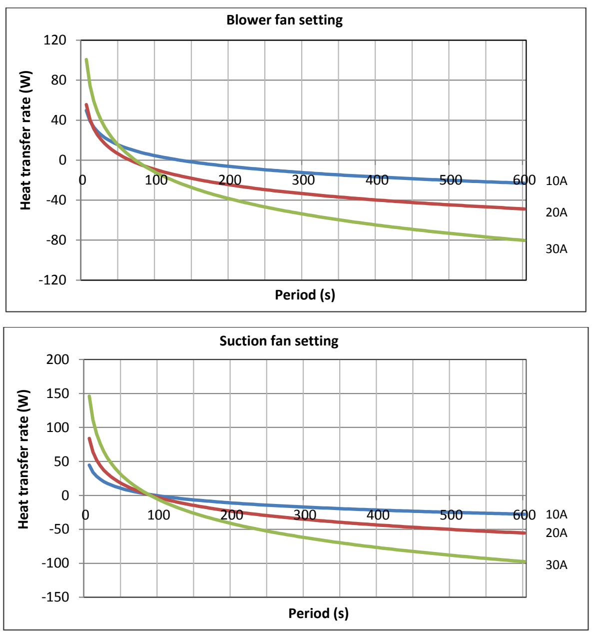

Fig. 7. Cooling profile for both suction and blower fan settings across all the loads

Conclusions

This work provides a preliminary approach in physical investigation of cooling channel designs. A 40 channel configuration was experimented based on a 3-cell air cooled PEMFC assembly. The stack temperature profiles were converted into dynamic thermal power profiles for individual cases.

The cooling profile provides information on the cooling response time which is less varied for negative pressure fan setting. The cooling rate is also significantly better for the negative pressure fan setting as air induction into the channels is less chaotic at that inlet, providing a stable flow stream within the cooling channels. The results of this work is a benchmark in experimental methodology for planned cooling channel design performance evaluation for PEM fuel cells which includes non-conventional channel geometries.

Acknowledgements

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References

[1] W. A. N. W. Mohamed, R. Atan. Optimizing air cooling capability of PEMFC through case-by-case cooling channel analysis. Proc. Int. Conf. on Advances in Mech. Eng. (ICAME) (2009) Malaysia.

[2] S-Wu Perng, H-Wen Wu. Heat transfer in a PEMFC flow channel. Ap. Therm. Eng. 29 (2009) 3579-3594.

[3] G. Zhang, Satish. G. Kandlikar. A critical review of cooling techniques in proton exchange membrane fuel cell stacks Int. J. Hydrogen Energy 37 (3) (2012) 2412-2429.

[4] M. Matian, A. Marquis, N. Brandon. Model based design and test of cooling plates for an air-cooled polymer electrolyte fuel cell stack, Int. J. Hydrogen Energy 36 (2011) 6051-6066.

[5] Y. Zhang, M. Ouyang, Q. Lu, J. Luo, X. Li. A model predicting performance of PEM fuel cell stack thermal system, Ap. Therm. Eng. 24 (2004) 501-513.

[6] C. Graf, A. Vath, N. Nicoloso. Modeling of the heat transfer in a portable PEFC system within MATLAB-Simulink, J. Pow. Sour. 155 (2006) 52-59.

[7] K.P. Adzakpa. Transient air cooling thermal modeling of a PEM fuel cell, J. Pow. Sour. 179 (2008) 164-176.

[8] Ana M. Lopez-Sabiron, J. Barroso, V. Roda, J. Barranco, A. Lozano, F. Barreras. Design and development of the cooling system of a 2 kW nominal power open-cathode polymer electrolyte fuel cell stack. Int. J. Hydrogen Energy 37 (8) (2012) 7289-7298.

[9] W. A. N. W. Mohamed, R. Atan, Thermal and Coolant Flow Computational Analysis of Cooling Channels for Air-Cooled PEM Fuel Cell, Applied Mechanics and Materials: Mechanical and Aerospace Engineering, 110-116 (2012) 2746-2753.

[10] C.S. Spiegel, Designing and Building Fuel Cells, McGraw-Hill New York, 2007, pp. 99.

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