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Thermal Assessment of Convective Heat Transfer in Air-Cooled PEMFC Stacks: An Experimental Study

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Abstract

This study presents an experimental stack-level thermal and hydrodynamic assessment of a model air-cooled PEM fuel cell. To mimic the heat generation inside the MEA, rubber heater films are used. Pressure drop along the stack channels and temperature distribution on the bipolar plate surface are measured for the channel Reynolds number range of 200-500 and the stack input power range of 100-250 W. Tests are performed with and without gas diffusion layers (GDL) to investigate the effect of GDL and its surface characteristics on the pressure drop and heat transfer. Our results indicate that, with the existing length of bipolar plates, a major part of plate minichannel is filled with the developing region. This leads to a higher heat transfer rates, thus more uniform stack temperature can be obtained with the penalty of higher fan power. The minimum measured temperature difference is about 10 ^{o}C and the values become more pronounced when the Reynolds number decreases. The existence of the GDL is observed to have negligible effect on the pressure drop.

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"Keywords: PEM fuel cells; thermal management; air-cooled; convective heat transfer; gas diffusion layer"

1. Introduction

The main goals of thermal management in fuel cell systems are to ensure that the stack operates within a reliable temperature range and the temperature is uniformly distributed within the entire stack. Various thermal management strategies have been experimentally examined based on cooling with the cathode air

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[1-4], cooling with a separate air flow [5-7], natural convection cooling [8-10], cooling with heat spreaders [11-13], single-phase liquid cooling [14-16], and phase change cooling [17]. For a comprehensive review on the thermal management issues in PEM fuel cells, the reader is referred to Refs. [18-20].

Nomenclature

A   channel cross-sectional area, m^2

C_p specific heat capacity, W/kg.K

f   Fanning friction factor,-

L   channel length, m

L_D developing flow length, m

Q   air flow rate, m^3/s

Re   Reynolds number,-

W_{heat} Input power by the heaters, W

Greek

Γ_c channel perimeter, m

μ air viscosity, Pa.s

ρ air density, Kg/m^3

Due to their simplicity, compactness, and lower operating costs in comparison with other designs, air-cooled PEM fuel cells (AC-PEMFC) are promising to be used in a variety of applications including fuel cell vehicles (FCV) and stationary power sources [18]. A typical AC-PEMFC comprises of a stack of cells, which are placed in series or in parallel to generate the required output voltage and current. In each cell, hydrogen and oxygen are carried to the anode and cathode sides of the membrane electrode assembly (MEA), respectively [21]. AC-PEMFCs complete an electrochemical reaction and combine hydrogen with oxygen to produce electricity releasing water and heat as by-products.[22]. MEA is comprised of a membrane coated by catalyst particles sandwiched between two gas diffusion layers (GDLs) [23, 24]. The gas diffusion layer plays an important role in overall performance of PEMFCs by enabling transport of gases, liquids, electricity, and heat within the cell and providing mechanical support to the membrane. [3, 25, 26].

In AC-PEMFCs, air stream on the cathode side, which provides the required oxygen for the chemical reaction is used for cooling the stack at the same time [27]. Proper stack design and air distribution have a significant effect on the AC-PEMFC performance and durability and has been the subject of several studies [27-35]. However, our literature review revealed a need for an experimental study that provides detailed information on the heat transfer and hydrodynamics of AC-PEMFC in both cell and stack levels; this is the subject of the present paper. A new experimental test bed is designed and built to investigate the flow and thermal transport within a stack of an AC-PEMFC at Simon Fraser University (SFU). Pressure drop and temperature distribution measurements are performed for a model stack under the assumption of uniform heat generation in the MEA layer. Tests are also performed with and without the gas diffusion layer (GDL) to investigate the effect of GDL surface characteristics, e.g. surface roughness, on the pressure drop and heat transfer.

2. Experimental procedure

An experimental testbed including six rubber heater sheets sandwiched between bipolar plates provided by Ballard Power Systems (Burnaby, BC) was designed and built at SFU (Surrey, BC). The rubber heater sheets with the nominal power of 180 ±10% watts per sheet were purchased from National Plastic Heater Inc. (Schomberg, Ontario). Toray TGP-H-120 carbon papers were used as the gas diffusion layers for the experiments. A high current power supply with the maximum power of 1.2 kW (50 Amp and 24 Volts) from Digimess (www.digimess.co.uk) was used for running the heaters. 15 T-type thermocouples with the accuracy of ±1 °C and a differential pressure transducer with the accuracy of ±2.5 Pa from Omega (Laval, Quebec), and a data acquisition system from National Instruments (www.ni.com) were used for measuring and recording the pressure drop across the stack and temperature map in the stack and the passing air flow. In addition, an IR camera (FLIR SC655, Portland, OR) was used to monitor the temperature distribution in the fuel cell stack, qualitatively. Air flow was provided by a variable speed wind tunnel. A schematic diagram of the experimental setup and the actual testbed are shown in **Error! Reference source not found.**a and Figure 2, respectively.
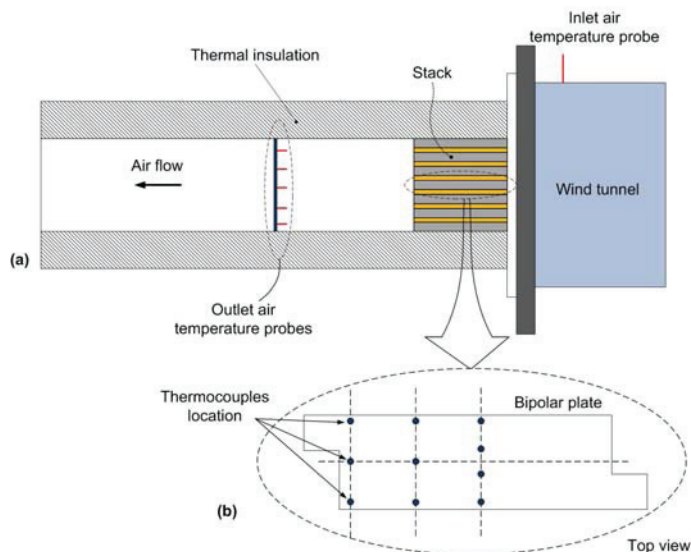

Figure 1: schematic of the test setup: (a) components and (b) location of thermocouples on the middle plate.

Rubber heater sheets were used to mimic the heat generation in the MEAs of an AC-PEMFC stack under the assumption of uniform heat generation. The amount of heat generated in the stack was controlled manually by adjusting the output current and voltage of the power supply. Ten thermocouples were embedded in the middle plate; four of them measured the surface temperature of the central channel and six of them measure the in-plane temperature distribution of the bipolar plate. Location of the thermocouples on the bipolar plate is shown in **Error! Reference source not found.**b. It should be noted that the temperature measurements were performed only in the half of the bipolar plate due to the expected symmetrical temperature distribution within the stack. The symmetry of the temperature distribution had been confirmed by IR camera images taken at different loads and flow conditions. Inlet air temperature was measured at one point; outlet air temperature was measured at five points and the averaged value was used in the calculation of the convective heat transfer. The test section structure

including the inlet and outlet plenum was fabricated using 6 mm-thick Plexiglass. Due to higher heat convection rate form the top surface, a 10 cm-thick layer of insulation material (glass wool) was attached to the top surface to reduce heat loss to the ambient. Air flow rate was controlled by changing the wind tunnel fan speed manually.

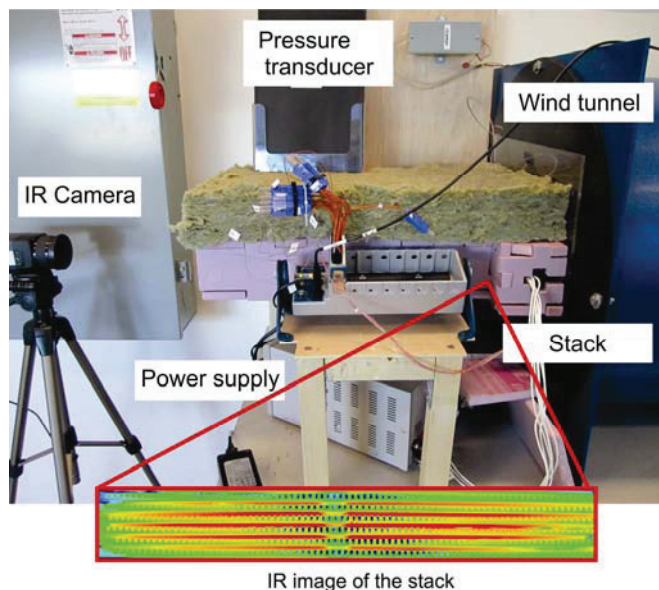Table 1 lists the experimental condition used in this study.

Figure 2: actual experimental testbed and a sample IR camera image (front view of stack) showing the symmetry in the stack temperature.

3. Results and discussions

3.1. Hydrodynamics

Pressure drop across the stack was measured with and without the GDL to investigate the effect of the GDL layer on the overall pressure loss. Smooth layers of transparent sheet with the thickness of 500 μm were used for the case without GDL. Figure 3 illustrates the variation of pressure drop versus flow rate for both cases, i.e., with and without GDL layers. It can be seen that the GDL presence has a negligible effect on the measured values of pressure drop. Poiseuille number (f Re), where f is the Fanning friction factor, is the common dimensionless number used for analyzing pressure drop in channels. The value of f Re depends on the characteristic length scale used for defining the Reynolds number. It should be noted that the selection of the characteristic length does not affect the calculated pressure drop. However, it has been shown that the use of the square root of cross sectional area, $\sqrt{A}$ leads to more consistent results, especially when various cross-sections are considered [36-38]. The experimental data are used to calculate the values of f Re as follows [39]:

$$f\,\mathrm{Re} = \frac{2\,A^{5/2}}{\mu Q \Gamma_c}\,\frac{\Delta P}{L}, \tag{1}$$

where Γ_c is the perimeter of a channel, ΔP is the pressure drop across a channel of length L, and Q is the volume flow rate that passes through a single channel.

Table 1: experimental conditions used in the present study.

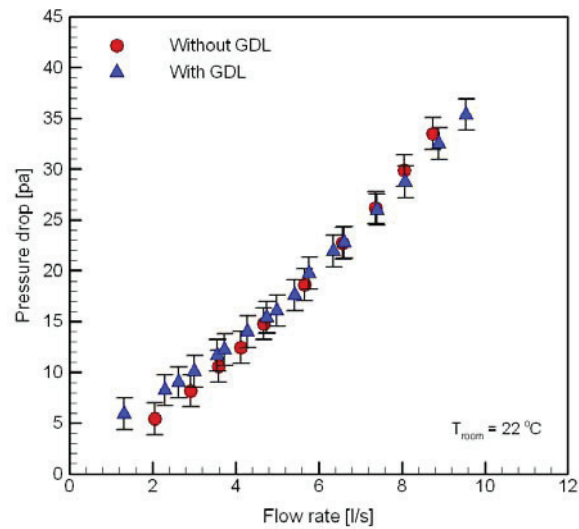| Parameter	Quantity
Flow rate [l/s]	2-10
Re	200-500
Channel length [cm]	7
Channel hydraulic diameter [mm]	2
Number of plates [-]	7
Number of channels per plate	81
GDL type	TGP-H-120
Input power (W)	100-250

Figure 3: measured values of pressure drop across the fuel cell stack with and without GDL over a range of flow rates.

In Figure 4a, the results are compared with the model of Bahrami *et al.* [37] proposed for calculating $f\,\mathrm{Re}$ of arbitrary cross section channels. It can be seen that the experimental data in lower Reynolds

numbers ($\text{Re} < 300$) are in great agreement with the model. However, when the flow rate increases, the Poisuelle number increases in a linear fashion with the Reynolds number indicating that the flow is no longer fully developed and the developing region fills a considerable part of the channel. This has been confirmed by independent numerical simulation performed using FLUENT software. Figure 4b shows the ratio of the developing length (L_D) to the total length of the stack channels, calculated from the following equation proposed by Shah [40]:

$$\frac{L_D}{L} = 0.05 \, \text{Re}_{\sqrt{A}} \, \frac{\sqrt{A}}{L}.$$

(2)

It can be seen that the developing region occupies more than 50% of the channel length beyond $\text{Re} = 300$.
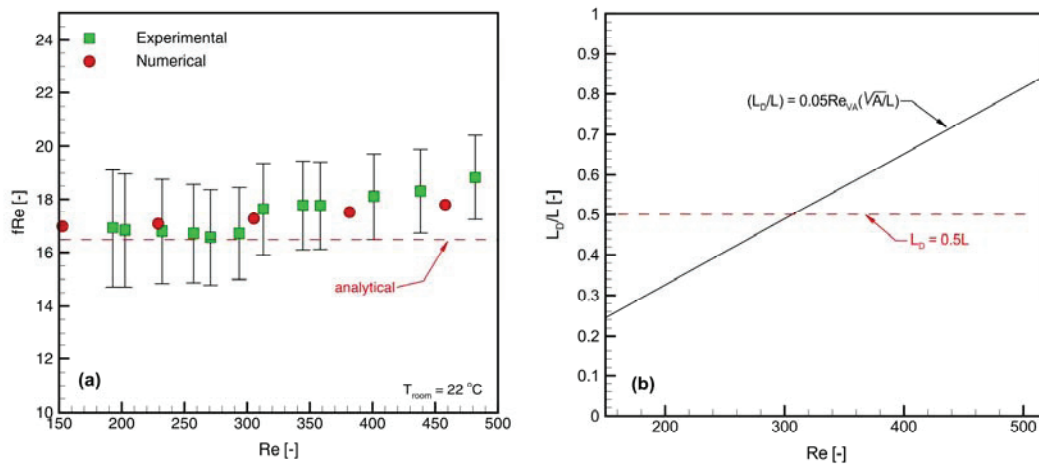

Figure 4: Effect of developing flow on $f\,\text{Re}$; (a) comparison with the analytical model of Bahrami et al. [37] and (b) The ratio of the developing length to the total length of the stack channels.

3.2. Heat transfer

The heat generation rate inside the stack (W_{heat}) was controlled by adjusting the output current and voltage of the power supply of the rubber heater sheets. The air temperature at the inlet and outlet of the stack were recorded in several locations and were recorded at several locations and the averaged values of the recorded temperatures were used in the calculations. Figure 5 shows the measured temperatures in various heights at the outlet of the stack for two different flow rates (Reynolds numbers) when the overall heat generation rate of the heaters were 150 W. The recorded temperatures in **Error! Reference source not found.** show a uniform temperature distribution at the outlet.

Using the total heat generation rate inside the stack by heaters and the air volumetric flow rate, the theoretical air temperature rise in the stack is calculated as:

$$\Delta T_{air} = \frac{W_{heat}}{\rho Q C_p}, \tag{3}$$

where C_p is the air specific heat capacity and Q is the volumetric flow rate. The theoretical calculations are compared with the measured average temperature rise across the stack over a range of volumetric flow rates and heat generation in Figure 6. There is a reasonable agreement between the experimental recordings and the theoretical values which means that the heat dissipation to the ambient is negligible especially in high volumetric flow rates.
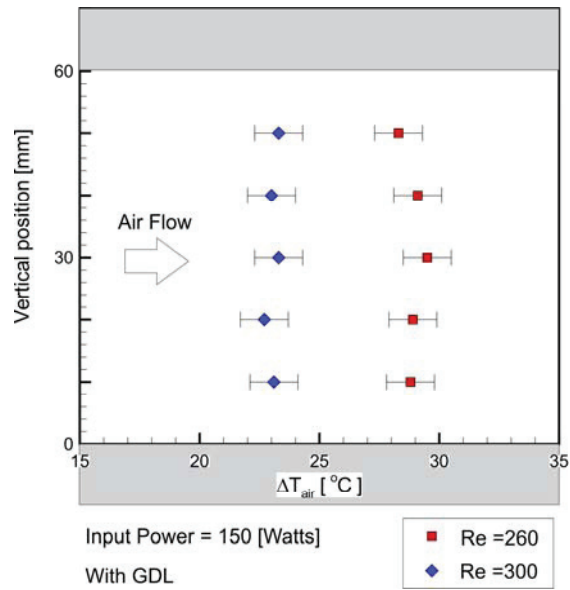

Figure 5: Measured temperatures in various heights at the outlet of the stack for two different flow rates.
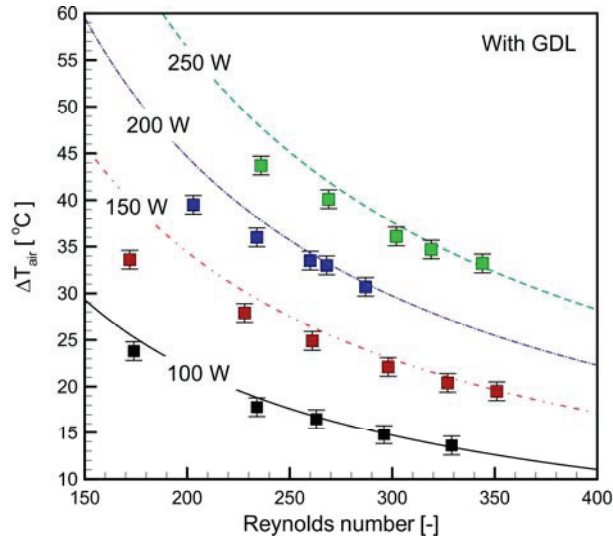
Figure 6: Comparison of the measured and theoretical air temperature rise across the fuel cell stack.

The surface temperature variation across the centerline of the bipolar plate, shown in **Error! Reference source not found.**b, is reported in Figure 7a. The results show that the surface temperature increases from the inlet towards the stack outlet. Variations in the temperature are steeper in the first half of the channel because the developing flow leads to higher heat transfer rates. The minimum measured temperature difference is about 10 ^{o}C; these values become more pronounced when the Reynolds number decreases. Our experimental data suggest that the maximum surface temperature occurs near the outlet of the stack. The effect of air velocity (Reynolds number) on the maximum surface temperatures is investigated in Figure 7b. As expected, the maximum surface temperature significantly drops with an air velocity increase. Moreover, the results suggest that for a typical AC-PEMFC with 250 W heat generation, the maximum surface temperature will be lower than 70 ^{o}C if the Reynolds number based on the channel's hydraulic diameter is higher than 220.
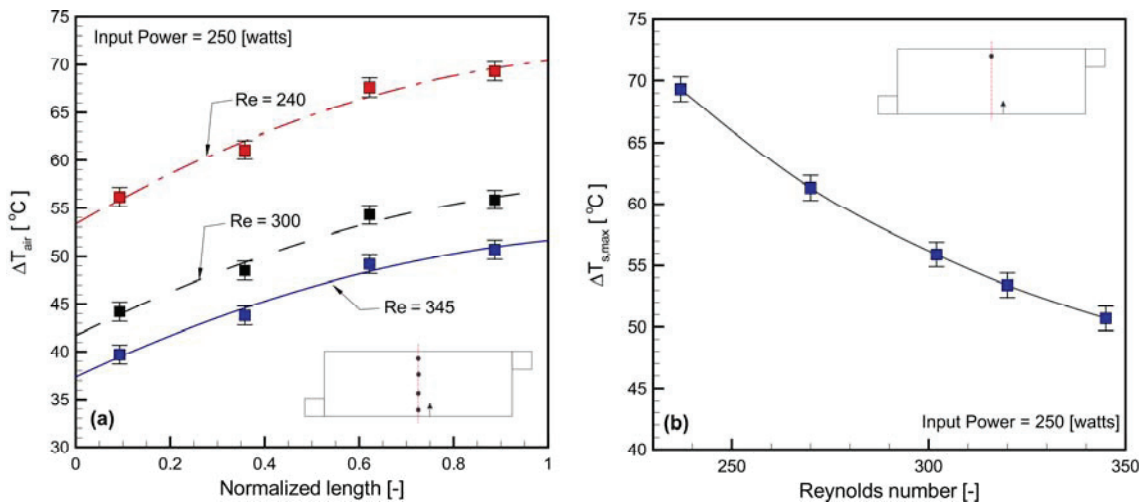
Figure 7: Bipolar plate surface temperature (a) variation over the centerline of the tested bipolar plates and (b) The effect of air velocity on the maximum surface temperature.

4. Summary and conclusions

Convective heat transfer in air cooled PEM fuel cell stack was investigated. An experimental setup was designed and built at SFU that enabled the measurement of pressure drop and heat transfer in the stack level of air cooled PEM fuel cells. Pressure and temperature distributions within a typical stack and the passing air flow were measured. The followings are the highlights of the present study:

- Gas diffusion layer (GDL) has negligible effect on the hydrodynamics (overall pressure drop) of the air flow across the stack.
- Developing flow in the air channels plays an important role on the hydrodynamics and heat transfer of the stack. Developing flow leads to steeper variations in the temperature at the first half of the stack with the penalty of higher pressure drop across the stack.
- The minimum measured temperature difference is approximately 10 $^{\circ}$C; this temperature becomes more pronounced when Reynolds number decreases.
- Our experimental data suggest that the maximum surface temperature occurs near the outlet of the temperature. This temperature reduces as the flow rate increases.

Acknowledgements

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