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Thermal and electrical energy management in a PEMFC stack – An analytical approach

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Abstract

An analytical method has been developed to differentiate the electrical and thermal resistance of the PEM fuel cell assembly in the fuel cell operating conditions. The usefulness of this method lies in the determination of the electrical resistance based on the polarization curve and the thermal resistance from the mass balance. This method also paves way for the evaluation of cogeneration from a PEMFC power plant. Based on this approach, the increase in current and resistance due to unit change in temperature at a particular current density has been evaluated. It was observed that the internal resistance of the cell is dependent on the electrode fabrication process, which also play a major role in the thermal management of the fuel cell stack.

Keywords: Fuel cell; PEMFC; Electrode; Thermal resistance

1. Introduction

Thermal management of PEMFC is a key to ensure high cell performance and efficiency. Heat and water are the sole byproducts of the electrochemical reactions in fuel cells. The irreversibility of electrochemical reactions and joule heating are the most important factors causing heat generation inside PEM fuel cells. In addition, the kinetics of electrochemical reactions directly depends on the operating temperature. The temperature distribution in the cell has a strong impact on the cell performance. It influences the water distribution by means of condensation and affects the multi component gas diffusion transport characteristics through thermo capillary forces and thermal buoyancy. Excessive local cell temperature due to insufficient or non-effective cell cooling may cause membrane dehydration, shrinking or even rupture. Hence, thermal and water management issues are strongly coupled and they have a direct impact on cell performance.

Thermal management includes the removal of the generated heat from inside the cell to the outside or to the surroundings. Further, a temporally and spatially uniform temperature distribution must be provided, in order to avoid hot spots in the membrane. The pumping power required for the coolant circulation has to be minimized for system optimization in order to ensure high overall cell efficiency. Therefore, pressure drop must be minimized while maximizing the heat transfer capability at the same time. The method employed to remove heat from the fuel cell stack depends on its size. Daugherty et al. [1] studied fuel cells of less than 100 W of capacity and used air convection to cool the cells and provide sufficient air flow to evaporate the water without using any fan. However, higher capacity fuel cell stacks requires cooling circuit that could be incorporated in the stack for thermal management. Computer simulations have been carried out to study the thermal management in a fuel cell by many groups along with the water management studies. Dumercy et al., [2] have developed a 3D steady state thermal

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modeling for a fuel cell stack which is helpful in defining the geometry of the fluids ducts. While a number of models assume a constant temperature of the fuel cell stack, Shan and Choe [3] have carried out dynamic analysis especially the temperature response to the dynamic load.

The thermal load can be managed simply by using fans without any water cooling system like the air-cooled PEMFC, which is widely used in sub kW and around 1 kW systems. Many systems have been reported wherein a single air blower is used to feed the reactant gas as well supply the air to cool the stack. The performance of an air-cooled system is highly dependent on ambient temperature and humidity. Air-cooled systems are expensive to build as each cell has to have channels for the anode and cathode plates for the cooling air to flow. In order to reduce the cost, novel methods are being developed and one such method is reported by Ruge and Hoekel [4] who have used a edge air cooling integrated with a fan. However, in case of tropical and sub tropical countries, air cooling concept has to be thought very seriously as the average temperature is about 35 °C. In such applications, liquid cooling is preferred and also design of the cooling plate play a major role for heat dissipation uniformly from the cells. Serpentine or meander cooling patterns have been used. These circumstances call for a flow geometry with minimum flow resistance between a volume subjected to two constraints: fixed total volume and fixed channel volume.

Although there have been a number of studies on heat and mass transfer in the reactant gas channels, there have been very limited studies on optimizing the cooling process of a fuel cell. Musser and Wang [5] employed a two-dimensional code to predict the temperature variation in the fuel cell. However, the two-dimensional analysis could not reflect on the real cooling arrangement which includes complicated configurations such as serpentine type structures. Chen et al. [6] have used a three-dimensional CFD code to investigate the coupled cooling process involved in fluid flow and heat transfer between the solid plate and the coolant flow. They investigated six different cooling modes in their analysis and have arrived at the conclusion that serpentine type flow mode is better than the parallel type mode.

Operating conditions of a fuel cell widely depend on the thermal management. It is used to control the cooling system, to maintain a good hygrometry level in the fuel cell and to optimize the efficiency of the system. If the gradients of temperature through the layers (MEA) are not taken into account, then the heat transfer can only be estimated along the channels. These studies are realized with water circulation on the external faces by forced convection.

Recently Faghri and Guo [7], reviewed the numerous technical challenges that exist in fuel cell technology development with respect to thermal management from single cells to system level for both low and high temperature fuel cells. A chaotic heat-exchanger for PEMFC cooling applications has been studied by Lasbet, et al. [8] in which they proposed a three-dimensional flow inside cooling channels using a novel channel geometry that generates chaotic flow and developed heat exchangers that can be easily reduced in size while preserving high thermal performance. A model has been developed by Yu et al. [9] for the water and thermal management for Ballard PEM fuel cell stack to investigate its performance. A general calculation methodology was developed to implement this model by knowing a set of gas feeding conditions like pressure, temperature, flow rate and stack physical conditions like channel geometry, heat transfer coefficients, operating current, etc. The model could provide information regarding the reaction products water and heat, stack power, stack temperature, and system efficiency, thereby assisting the designer in achieving the best thermal and water management. Furthermore, if the stack undergoes a perturbation, such as the initial start-up, quick change in current, or a shutdown, the model could predict the dynamic information regarding stack temperature, cell voltage, and power as a function of time. In another model for thermal coupling in fuel cell stacks, developed by Promislowa et al. [10], the steady state thermal transfer in polymer electrolyte membrane fuel cell stacks using straight coolant channel was considered, ignoring the impact of the gas and coolant channel geometries. The model provides estimates on two important quantities: the local temperature difference between coolant and membrane, and the spread of heat from an anomalously hot cell to its neighbours in a stack environment.

However, none of these models address the heat generation due to electrodes and their fabrication process. Hence, in the present paper, the thermal heat evaluation from a fuel cell stack has been reported. The study is aimed to know the ability of the heat fluxes to cross through the various layers of the cells and to quantify the heat by taking in to consideration of the operating current, pressure, flow rate, channel dimensions, coefficient of heat transfer coolant volume, etc. The distribution of temperatures is obtained for different current densities. An analytical method has been developed to find out the change in current and resistance due to unit change in temperature at a particular current density, without changing the coolant flow rate. This approach will be helpful in identifying the thermal and electrical output for a PEM based fuel cell power plant of large capacity for cogeneration.

2. Experimental

Four membrane electrode assemblies of 153 cm^2 electrode area were made by a proprietary process in use at Centre for Fuel cell technology [11–13]. The MEA's were kept in between two graphite bipolar plates with grooved flow fields for fuel and oxidant supply. The 4 cells assembly is made with 2 cell repeat units consisting of monopolar plate for fuel/oxidant, bipolar plate for fuel and oxidant and another bipolar plate for oxidant and coolant, as shown in Fig. 1. The gas feed plate made of acrylic and current collection plate made of copper is kept on the ends and

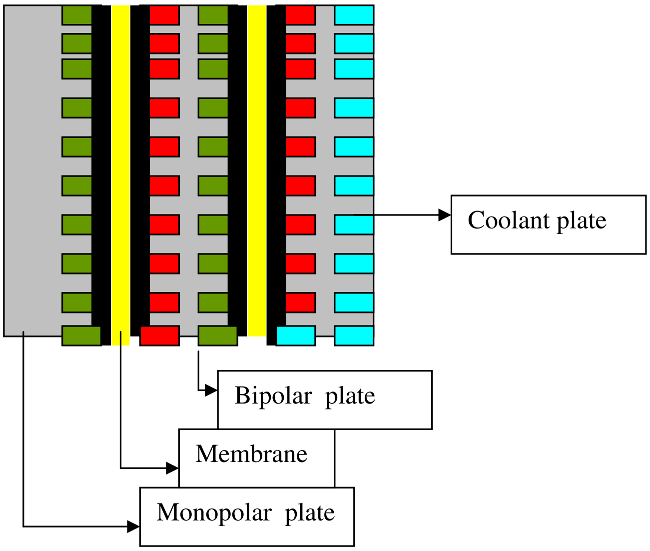

Fig. 1. Schematic of the assembly-2 cells – repetitive unit.

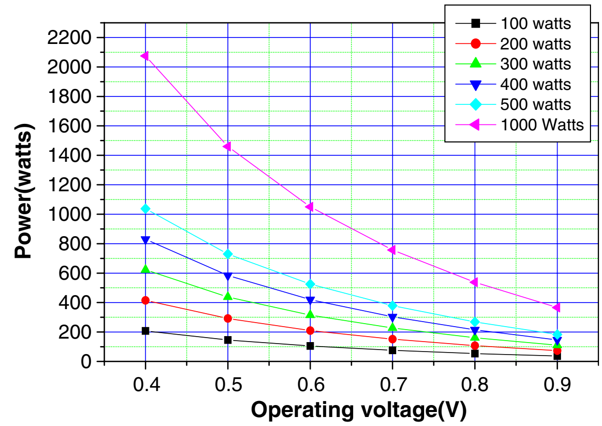

Fig. 2. Theoretical heat evaluation based on the operating voltage.

the whole assembly is tightened with the help of endplates, bolts and nuts. The fuel and oxidant used are hydrogen and air from compressed cylinders and compressor, respectively. Thermocouples were inserted at the coolant inlet, outlet and in the stack for measuring and monitoring the temperature. The cells were humidified from a conventional bubble type heated humidifier and the humidity is measured at the stack inlet and outlet. Temperature of the coolant at the inlet and outlet of the stack are measured using a thermometer for quantifying the heat output. A needle valve flow controller is used for regulating coolant supply to maintain the temperature of the stack during measurements. The stack is connected to a test bench consisting of bubble humidifiers, temperature controllers and a DC electronic load box.

3. Results and discussion

To get the thermal energy released from the fuel cell power module, it is necessary to know all internal power sources. In that way, chemical energy released by consumption of hydrogen is given by equation

$$P_{\text{chemical}} = \Delta H_{\text{H}_2\text{O}} \cdot (1/2)F \quad (1)$$

where F is the Faraday's constant (96,487 coulombs/mol)

The electrical energy supplied to the load is

$$P_{\text{electrical}} = V * I \quad (2)$$

Hence the internal thermal power is the difference in power between chemical and electrical output. This thermal output is based on the operating voltage of the cell and theoretical voltage, which is calculated from the open circuit voltage. Fig. 2 shows the thermal energy output for various operating voltages. From the figure it is clear that when the operating voltage decreases the thermal output increases. The ratio between the electrical power output and thermal output is unity, if the operating voltage is 0.6 V at all power levels ranging from 100 W to 1 kW. However, when the operating voltage of the cell decreases, the ratio increases to 2 for an operating voltage of 0.5 V. This shows that twice the energy is going as heat output instead of electrical output. In a water cooled stack, the two assumptions are made: Heat produced is mainly due to electrochemical reaction and the heating due to ohmic resistance of the components involved in stack assembly. The heat generated is generally removed by circulation of coolant, since the other modes of heat removal by natural convection and radiation are negligible when the ambient temperature is high. The stack operating temperature is 50 °C and the inlet of gas temperatures is 55 °C and 60 °C for oxidant and fuel, respectively. The quantifiable heat from the coolant is given by

$$Q = \dot{m} C_p \Delta T \quad (3)$$

where $\dot{m}$ is the mass flow rate of water (coolant), C_p is the specific heat of water at constant pressure and ΔT is the temperature difference between inlet and the outlet of the stack. And the total heat energy produced is given by

$$Q = I^2 R \text{ (watts)} \quad (4)$$

The relation between the operating current, temperature, voltage and resistance using the data obtained from the 100 W stack has been evaluated, which can be extrapolated to higher wattage stacks. The polarization curve of the 4 cell stack assembly is shown in Fig. 3, using humidified reactants of hydrogen and air at 90% and 85% RH, respectively, when the stack temperature is at 50 °C. The electrical power generated from the 4 cell assembly is 83.24 W at 40 amps and a voltage of 2.08 V and thermal energy was found to be 108.33 W (calculated from Eq. (3)) when the inlet and outlet temperatures of the coolant are measured as 30 °C and 38 °C, respectively. However, quantification of heat from the stack is 10% less compared to theoretical calculation based on Eq. (2) which can be attributed to

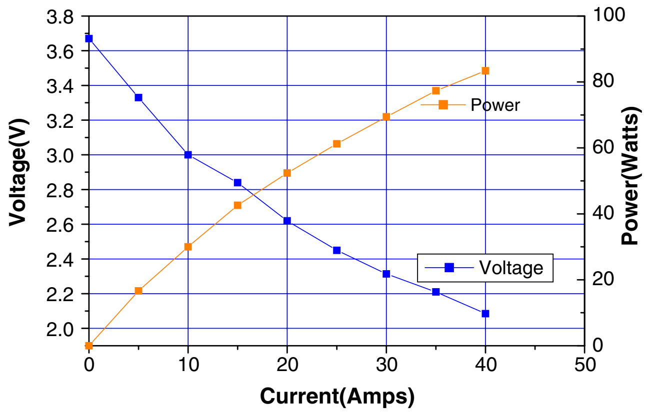

Fig. 3. Fuel cell polarization curve for the 4 cell assembly at 60 °C with humidified reactants hydrogen (RH 90%) and air (RH 85%).

natural convection/radiation or lost through the reactant air/fuel flow.

The thermal and electrical resistance can be calculated as 67.7 mΩ and 52 mΩ, respectively, from the following equations

$$R_{\text{Thermal}} = Q/I^2 \quad (5)$$

$$R_{\text{Electrical}} = V/I \quad (6)$$

By combining Eq. (3) and (4), the rise in current due to each unit of temperature change, (case 1) and the rise in resistance (case 2), has been evaluated from the following equations.

$$I_1^2 R_1 = mC_p \Delta T_1 \quad (7)$$

$$I_2^2 R_2 = mC_p \Delta T_2 \quad (8)$$

Eq. (7) and (8) gives

$$mC_p(\Delta T_2 - \Delta T_1) = (I_2^2 - I_1^2)(R_1 - R_2) \quad (9)$$

From Eq. (9), the rise in current and resistance due to each unit rise in temperature is computed analytically and is given in Fig. 4. Table 1 lists the current and resistance value due to temperature change for case 1 and case 2 based on

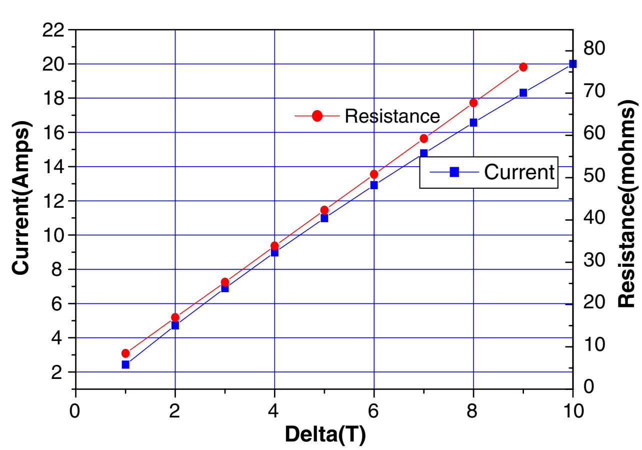

Fig. 4. Variation of current and resistance with respect to rise in temperature.

Table 1
Change in current and resistance with respect to unit temperature change

Change in temperature (ΔT)	Case 1 current (Amps)	Case 2 resistance (mΩ)
1	42.43	76.17
2	44.72	84.64
3	46.9	93.01
4	48.99	101.56
5	50.99	110.02
6	52.92	118.49
7	54.77	126.95
8	56.57	135.42
9	58.31	143.88
10	60	152.34

Eq. (7), respectively. The starting current was assumed as 40 A and then the system was allowed to increase in temperature without changing the mass flow rate of the coolant. For the evaluation of thermal resistance change, thermal resistance 67.7 mΩ has been taken as the base value and from which the resistance due to incremental temperature change has been evaluated.

From Table 1, it is clearly seen that thermal resistance increases by about three times for a temperature difference of 10 °C whereas the current increases by about 50% only. This is mainly due to the high electrical resistance by the cell and the other components. It is clear that the internal electrical resistance of the electrode play a major role thereby decreasing the current that can be drawn from the stack for every unit increase in temperature. In order to differentiate the contribution due to electrode and the assembly, the assembly was kept constant and the electrode fabrication procedure was changed by varying certain parameters in the electrode fabrication process by addressing the gas diffusion layers and the catalyst layer [14]. We identified the process which gives the lower internal resistance, which is evaluated from the heat output. This internal resistance calculated is of real significance as it gives the resistance under the fuel cell operating conditions with both the gases being humidified, compared to resistance values obtained from four probe technique or ac impedance method.

Fig. 5 shows the electrical and thermal output from a single fuel cell based on three different process and catalyst. From the figure it is clear that the thermal and electrical energy output is directly related to the variables in the process as well as the process also. From the Figure it is seen that at various currents namely 18, 25 and 32 amps, the thermal energy and electrical energy are equal depending on different electrode fabrication processes. This figure clearly indicates that the process which gives higher current for which both thermal and electrical energy are equal can be chosen for higher capacity stack development, which will reduce the internal resistance of the stack.

Fig. 6 shows the change in internal resistance when moving from one process to the other for two current densities viz., 200 and 300 mA/cm^2. It is clear from the figure that the process 3 gives lower internal resistance for both the

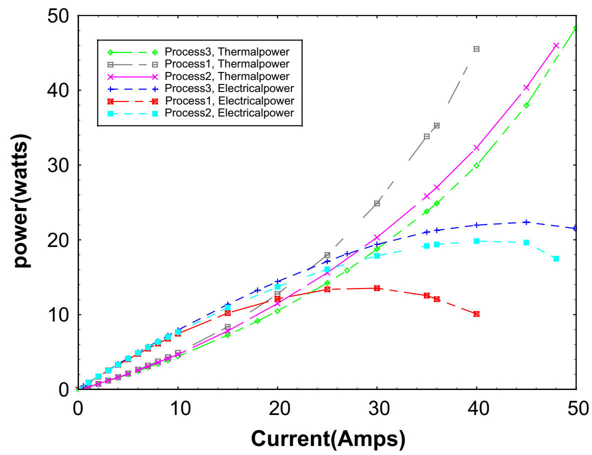

Fig. 5. Thermal and electrical output from a single cell for various fabrication process.

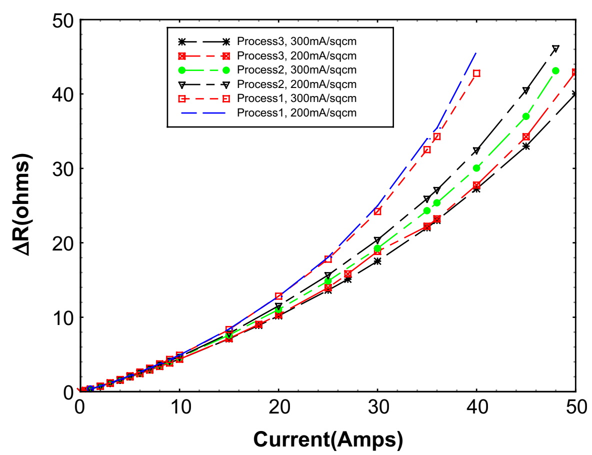

Fig. 6. Change in internal resistance due to variation in current density.

current densities compared to process 1 and 2. Hence in order to decrease the internal resistance, attempts can be made in the direction of electrode fabrication process as it is clear from the results, in addition to reducing the resistance due to the cell components of the assembly.

4. Conclusion

The electrical and thermal resistance of a PEM fuel cell stack has been evaluated using an analytical approach. Based on the heat generated at a particular current density by keeping the mass flow rate of coolant constant, it has been shown that the internal resistance of the electrode increases due to increase in current density with respect to change in temperature. Thermal and electrical resistance of the electrodes were found to be 67.7 and 52 mΩ, respectively, for a stack assembly of 4 cells. It was observed that the increase in thermal resistance is found to be three times and the current increase by 50%, for a change in temperature of 10 °C. The electrode fabrication process play a major role in reducing the internal resistance of the stack in addition to the stack components. This study is helpful in evaluating the thermal output from a small residential power plant for cogeneration.

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