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FUEL CELL THERMAL MANAGEMENT WITH THERMOELECTRIC COOLERS

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ABSTRACT

Thermoelectric coolers are utilized along the periphery of a Bipolar plate in a Proton Exchange Membrane (PEM) fuel cell to cool the adjacent Membrane Exchange Assemblies (MEAs) where the majority of the waste heat is generated. These solid-state microcoolers (MICs) can be built in many configurations for unusual applications where parasitic thermal energy management is required. A fuel cell application is ideal with the cell powering the MICs.

A thermal model is developed to use the Bipolar plate as the cold junction plate of the MICs. The heat generated in the cell membrane is modelled as a uniform flux on the Bipolar plate's surface, which is manifested as a generation term in the heat conduction equation. Therefore the temperature field can be modelled in the Bipolar plate, predicting the MIC's cooling effect on it and in adjacent MEAs, and provide the temperature distribution throughout the selected design of the plate. Thus the temperature field in the MEA region, as well as the temperature gradient in the fuel cell, can be predicted.

Minichanneling is used in the design of the Bipolar plate gas flow channels to take advantage of the high heat transfer coefficients that take place.

The model shows that the MICs' improved heat management of the fuel cell maintains the cell stack operating temperature between 45C and 60C, an acceptable range that precludes the need for any internal liquid cooling or external humidification of feed gases.

INTRODUCTION

Typically in automotive applications, fuel cell cooling (forced air and/or internal cell liquid cooling) and feed gas humidification are required to maintain cell output, adding cost, bulk, and complexity, and robbing a portion of the fuel cell power output. Studies have shown that if the cell component temperatures remain in the 45C to 60C range, slight performance reduction can be justified to eliminate the required humidification (and cooling) auxiliary equipment [Büchi and Srinivasan, 1997].

Solid state microcoolers (thermoelectric generators used in the cooling mode) have been introduced as a reliable, cost-effective and practical means for thermal management in several electrochemical power systems [Parise, 1997, 1998, 1999, and Parise and Jones, 2001]. This unique cooling system is now being applied to thermal management in PEM fuel cells to cool the Bipolar plate.

The Bipolar plate is not only the electrical contact between adjacent electricity-producing MEAs, but also provides the flow channels for the feed gases to the cell. Therefore the intimate thermal contact between the waste heat producing MEAs, the Bipolar plate, and the feed gases flowing in the channels of the Bipolar plate, provides a unique opportunity to combine the plate with the MICs as the cold junction plate.

Figure 1 shows the basic configuration of the Bipolar plate with channels on both sides and the MICs around the full periphery, obviously the top portion removed for illustrative purposes. The thermoelectric generator (TEG) elements of the MICs are shown much larger for clarity. In actuality these coolers will be in the micron range [Fleurial et al, 1999], which also provides a unique way of controlling the thermal flux along the plate's edge.

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This ongoing research effort has been expanded to a 2-D thermal model for cooling the fuel cells, and includes the thermal effects of advection on the Bipolar plate from the hydrogen fuel gas flowing on one side of the plate and the air (oxygen supply) on the opposite side of the plate.

BACKGROUND

Typically PEM fuel cells are about 50% efficient with half the energy produced manifesting as waste heat that must be removed. This internal heating causes membrane dry-out which greatly reduces the performance of the cell [Badrinarayanan et al, 2001]. Therefore the MICs will be used to cool the fuel cell by maintaining the temperature of the Bipolar plate in a specified temperature range that allows acceptable reaction rates to occur, while at the same time reducing or eliminating the need for reactant gas humidification.

A preliminary study, utilizing a one-dimensional conduction heat transfer model, while neglecting the effects of gas flow (and hence advection effects) in the fuel cell, shows that the MICs can maintain the internal components of the fuel cell below the desired 60C temperature range, eliminating the need for external humidification [Parise and Jones, 2002]. However, the simple model predicts temperatures possibly below acceptable limits for proper cell reaction rates to take place.

One prime advantage for using MICs to cool the Bipolar plate is the modular approach that can be used to cool different regions as needed. Since the MICs are comprised of many cooling junctions that form a cooling matrix, individual junctions can be cooled separately based on the local heat load. This matrix cooling effect is taken advantage of in the model to meet the reduced cooling load requirements in the extreme external corners of the plate while concentrating the bulk of the cooling load in the plate's center portion.

Currently auxiliary equipment is required for both the cooling of the cell and the management of water in the cell membrane. This equipment adds an estimated 20% to the fuel cell volume and puts a parasitic load on the energy output of the cell. Initial studies using the MICs indicate that the energy loss from the cell will be reduced while the MICs provide a better control scheme for maintaining favorable operating conditions in the fuel cell stack.

MODELLING APPROACH

Heat generation takes place primarily in the MEAs which are in good thermal contact with the Bipolar plates. The laminate construction of the fuel cell stack, MEAs alternating with Bipolar plates, makes utilizing the Bipolar plate by the MICs as the cold junction plate ideal for cooling the cell. For the model, the exothermic reactions that take place are considered to be uniform throughout each MEA region in contact with the Bipolar plate. This waste heat appears as a flux on the surface of the Bipolar plate and is modelled as a generation term in the conduction equation.

There are channels in the Bipolar plate for which the feed gases flow and must be brought into contact with the MEAs for the reactions to take place. Thus the thermal contact between the MEAs and the Bipolar plate is by conduction between the channels and through advection with the flowing gases in the channel regions. A parameter is used to specify the percentage of plate/MEA contact by conduction or by the flowing gases in the channel areas. For the model, 65% is advection and 35% is conduction.

To improve the convective heat transfer coefficient between the feed gases and the Bipolar plate/MEA interface, reduced hydraulic diameters will be used in the channels. By definition, a minichannel has a hydraulic diameter on the order of 3mm to 200μm, while a microchannel has a hydraulic diameter on the order of 200μm to 20μm. Hydraulic diameters on the order of 1mm to 100μm are considered ideal for heat transfer applications in automotive fuel cell design [Kandlikar, 2002]. For the model, the channels are 325μm wide by 250μm deep, and run the full length of the Bipolar plate (10cm), with a distance of 175μm between channels.

The cooling profile by the MICs along the edges of the Bipolar plate is input as a linear function with maximum cooling at the center and minimum at the corners. This facilitates concentrating the cooling where it is needed most and reduces the overall cooling load that the fuel cell must provide.

The by-product H_2O produced by the cell is considered in the vapor form, hence taking advantage of the latent heat of vaporization to aid with removal of some of the parasitic heat. This is an assumption that will have to be tested in the future when a prototype cooler is built and tested. For the model, the Bipolar plate is graphite. The MICs are made up of p-n doped bismuth telluride junctions with a total cross-sectional area of 0.132mm^2 and lengths of 0.25mm. The full development of the fuel cell and all the MIC equations are presented in previous works [Parise and Jones, 2001, 2002].

EQUATION DEVELOPMENT

A two-dimensional, steady-state heat conduction model for the anisotropic Bipolar plate is developed which includes heat generation and the thermal effects of the fuel feed gas hydrogen on one side of the plate and the oxygen gas flow provided by air on the opposite side of the plate. Figure 2 shows the coordinate system chosen for the model with appropriate boundary conditions. The conduction equation for the plate is

$$\beta_x[\partial^2 T_B/\partial x^2] + \beta_y[\partial^2 T_B/\partial y^2] + q''_B/k_B t_B = 0, \quad (1)$$

where T_B is the local plate temperature, x is the coordinate normal to the direction of gas flow, y is the coordinate in the direction of gas flow, β_x and β_y are cross-section correction factors for the conduction section not being of uniform thickness in the x and y directions, respectively. That is, the ratio of the thermal conductance in the x or y direction to the thermal conductance for a plate of uniform thickness t_B, and k_B is the thermal conductivity of the plate. The term q''_B is the heat flux incident on the surface area of the Bipolar plate. Thus

$$q''_B = \gamma q''_{MEA} + (1-\gamma)(q''_a + q''_h), \qquad (2)$$

where γ is the fraction of plate surface area in contact with the MEA surface and q''_{MEA} is the heat flux from the MEA, q''_a and q''_h are the heat fluxes from the air and hydrogen gas streams, respectively. In the model,

$$q''_a = h(T_a - T_B), \text{ and } q''_h = h(T_h - T_B), \qquad (3)$$

where h is the convective heat transfer coefficient between the gases and the plate.

The boundary condition along the centerline is an axis of symmetry, that is, at x = 0

$$\partial T_B/\partial \big|_{x=0} = 0. \qquad (4)$$

There is a match of temperatures and heat fluxes between the Bipolar plate and the cold junction of the MICs at the remaining three boundaries where the MICs are installed. That is,

$$T_B(L,y)=T_{C,y},\ T_B(x,0)=T_{C,X1},\ T_B(L,y)=T_{C,x2}, \qquad (5)$$

and

$$\begin{aligned} q''_{C,y}(y) &= -k_B\, \partial T_B/\partial x\big|_{x=L}, \\ -q''_{C,x1}(x) &= -k_B \partial T_B/\partial y\big|_{y=0}, \\ q''_{C,x2}(x) &= -k_B \partial T_B/\partial y\big|_{y=l}, \end{aligned} \qquad (6)$$

where L is the length of the Bipolar plate in the x direction, and l is the length of the Bipolar plate in the y-direction, the direction of gas flow, the T_c's are the cold junction temperatures of the MICs, and the q''_c's are the cooling fluxes at the Bipolar plate edges.

The relationship between the heat flux at the cold junction of the MICs appearing in Equation (6), q''_c, the cold junction temperature and the thermoelectric equations come from Parise and Jones [2001], and Angrist [1982].

The temperature of the MIC hot junction, T_H, is a function of the local coordinate, x or y, and depends on the heat flux at the hot junction through

$$q''_H = [(UA)_H/(A_n + A_P)](T_H - T_\infty), \qquad (7)$$

where $(UA)_H$ is the overall conductance between the hot junction, the prescribed underhood air temperature is T_∞, and A is the cross-sectional area for either the n or p element of the MICs. The A_H term in the $(UA)_H$ value is the total heat transfer surface area over the base area of a MIC junction, $A_n + A_p$. The $(UA)_H$ can be produced by, for example, forced convection over a fin assembly in intimate contact with the hot junction of the MICs. The heat flux at the hot junction, q''_H, is from

$$q''_H = q''_C + I_{TE}^2 R_{TE}, \qquad (8)$$

where I_{TE} is the current to the MICs and R_{TE} is the electrical resistance of the MIC junction, a function of the TEG element geometries and electrical resistivity.

The mass flow rates for the two gases are very small, of the order of 10^{-7}kg/s. And because of the small scale of the channels, the convective heat transfer coefficient in the channels, h, is on the order of $1000 W/m^2K$. For steady state gas flow in the fuel cell, it can be shown with an energy balance on either gas that

$$T_g = T_B + q''_{MEA}/2h, \qquad (9)$$

where T_g is the gas local temperature. This shows that the gases very quickly attain the temperature of the Bipolar plate and influence very little the plate's temperature.

METHOD OF SOLUTION and PARAMETERS

Equations (1) - (9) were solved numerically by writing equation (1) and the associated boundary conditions in finite-difference form on a uniform grid. All derivatives were approximated using second-order accurate differences. The resulting system of non-linear algebraic equations was solved by iteration and relaxation using MATLAB. The analysis showed that the results were independent of the mesh size for a grid of 21 by 42 nodes, x-direction by y-direction, respectively. A relative convergence criterion of better than 0.001 was used for the temperature at each node. Less than 1000 iterations were required to achieve convergence.

The geometry of the MICs was chosen to optimize the ratio of their cross-sectional areas, and the number of junctions, 490, to meet the cooling requirements of the Bipolar plate. To remove the heat at the hot junctions, the convective heat transfer coefficient was chosen as $5000 W/m^2K$, with an ambient temperature of 320K.

The fuel cell current flux is chosen as $800 mA/cm^2$, the maximum output of the cell. The fuel gas is pure hydrogen with an excess air flow of 200%. The nominal thickness of the Bipolar plate used is 2mm.

RESULTS

The model predicts the temperature field in the Bipolar plate with and without the use of the MICs. Figure 3 shows the power input to the MICs with the resulting cooling heat flux, q''_c, at the cold junctions shown in Figure 4. The energy requirements of the MICs are based on the cooling load and MIC geometry. The current input to the MICs is linear from the corner of the Bipolar plate to the center of the side, with minimum input at the corners and the maximum value at the center. The slightly parabolic cooling flux shown in Figure 4 is due to the I^2R losses in the MIC TEG elements.

The temperature profiles of the MIC hot junctions are in Figure 5. This is the temperature at which the parasitic heat must be removed from the fuel cell external surface, based on the MIC geometry chosen, Bipolar plate design, and fuel cell external geometry.

Figure 6 and Figure 7 show the temperature profiles of the Bipolar plate at the fuel cell centerline and along the external edge, both with and without the MICs, respectively. The maximum temperature in the Bipolar plate with cooling is about 61C, and the minimum temperature is 48C. These are well within the desired limits. When the MICs are shut off as shown in Figure 7, the maximum temperature jumps to 78C.

The gas flow rates are so small that there is a negligible influence on the temperature of the Bipolar plate or the MEAs in general. In fact the flowing gases quickly reach and maintain the temperature of the Bipolar plate, thus there are negligible entrance effects as well.

The load requirements to cool the fuel cell with the MICs were about 7% of the total fuel cell output.

At the chosen current flux of 800mA/cm^2, the fuel cell produced 0.532 volts. This corresponded to an electrical output of 21.3W, with the waste thermal energy being 28.7W. Therefore the cell efficiency was calculated at 42.5%.

Shown in Figure 8 are the thermal gradients throughout the entire Bipolar plate region both with and without the benefit of the MICs. This is very illustrative of the influence the MICs have on the Bipolar plate temperature, and in particular the type of thermal gradient that can be produced throughout the fuel cell stack.

DISCUSSION

The induced temperature profile or flux of the MICs along the edge of the Bipolar plate enhanced the performance of the cooler. The corners of the Bipolar plate showed to have very little (or no) cooling requirements. The simple linear cooling profile used in the model was adequate enough to maintain the internal centerline temperature of the fuel cell in an acceptable range, while at the same time maintaining the corners of the cell at a high enough temperature to promote good chemical reactions.

The load requirements for cooling the cell are reduced from 12% of fuel cell output in the 1-D model to about 7% in the 2D model, obviously from the better perspective of having cooling on three sides.

Early tests using a constant profile along all three edges produced unacceptably low temperatures at the corners of the Bipolar plate while trying to maintain the center temperature around 60C. Also, the load requirements on the cell to drive the MICs reached about 11%.

When the MICs are shut off, the maximum temperature in the plate reached only about 78C, which would be considered a normal operating range for a PEM fuel cell. Therefore the VI relationship, and perhaps the heat generation equation used in the model, may be providing slightly conservative values. However, there appears to be enough parameter adjustment still available in the operation of the MICs to offset any increased cooling requirements needed to abridge this issue. MIC junction count, MIC geometry, temperature profile (or MIC cooling flux) along the edges, Bipolar plate thickness and/or cross-section configuration, heat transfer augmentation on surfaces, etc., are but a few of the many parameters that can be adjusted to improve the operation of the cooler. Also, data from a prototype will be very helpful in confirming the efficacy of the cooler while useful in identifing the many operational parameters.

CONCLUSIONS

The use of the MICs with a specified thermal profile at the Bipolar plate's edge allowed the fuel cell to operate in an acceptable temperature range throughout the MEA region. The simple linear cooling profile improved the effectiveness of the cooling system considerably. A more dynamic and/or aggressive temperature profile will improve the temperature field further. A prototype study with temperature sensors in the Bipolar plate's region of most concern will provide valuable input to the control scheme necessary to optimize the performance of the MICs in cooling the fuel cell.

The dynamic control of the temperature inside the Bipolar plate will also reduce the amount of energy needed from the cell output for the cooling load. Currently 6% to 7% is necessary to operate a PEM fuel cell. The MICS may reduce this value to less than 5% with the proper control scheme. The prototype study will hopefully bear this out.

DEDICATION

The authors dedicate their research to Eric Jones and Joey Parise, two youths whose early passing from this life precluded their chances for fulfilling the dreams of inquisitive minds. God rest their souls.

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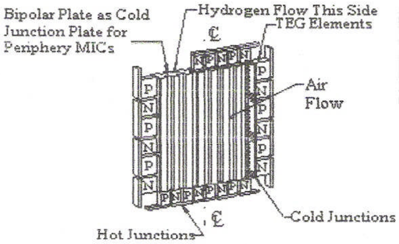

FIGURE 1: Fuel Cell MIC with Bipolar Cold Junction Plate

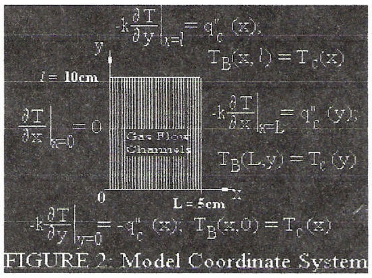

FIGURE 2: Model Coordinate System

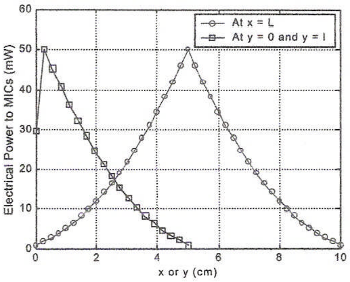

FIGURE 3: Electric Power Profile to Drive MICs.

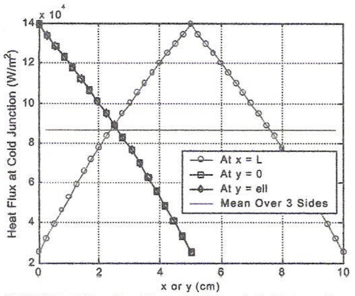

FIGURE 4:Cooling Flux of MICs at Cold Junction.

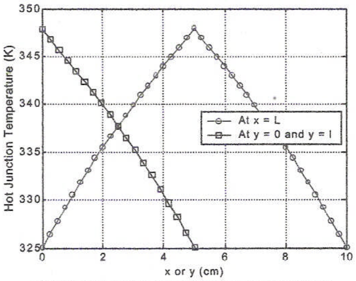

FIGURE 5: MIC Hot Junction Temperature.

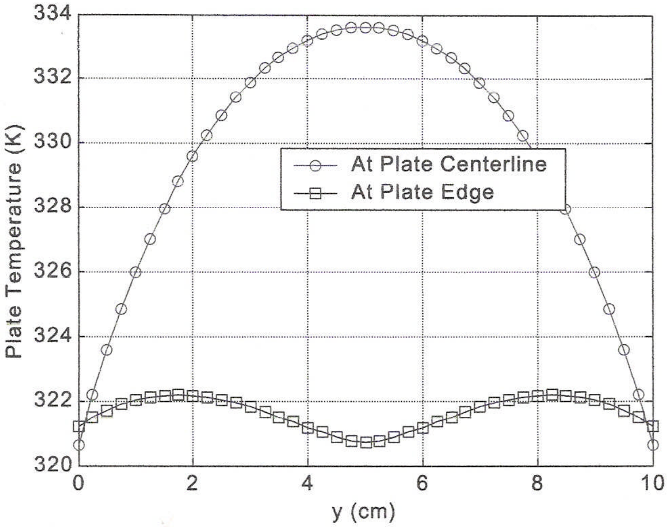

FIGURE 6: Bipolar Plate Temperature Profile at Centerline and Edge with MIC Cooling.

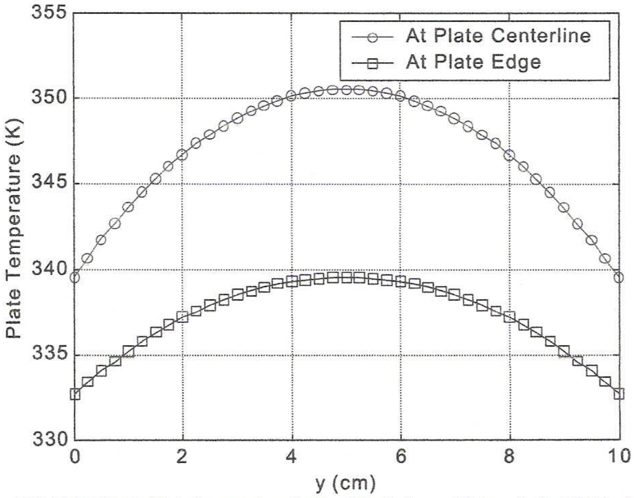

FIGURE 7: Bipolar Plate Temperature Profile at Centerline and Edge with No MIC Cooling.

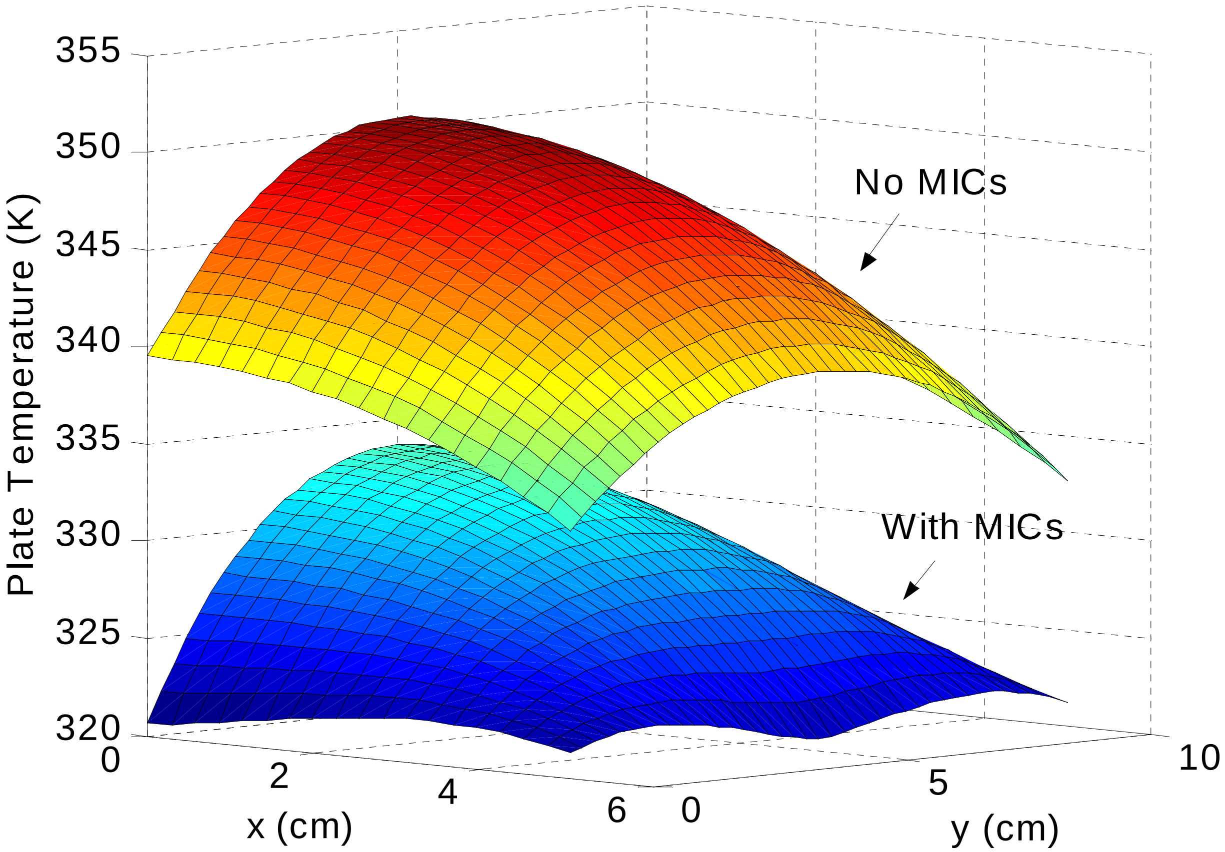

Figure 8: Comparison of Thermal Gradient in Bipolar Plate with and without MIC Cooling.