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Fuel Cell Thermal Management with MicroCoolers

R.J. Parise
PARISE RESEARCH TECHNOLOGIES, Suffield, CT 06078

G.F. Jones
Department of Mechanical Engineering, Villanova University, Villanova, PA 19085

ABSTRACT

Thermoelectric generators (TEGs) are unique solid-state components that can be used as a cooling device when supplied with electric power. These microgenerator coolers (MICs) can be built in many configurations for unusual applications where parasitic thermal energy must be managed. Such an application is in Proton Exchange Membrane (PEM) fuel cells where waste heat is generated during electrical energy production. This heat generation reduces fuel cell performance, can damage cell components and increases system operating costs.

A thermal model is developed to utilize the bipolar plate in a PEM fuel cell to double as the cold junction plate of a MIC. The bipolar plate is in full electrical (thus thermal) contact with the Membrane Exchange Assembly (MEA), where the majority of heat is generated.

The waste heat in the cell membrane is modelled as a uniform flux on the bipolar plate's surface. This flux is manifested as a generation term to develop a two-dimensional, steady-state heat conduction model in the bipolar (cold junction) plate, thus predicting the MIC's cooling effect on the bipolar plate, and in adjacent MEAs.

This model provides the temperature distribution in the selected design of the cold junction plate, hence throughout the bipolar plate, and can be used to predict the temperature field in the MEA region, as well as the temperature gradient in the fuel cell.

The preliminary, one-dimensional study presented here utilizes this thermal management scheme inside the fuel cell to show that the interior centerline temperature of the bipolar plate can be maintained at 60C or less throughout the full power range of the cell, eliminating the need for external humidification. And at maximum fuel cell power output (440mW/cm^2), the MIC required approximately 12% of the cell output to maintain this bipolar plate centerline temperature.

Thus the model shows that the improved heat management capability inside the fuel cell with MICs will provide a better performing cell that can meet the severe operating conditions required for the automotive industry.

INTRODUCTION

For small fuel cell systems (~200W) the source of oxygen, typically supplied by air, is sufficient to cool the cell and limit the thermal effects on the membrane. However, in the large cells used for the automotive industry, power consuming auxiliary equipment (usually fans or air compressors for air-cooled systems, and/or liquid cooled radiators) is required to limit fuel cell operating temperatures. And since fuel cells operate at a lower temperature (80C) than internal combustion engines (125C), the size of the cooling radiator becomes an issue in the design of the vehicle [1].

Therefore a means of removing the thermal energy at the point of production, inside the cell, can be accomplished using the MICs in the fuel cell case, and/or between membrane electrode assembly (MEA) pairs where the heat is produced. These MICs are powered directly from the electrical energy produced by the fuel cell and can be designed to have very favorable cooling characteristics and made to fit on bipolar plates of any configuration. Some typical bipolar plate schemes are discussed by Murphy et al [2].

Along with thermal management of the fuel cell interior is water management in the cell membrane [3, 4]. To optimize fuel cell performance, humidification of the feed gasses is utilized to maintain cell stack moisture retention [5]. Good membrane water content promotes the migration of H$^+$ ions from the anode to the cathode. Hence the use of self-humidifying polymers is also being developed [6]. Even though water is a by-product of the fuel cell reaction, several mechanisms [7] can cause cell membrane dryout during severe operating conditions.

One such mechanism is the drying effect the cell feed gasses have, depending on their relative humidities. And the warmer the feed gasses, the higher the affinity they have for moisture. Typically, fuel cell operation in the

80C range [8] requires humidifying both the combustion air and the H_2 fuel. And increasing cell stack temperature, to a point, increases cell output, but increased humidification is required.

Indeed, an estimated 20% of the fuel cell stack volume and mass are needed to provide humidification. However, studies [9] have shown that by reducing and maintaining the fuel cell operating temperature below about 60C, with slight cell performance degradation, humidification of the feed gasses is not necessary. In fact, lost performance is no greater than the loss in power due to the auxiliary equipment required to perform the cooling and humidification processes, thus providing the capability of eliminating mechanical equipment that can fail and/or must be maintained.

Thus the research has shown that in a Nafion^{TM} membrane fuel cell (Nafion^{TM} is a registered trademark of DuPont), if the MEA region can be maintained at a temperature less than 60C, humidification can be eliminated without an overall detriment to the operation of the cell.

At the other end of the spectrum, for the fuel cell reactions to occur at reasonable rates, the cell should be maintained at a temperature above 45C to 50C. This aspect of the model performing at the lower end of the operating temperature range will be discussed later.

These are the ultimate goals of the MICs: eliminate or reduce significantly the requirement for liquid cooling; reduce significantly feed gas volumetric flowrate requirements where the primary concern is fuel stack cooling; and maintain the 15C temperature difference in the fuel cell stack to eliminate the need for feed gas humidification. This will reduce considerably the auxiliary equipment power requirements that must be supplied by the cell stack. Hence a fuel cell that can be optimized to operate in the temperature range between 45C and 60C will perform with these advantages over current fuel cell designs.

BACKGROUND

The concept of solid state microcoolers in electrochemical power systems was introduced initially for cooling current automotive batteries with future use in hybrid-electric and all electric vehicles [10, 11, 12]. Previous research in electrochemical batteries where MICs have been employed has shown that lead-acid battery recharge time can be reduced 40% with internal cooling [13]. In Ni-Zn batteries where quick discharge is a problem, discharge times have been increased 2-1/2 times the normal rate without thermal damage to internal battery components while utilizing the cooler [14]. Now this same cooling concept is being applied inside fuel cells.

Typically PEM fuel cells are about 50% efficient: half the electric power generated in the cell is available for producing useful work, while half is waste heat that must be removed. Internal heating causes membrane dryout which greatly reduces the performance of the cell [15]. 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 for acceptable reaction rates to occur, while at the same time reducing or eliminating the need for reactant gas humidification.

The advantages of utilizing the MICs in fuel cell cooling now become apparent. And the model indicates the power requirements needed for the use of MICs as auxiliary cooling equipment are comparable to (or slightly less than) the requirements for existing auxiliary equipment (compressors, fans, large liquid radiators, etc.), without additional tubing or ducting. The MICs require simple electrical wiring for power to operate.

MODELLING APPROACH

Heat generation in the fuel cell takes place primarily in the MEAs at both electrode sites where electron stripping (anode) and by-product H_2O formation (cathode) are exothermic reactions, as well as other locations where ohmic heating occurs (in electrodes, bipolar plates, contact surfaces between the two, exchange losses in the membrane, etc.). The laminate construction of the fuel cell stack, alternate MEAs with bipolar plates, all in good thermal (and electrical) contact, lends itself to cooling the bipolar plates. Hence the heat generated in the MEAs can be removed from the local site using the bipolar plate which is typically both a good thermal and electrical conductor.

Figure 1 illustrates the basic MIC cooling concept in the fuel cell. Figure 1(a) shows the typical PEM fuel cell stack with two MEAs in series with a bipolar plate. The bipolar plate is in thermal and electrical contact with the MEAs, and its edge boundary is in thermal contact with the MIC, as seen in Figure 1(b). Also shown in the broken line region is the area of interest for the 1-D thermal model.

The parasitic heat in the fuel cell is a thermal flux that occurs at the surface of the bipolar plate (both sides - one side in contact with the cathode of one adjacent MEA, the other side in contact with the anode of the other adjacent MEA), and is modelled as a generation term inside the plate. That is, the close proximity of the exothermic reaction to the bipolar plate surface, coupled with the thermal conductivity of the plate being almost two orders of magnitude larger than the thermal conductivity of the membrane, minimizes the effect of any minor losses that may occur in utilizing this assumption. Hence the losses can be ignored.

Figure 1(c) shows the thermal influence the bipolar plate has on the MEAs, and the thermal path for the parasitic heat used in the model. Figure 2(a) therefore shows how the thermal energy in the MEAs is modelled as a surface flux on the bipolar plate, the bipolar plate being cooled by the MICs on the external edge.

This is the modelling approach that will be used. By controlling the temperature in the bipolar plate, the temperature in the MEAs (and fuel cell stack overall) can be maintained at a desirable level.

In this initial study, the thermal model will consider only the mechanisms of conduction heat transfer between the bipolar plate and the MEAs, and the boundary in thermal contact with the MICs. That is, no flowing gasses will be considered in the model. Therefore any cooling benefits that will occur due to introducing gasses at the ambient temperature (and almost always less than the operating temperature of the fuel cell) will be ignored. Future research will include the advantage of using this additional cooling available to the fuel cell stack. This will be addressed later in discussing the results of the model.

EQUATION DEVELOPMENT

The two-dimensional model for heat conduction in the internal cooling of other electrochemical battery systems has been developed elsewhere [14]. For this initial study using MICs for thermal management in PEM fuel cells, a simple one-dimensional thermal model is developed.

Figure 2(b) illustrates the configuration of the 1-D region of interest in the bipolar plate. At the centerline of the bipolar plate, x=0. At the edge in contact with the MICs, x=L. Therefore this represents the region being cooled by the MICs. Figure 3 shows the basic configuration used for the model, which will be discussed shortly.

FUEL CELL MODEL - The fuel cell voltage-current relationship used for the model is [16]

$$\begin{aligned} V = E &- (i+i_n)\bullet r \\ &- C\bullet \ln[(i+i_n)/i_o] \\ &+ B\bullet \ln[1-(i+i_n)/i_l], \end{aligned} \qquad (1)$$

where V is the output voltage of the fuel cell, i in mA/cm^2 is the current produced, E is the maximum voltage, typically based on the Gibbs free-energy change and calculated using $-\Delta g_f/2F$, F being the Faraday constant or the charge on one mole of electrons, and $-\Delta g_f$ is a function of temperature. For the temperature operating range of the fuel cell, the value of E would range from about 1.14 volts to 1.23 volts. Therefore, in the model, a constant value of 1.2 volts is used.

The other values are chosen as follows [17]: i_n is 2 mA/cm^2, r is 30×10^{-6} kΩ-cm^2, C is 0.06 volts, i_o is 0.067 mA/cm^2, B is 0.05 volts, and i_l is 1000 mA/cm^2. The values chosen for the parameters in Equation (1) are considered typical to account for the various losses associated with the output of the fuel cell. Figure 4 shows how the voltage varies with the current for Equation (1).

Some of the inherent losses in the fuel cell are quantified as follows: the term $(i+i_n)\bullet r$ are the ohmic losses due to electrical resistances of electrodes and the flow of ions in the membrane; $C\bullet \ln[(i+i_n)/i_o]$ are losses due to fuel cross-over at the cathode for H_2 fuel, internal currents or electron diffusion from anode to cathode through the membrane, and over activation or voltage losses caused by reaction rates at the electrodes influenced by cell temperature, electrode roughness, reactant concentration, etc.; $B\bullet \ln[1-(i+i_n)/i_l]$ are the losses due to mass transport of the reactants and concentration gradients of O_2 at the cathode, especially when air is the O_2 source, and H_2 depletion at the anode due to subsequent pressure losses in supply lines and ducts. Therefore the equation is considered a good representation of the voltage-current characteristics for a typical PEM fuel cell.

HEAT CONDUCTION MODEL - Since the primary focus of this study will be the one-dimensional model, the Fourier Law for heat conduction with internal heat generation is:

$$\partial^2 T/\partial x^2 + q''_{FC}/k_{bip}t_{bip} = 0, \qquad (2)$$

where T is the local temperature T(x), and k_{bip} and t_{bip} are the thermal conductivity and the thickness of the bipolar plate, respectively. For the cooling of the fuel cell, the generation term is:

$$q''_{FC} = (1/2\ Q''_{FC} + 1/2\ Q''_{FC}) = Q''_{FC}$$

where q''_{FC} is the heat addition on the surface of the bipolar plate, both sides, per unit length due to the exothermic reactions that take place in the MEAs. In the fuel cell, Q''_{FC} is waste heat generated in each MEA per unit area. For the model, 1/2 of Q''_{FC} is manifested as a unit surface flux on either side of the bipolar plate. Hence the bipolar plate will be the cold junction plate for the MIC and all the cooling (and parasitic heat removal) will take place in the bipolar plate. The one-dimensional, steady-state heat conduction equation is then solved in the bipolar plate.

For the fuel cell, the heat produced in the MEA is calculated using

$$Q''_{FC} = i\bullet(1.25 - V)$$

where the heat generated, Q''_{FC}, is in mW/cm^2, and i and V are from Equation (1). The 1.25 corresponds to the by-product H_2O in 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.

The heat generation takes place in the MEAs, which are in close thermal contact with the bipolar plates. In this model, the bipolar plate will be the thermal conduit used to remove the parasitic heat from the fuel cell's interior, with the maximum temperature in the cell at the bipolar plate centerline.

The boundary conditions for the 1-D case are the same as the 2-D case [18]. That is, the boundary at x=0 is an axis of symmetry and the TEG cold junctions are at T_c. Refer to Figure 3 again. The centerline for the region of cooling in the fuel cell bipolar plate is an axis of symmetry. Hence the boundary condition at the centerline is:

$$\text{at } x = 0: \qquad \partial T/\partial x\,|_{x=0} = 0. \qquad (3)$$

At the external edge of the bipolar plate where the cold junctions of the MIC are in thermal contact with the cold junction plate (bipolar plate), the boundary is maintained at temperature T_c, and the boundary condition is:

$$\text{at } x = L: \qquad T(L) = T_c. \qquad (4)$$

The solution for one-dimensional heat flow in the fuel cell bipolar plate is:

$$T(x) = [q''_{FC}L^2/k_{bip}t_{bip}][1-(x/L)^2] + T_c. \qquad (5)$$

Therefore the temperature distribution can be determined in the bipolar plate reflecting the general temperature profile in the fuel cell.

THERMOELECTRIC EQUATIONS - The cooling created by the solid state cooler, q_c, is the Seebeck cooling effect of the thermoelectric junction, which is also influenced by the ohmic heat generation in the TEG elements and the thermal conduction of heat from the hot to the cold junctions. Therefore the heat removed per cold junction is:

$$q_c = \alpha T_c I_{cool} - 1/2\, I_{cool}^2 R_{cool} - \kappa_c \Delta T, \qquad (6)$$

where

$$R_{cool} = (\rho_n \ell_n/A_n) + (\rho_p \ell_p/A_p),$$

and

$$\kappa_c = (\lambda_n A_n/\ell_n) + (\lambda_p A_p/\ell_p).$$

The parameters of the p- and n-type TEG materials are the combined Seebeck coefficients, α_p and α_n, of the two materials, $\alpha = |\alpha_p| + |\alpha_n|$; the thermal conductivities, λ_p, λ_n; and the electrical resistivities, ρ_p, ρ_n. The geometries of the TEG elements are the lengths of the elements ℓ_p, ℓ_n and the areas A_p and A_n. Also, I_{cool} is the current required for cooling at the TEG junction, and $\Delta T=(T_h-T_c)$, where T_h is the temperature of the hot junction.

The voltage required by the MICs is

$$V_{cool} = \alpha\Delta T + I_{cool}R_{cool}.$$

Therefore the power utilized by the MICs, $P_{cool}= V_{cool}I_{cool}$, becomes

$$P_{cool} = \alpha\Delta T I_{cool} + I_{cool}^2 R_{cool}.$$

For a single-cell model where the potential of the one cell is not great enough to drive the MICs, power consumption by the MICs is not a valid comparison.

However, when the single cells are combined to increase the output potential of the fuel stack, the current requirement of the MICs per cell remains the same, and is a good indication of the energy needed for their operation.

That is, the parasitic load of the cooler on the power output of the fuel cell can be established by considering the current requirements to drive the MICs. The power output of the fuel cell with no MICs is $P_{noMIC} = V \bullet I_{fc}$, where I_{fc} is the total current produced by the cell; and the output with the MICs is $P_{MICs} = V \bullet [I_{fc} - I_{cool}]$. Therefore the percent reduction in power output of the cell can be calculated with the expression $\{[P_{noMIC}-P_{MICs}]/P_{noMIC}\}\bullet 100\%$, or, simplifying, as

$$\%\ \text{Power loss} = [I_{cool}/I_{fc}]\bullet 100\%.$$

Hence the reduced current output of the fuel cell due to MIC current usage can be utilized as a barometer to quantify the demand on the cell for the cooling load, and used as a comparison with other types of auxiliary equipment needed for cooling and/or humidification.

In MIC development, the figure of merit is utilized to optimize the p- and n-type material geometries for the electrical and thermal properties of the thermoelectric generating elements [19]. Therefore, for the MIC thermoelectric junction design, an area ratio is selected such that

$$A_n/A_p = [\rho_n\lambda_p/\rho_p\lambda_n]^{1/2}$$

and

$$\ell_p = \ell_n.$$

The MIC combines a series of the TEG junctions to produce the required cooling on the bipolar plate. Over the past several years, the MICs have reached proportions in the micron range [20]. These dimensions and the application to the external edge of the bipolar plate make the MICs ideal for use in fuel cell cooling. For the model, 100 junctions are needed, the MICs remaining in the millimeter range. In this preliminary investigation, the hot junction temperature, T_h, is chosen as 310K for an ambient air temperature of 300K. The TEG elements are bismuth telluride, 0.025cm high.

THERMAL MODEL WITH NO MIC COOLING

The one-dimensional thermal cooling model is compared to the fuel cell bipolar plate centerline temperature without the MIC cooling present. The bipolar plate is then cooled solely by forced convection over the plate's edge. No augmentation is considered for the model comparison.

The 1-D equation to be solved is the same as Equation (2). The new boundary conditions for the bipolar plate become:

$\partial T/\partial x|_{x=0}$: $\partial T/\partial x=0$

and

$\partial T/\partial x|_{x=L}$:

$$-k_{bip}\partial T/\partial x|_{x=L}=h_{conv}(T|_{x=L}-T_{amb}),$$

where h_{conv} is the convective heat transfer coefficient of the moving fluid at the edge of the bipolar plate and T_{amb} is the local temperature of the cooling fluid. Therefore the centerline of the bipolar plate is still an axis of symmetry, and the edge is now exposed to a cooling fluid.

The solution to the temperature distribution in the bipolar plate becomes

$$T(x)=(q''_{FC}L/t_{bip})\{(L/k_{bip})[1-(x/L)^2]+[2/h_{conv}]\}+T_{amb}. \quad (7)$$

This provides the centerline temperature (at x=0) of the bipolar plate when the edge of the plate is cooled by forced convection.

METHOD OF SOLUTION

The primary goal of the MIC cooling is to maintain the internal temperature of the fuel cell (the centerline of the bipolar plate) between a temperature range of 50C to 60C as the fuel cell produces electric power over the full gamut of power output. For the model, fuel cell output is 50 mA/cm^2 to 900 mA/cm^2, corresponding to a voltage output of 0.797 volts to 0.488 volts, respectively.

A simple iteration is used to minimize the current input to the MIC while at the same time not allowing the centerline temperature of the bipolar plate to exceed 60C. Initially, at low cell power output, the heat generated precludes the need for MIC cooling. Therefore the current input to the cooler, I_{cool}, is zero. When the centerline temperature of the bipolar plate approaches the 60C upper limit, the MIC cooling is initiated. This temperature is about 53C.

For the model, a graphite bipolar plate is used with k_{bip}=2.1W/cm-K, t_{bip}=0.1cm, and L=4.0cm.

RESULTS

The results of the cooling model are shown in Figure 5, where the bipolar plate centerline temperature, T_{CL}, is shown with and without the MIC operating. With no MIC cooling, the centerline temperature of the bipolar plate quickly approaches unacceptable levels, even with excessive convective cooling at the bipolar plate boundary. Heat transfer augmentation is not considered at the edge of the bipolar plate in contact with the ambient fluid because auxiliary equipment is still necessary to operate the cell under normal conditions.

However, with the MICs cooling, when T_{CL} approaches the upper limit of 333K at around 250mA/cm^2, the coolers are turned on and the cell temperature remains in the acceptable range up to the full power output.

Also shown on the figure is the cold junction temperature, T_c, of the MICs, which corresponds to the temperature of the external edge of the bipolar plate. The ramifications of this temperature will be discussed shortly.

Figure 6 shows the amount of fuel cell current output required to cool the cell, both in amps and as a percentage of total cell current output. At full power output of the cell, less than 13% of the useful energy is required to maintain the centerline temperature of the bipolar plate (hence the cell), at the desired level. This corresponds to less than 1/2 amp to cool the cell. Therefore replacing much of the other auxiliary equipment used to maintain membrane moisture will utilize about 13% of the cell output at maximum output to use the MICs.

Figure 7 has been included to show the temperature distribution in the bipolar plate for three different current fluxes of the fuel cell. At 100mA/cm^2, there is no MIC cooling requirement and the bipolar plate centerline temperature stays well within the design limits. For the 400mA/cm^2 and 800mA/cm^2 current outputs of the cell, MIC cooling is required and the bipolar plate again remains within the design limits.

DISCUSSION

In this preliminary investigation with the simple 1-D model, the MICs have successfully reduced the centerline temperature of the bipolar plate without utilizing an undue amount of usable fuel cell electrical output. In fact, the energy utilized by the MICs is slightly higher than the level currently used by auxiliary equipment. However, the volume, mass and complexity of the MICs are considerably less than those of the other auxiliary equipment needed to accomplish the same goals.

Also, once the benefits of the feed gas cooling are added to the model, energy requirements to cool the cell should be reduced significantly, and the same performance may be achieved with far less equipment.

Diametrically opposed to the cooling benefits of the feed gas streams is another effect which must be addressed in the two-dimensional model when the effects of these gas flows are included.

The temperature of the bipolar plate at x=L shown in Figure 7 for the case of $i = 800 mA/cm^2$ is well below the desired level of 325K for the fuel cell to operate. This temperature would reduce reaction rates to an unacceptable level in the cell, reducing performance considerably.

This is the point in the thermal model that is being developed at which the "warming" effect of the feed gasses will be needed. Currently the model is being improved to utilize this thermal energy to offset the overcooling caused by the MICs. A heating scheme is being considered where the hot junctions of the MICs can be used to raise the temperature of the feed gasses slightly above ambient to take full advantage of the available thermal energy produced in the fuel cell.

Hence two opposing phenomena will be addressed in the next generation of the thermal model. In fact a slightly altered MIC scheme is being considered to take advantage of both these effects. Therefore the temperature gradients the model currently predicts across the bipolar plate will be reduced significantly, and any problems that may be envisioned due to their existence will be eliminated.

At this juncture in the development of the model, no presumptions are being made for removal of the parasitic heat from under the hood of the vehicle. Without considering the flow of feed gasses through the cells, and the influences they will have on the stack temperature, it is too early to determine any scheme that will benefit the operation of the fuel stack with the MICs, hence the 310K hot junction temperature is considered reasonable. However, systems utilizing both liquid and air cooled MIC hot junctions are being considered in future development of the model.

CONCLUSIONS

This preliminary study shows the promise of keeping the fuel cell stack within the temperature confines of 45C to 60C, utilizing solid state MICs and averting the necessity for humidification or other complicated equipment or cooling systems. The energy requirements needed to cool the fuel cell are well within the limits required for other auxiliary equipment currently used in fuel cell designs.

Future work will focus on a two-dimensional model that will include the benefits of the feed gasses to redirect some of the parasitic thermal heat in the fuel cell, while at the same time requiring less of the fuel cell power output to drive the MICs.

DEDICATION

The authors dedicate this 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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CONTACT

R.J. Parise, President, PARISE RESEARCH TECHNOLOGIES, 101 Wendover Road, Suffield, CT 06078

NOMENCLATURE

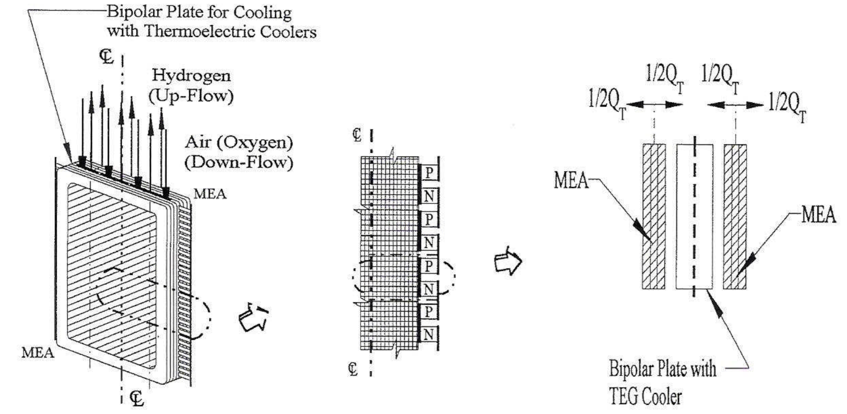
A	TEG element area, cm^2
B	V-I equation constant, volts
C	V-I equation constant, volts
E	max fuel cell voltage, volts
F	Faraday constant, coulombs/mole
Δg_f	Gibbs free-energy, kJ/mole
h_{conv}	bipolar plate edge convective heat transfer coefficient, W/cm^2-K
i	current flux or parameter, mA/cm^2
I	current, amps
k	thermal conductivity, W/cm-K
ℓ	TEG element length, cm
L	bipolar plate length, cm
P	power, Watts
P_{MICs}	fuel cell power with MICs, Watts
P_{noMIC}	fuel cell power no MICs, Watts
q_c	cooling by MICs, Watts
q''_{FC}	heat to bipolar plate, mW/cm^2
Q''_{FC}	heat generated in MEA, mW/cm^2
r	V-I equation parameter, kΩ-cm^2
R	electrical resistance, ohm
t	thickness, cm
T	temperature, K
V	fuel cell voltage, volts
V_{cool}	MIC voltage, volts
x	independent variable, cm

GREEK

α	Seebeck coefficient single material, or combined materials, $\lvert\alpha_p\rvert+\lvert\alpha_n\rvert$, volts/K
λ	TEG thermal conductivity, W/cm-K
κ_c	MIC thermal conductance, W/K
ρ	TEG electrical resistivity, ohm-cm

SUBSCRIPTS

amb	local ambient condition
bip	bipolar plate
c	cold junction or bipolar plate-MIC interface
CL	bipolar plate centerline at x=0
cool	cooler
fc	fuel cell
FC	fuel cell
h	TEG hot junction temp
I	V-I equation parameter
n	n-type TEG material, or V-I equation parameter
o	V-I equation parameter
p	p-type TEG material



1(a)
Bipolar Plate with Standard
MEAs Configuration.

1(b)
Section of Bipolar Plate Showing
1-D Model Location

1(c)
End View of Cooled Section

Figure 1: Shows MIC Location on Bipolar Plate and Thermal Model Region.

FCFIG1D1.CAD

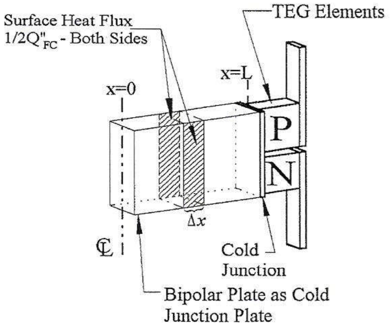


Figure 2(a): TEG Junction Details with Bipolar Plate.

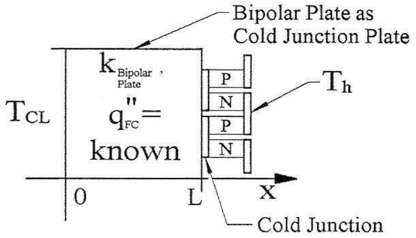


Figure 2(b): Thermal Model Configuration Showing MIC and Bipolar Plate.

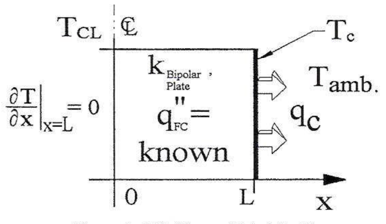


Figure 3: 1-D Thermal Model with Boundary Conditions.

FCFIG1D2.CAD

Parise

FCSAE1D0.CAD

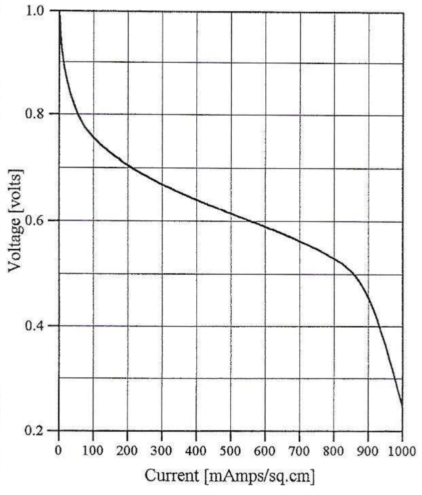


Figure 4: Fuel Cell Voltage-Current Output

FCFIG1D3.CAD
fromFCV-IOUT

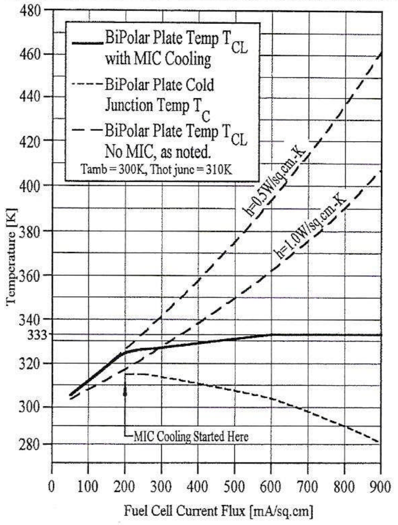


Figure 5: Bipolar Plate Centerline Temperature with MIC Cooling and Load Requirements, and Bipolar Plate Centerline Temperature with No MIC Cooling.

FCFIG1D5.CAD

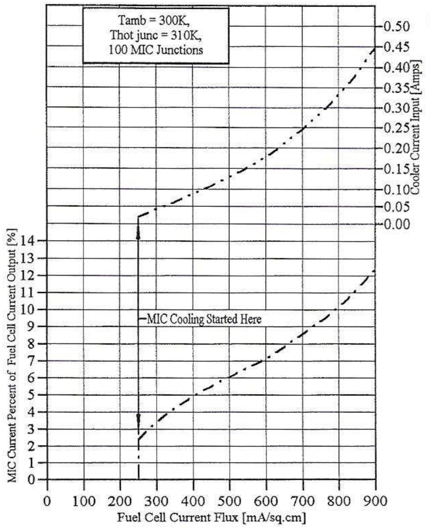


Figure 6: MIC Energy Input [Amps] and % Fuel Cell Output to Cool Cell Interior.

FCFIG1D4.CAD

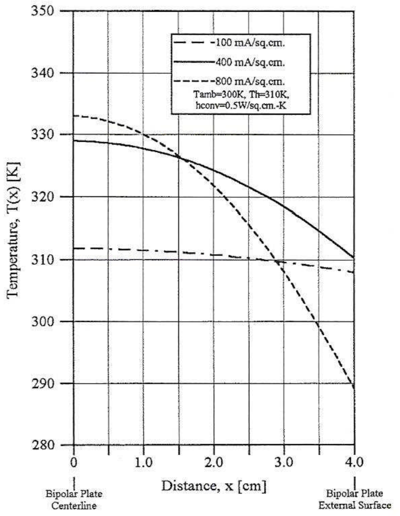


Figure 7: Temp Distribution in Bipolar Plate

FCFIG1D6.CAD

Parise

FCSAE1D1.CAD