Advanced Fuel Cell System Thermal Management for NASA Exploration Missions

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Abstract

The NASA Glenn Research Center is developing advanced passive thermal management technology to reduce the mass and improve the reliability of space fuel cell systems for the NASA exploration program. An analysis of a state of the art fuel cell cooling systems was done to benchmark the portion of a fuel cell system's mass that is dedicated to thermal management. Additional analysis was done to determine the key performance targets of the advanced passive thermal management technology that would substantially reduce fuel cell system mass.

Introduction

The purpose of this study was to analyze a single passive cooling plate that would absorb the heat from adjacent fuel cells within a fuel cell stack system. The results of this analysis was to provide insight into the requirements of a cooling plate in terms of its thermal conductivity, thickness, and specific gravity that would result in a passive cooling system for a fuel cell stack that would provide the essential uniform thermal sink while having lower mass.

Background

The heart of a fuel cell is an electrochemical "cell" that combines a fuel and an oxidizing agent, and converts the chemical energy directly into electrical power, water and waste heat. The fuel cells used by NASA are hydrogen-oxygen fuel cells. The fuel cells likely to be used by NASA in the future are acid-based Proton Exchange Membrane (PEM) hydrogen-oxygen fuel cells. An illustration of this type of cell is shown in figure 1. A hydrogen molecule reacts at the anode to create a pair of protons and electrons. The proton ion exchange membrane conducts the protons which were generated at the anode from the anode to the cathode. The electrons which were also generated at the anode are conducted through the electrical load that is connected to the fuel cell and also reach the cathode. The hydrogen protons and the electrons are reacted at the cathode with an oxygen atom to produce a molecule of water. An illustration of a "stack" of cells connected electrically in series (shown in fig. 1) is usually employed in applications. The energy released as a result of this reaction is called the enthalpy of formation. When the product formed is liquid water (as opposed to water vapor), the enthalpy of formation is also referred to as the Higher Heating Value (HHV) of hydrogen. When the product formed is water vapor, the enthalpy of formation is referred to as the Lower Heating Value (LHV) of hydrogen. When the reaction occurs at 298 K the energy released is called the standard enthalpy of formation. The negative sign associated with the Gibbs free energy indicates that this reaction is spontaneous. Not all of this change in enthalpy is available for the generation of electricity. The maximum amount of energy available for the generation of
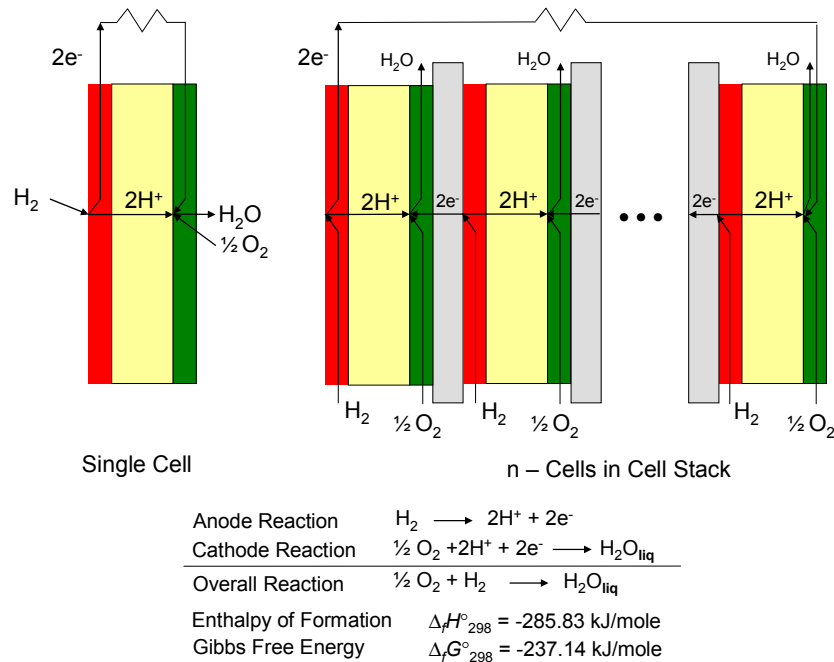
Figure 1.—Proton Exchange Membrane Fuel Cell.

electricity is the change in Gibbs free energy which is the difference between the enthalpy of formation and the energy losses associated with the change in entropy. This is described in mathematical terms as

$$\Delta G = \Delta H - T\Delta S \tag{1}$$

where
ΔG change in Gibbs free energy, kJ/mole of water formed
ΔH enthalpy of formation, kJ/mole mole of water formed
T reaction temperature, K
ΔS change in entropy, kJ/K/mole of water formed

Table 1 shows tabulated values for the change in Gibbs free energy and the enthalpy of formation of liquid water at one atmosphere of pressure as a function of temperature.

TABLE 1.—THERMODYNAMIC PROPERTIES
OF LIQUID WATER (REF. 1)

Temperature, K	ΔG, kJ/mole	ΔH, kJ/mole	$T\Delta S$, kJ/mole
298.15	−237.141	−285.830	−48.689
373.21	−225.160	−283.454	−58.294

It should be noted that the ΔH changes very little (less than 1 percent change) from room temperature to the boiling point of water; also the ΔS is negative because the entropy of the two reactant gases is greater than the product water. The reduction in entropy means there must be waste heat generated in the reaction that is released into the ambient environment (i.e. the ambient environment's entropy increases), moreover the amount of waste heat per mole increases with increasing temperature.

The Gibbs free energy, ΔG is related to the fuel cell voltage by the equation

$$\Delta G = -nFE_{rev}(0.001 \text{ kJ/W-sec})$$ (2)

where
n   number of electrons per mole of water formed (2 moles of electrons per mole of water formed)
F   Faraday's constant (96,487 A-sec/mole of electrons)
E_{rev} reversible cell voltage, Volt

Similarly, an equation can relate the enthalpy of formation, ΔH, to a hypothetical, thermal neutral voltage.

$$\Delta H = -nFE_{therm}(0.001 \text{ kJ/W-sec})$$ (3)

where
E_{therm} thermal neutral cell voltage, Volt

The calculation of the reversible cell voltage and the thermal neutral cell voltage based on the thermodynamic data contained in table 1 is shown in table 2.

TABLE 2.—REVERSIBLE CELL VOLTAGE AND
THERMAL NEUTRAL CELL VOLTAGE

Temperature, K	ΔG, kJ/mole	ΔH, kJ/mole	E_{rev}, V	E_{therm}, V
298.15	−237.141	−285.830	1.229	1.481
373.21	−225.160	−283.454	1.167	1.469

Both the reversible cell voltage and the thermal neutral cell voltage are commonly used. It is useful to compare the actual fuel cell voltage to the reversible cell voltage which represents the maximum fuel cell voltage obtainable. The thermal neutral voltage is hypothetical because as earlier stated, not all of the energy from the change in enthalpy is available to do useful work (i.e., produce a voltage). The thermal neutral voltage is useful for calculating the thermal efficiency of the fuel cell process and the waste heat generated by a fuel cell.

Several efficiencies can be calculated. A maximum theoretical energy efficiency can be calculated

$$\eta_t = \frac{\Delta G}{\Delta H} = \frac{E_{rev}}{E_{therm}}$$ (4)

where
η_t maximum theoretical energy efficiency

Using values from table 2, it can be shown that the maximum theoretical energy efficiency of a fuel cell is about 83 percent at 298 K and falls to about 79 percent at 373 K. An actual energy efficiency can be calculated

$$\eta_a = \frac{W_a}{\Delta H} = \frac{I_a E_a}{I_f E_{therm}}$$ (5)

where

η_a actual energy efficiency
W_a actual electrical energy produced, kJ/mole
I_a actual fuel cell output current, Ampere
I_f theoretical fuel cell output current, Ampere
E_a actual fuel cell voltage, Volt

It is often useful to evaluate a fuel cell's voltage performance with what is theoretically possible. A voltage efficiency can be calculated

$$\eta_v = \frac{E_a}{E_{rev}} \tag{6}$$

where

η_v voltage efficiency

Similarly, it is useful to evaluate a fuel cell's current performance with what is theoretically possible. A current efficiency can be calculated.

$$\eta_i = \frac{I_a}{I_f} \tag{7}$$

where

η_i current efficiency

Equations (4), (6), and (7) can be substituted into equation (5) to yield,

$$\eta_a = \eta_i \eta_v \eta_t \tag{8}$$

To analyze the thermal management, a convenient calculation of the heat generated by a fuel cell is needed. Since all the energy that is not converted to electrical energy is dissipated as heat, the heat generated by a fuel cell can be calculated as,

$$Q = (\Delta H - W_a)\dot{m}_{H_2O}(1000 \text{ W - sec/kJ}) \tag{9}$$

where

Q   waste heat generated by the fuel cell, Watt
$\dot{m}_{H_2O}$ fuel consumption, moles of water produced per second

Substituting equations (3) and (5) into equation (9) and simplifying,

$$Q = \left(-nFE_{Therm} + nF\left(\frac{I_a}{I_f}\right)E_a\right)\dot{m}_{H_2O} \tag{10}$$

The fuel consumption is related to the theoretical fuel cell output current as shown in equation (11).

$$\dot{m}_{H_2O} = \frac{I_f}{nF} \tag{11}$$

Substituting equations (11) into equation (10) and simplifying,

$$Q = \left(-I_f E_{Therm} + I_a E_a\right) \tag{12}$$

Typically the actual fuel cell output current is approximately equal to the theoretical fuel cell output current. Assuming the two quantities are equal to each other, equation (12) can be further simplified to,

$$Q = I_f\left(-E_{Therm} + E_a\right) \tag{13}$$

Taking equation (13) and dividing by the active area of the fuel cell

$$\frac{Q}{A} = \frac{I_f}{A}\left(-E_{Therm} + E_a\right) = q = i_f\left(-E_{Therm} + E_a\right) \tag{14}$$

where
q   fuel cell waste heat density, W/cm^2
i_f theoretical fuel cell output current density, mA/cm^2
A   Total active area of the fuel cell stack, m^2
A_{cell} Active area of a single cell in the fuel cell stack, m^2

Figure 2 plots the fuel cell heat generation density (the heat generated per unit of cell area) versus the fuel cell output current density (ref. 2). NASA's fuel cell applications typically optimize in the lower current density range ($\leq$400 mA/cm^2), so the heat generation expected from NASA's fuel cells is generally $\leq$0.3 W/cm^2.
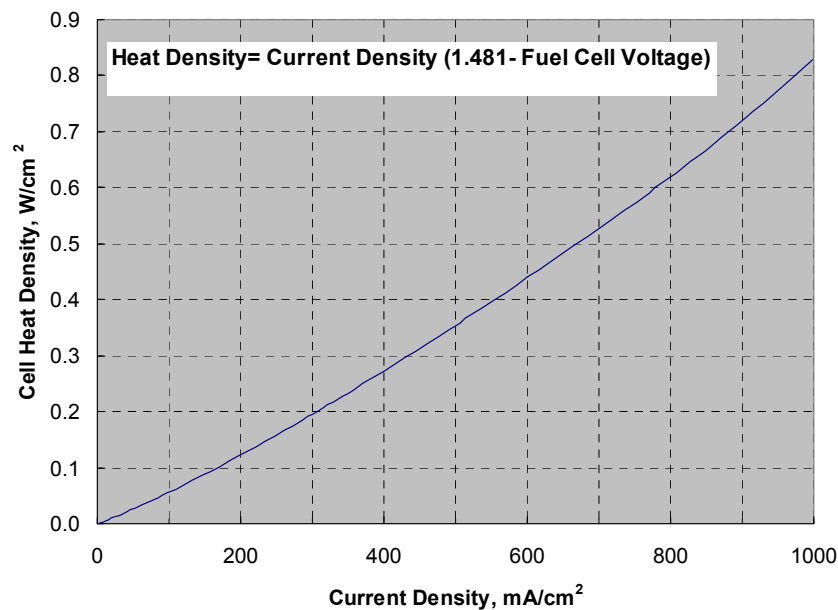

Figure 2.—Fuel cell heat generation, A/cm^2.

Fuel Cell Active Area Cooling Analysis

An analytical model of a typical fuel cell cooling plate is shown in figure 3. Heat is absorbed from the fuel cells on either side of the cooling plate. Typically a liquid coolant is circulated within the plate and heat is removed convectively as the coolant passes through plate and out of the fuel cell stack. A passive cooling plate must conduct the heat within the plane of the plate out to one or more of the edges of the plate so that the heat can be transferred to a heat sink external to the fuel cell stack. Figure 4 shows the difference between a conventional fuel cell thermal management system and a passive fuel cell thermal management system. The benefits of the passive approach are reductions in mass, system complexity, and parasitic power as well as improvements in system reliability.
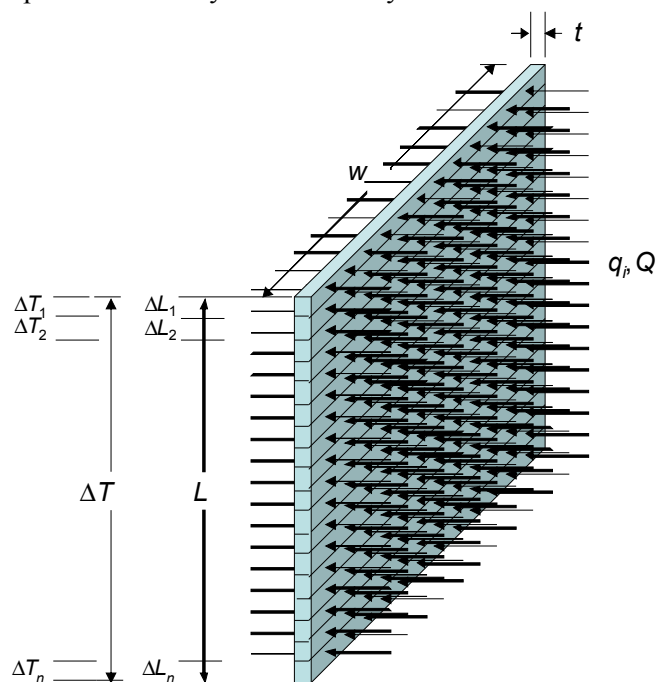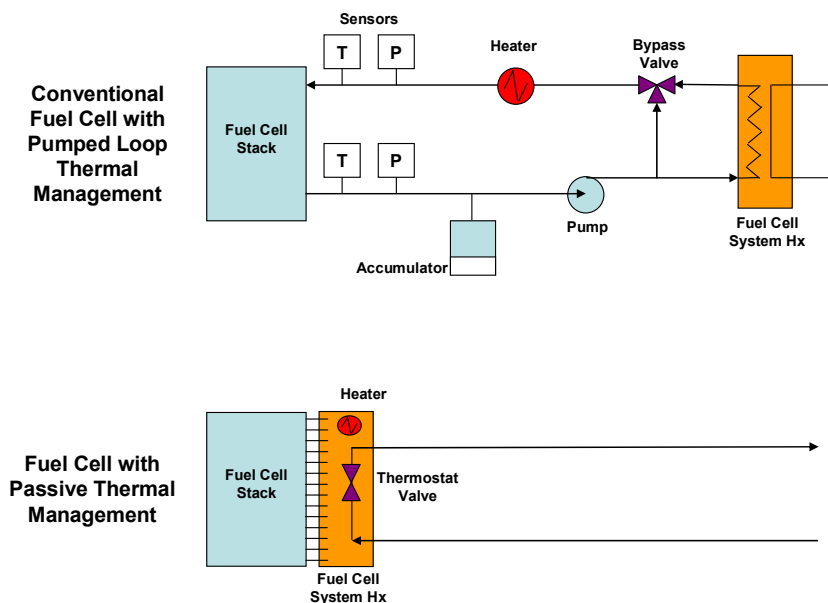
Figure 3.—Fuel cell cooling plate model.

Figure 4.—Fuel Cell Thermal Management Systems.

The key to making the passive approach workable is making the cooling plates light enough yet highly thermally conductive so that the heat can be effectively removed and also provide each cell in the fuel cell stack a thermally uniform heat sink. Analytical expressions are needed to relate the thermal performance of a passive cooling plate to its physical characteristics. In this analysis the cooling plate is modeled as a series of small planar elements stacked edge to edge. The total amount of heat entering the first, top-most plate (from both sides) is

$$\Delta Q_1 = q_1 \Delta A_1 \tag{15}$$

where
ΔQ_1 heat transferred through the 1st planar element, Watt
q_1 heat density absorbed by the 1st planar element, W/cm^2
ΔA_1 surface area of the 1st planar element, cm^2

The heat absorbed by the first planar element must be conducted to the next lower plate. This heat can be approximated as

$$\Delta Q_1 = \frac{(ktw\Delta T_1)}{\Delta L_1} \tag{16}$$

where
k   thermal Conductivity of the planar material, W/m/K
t   thickness of the planar material, cm
w   width of the planar elements, cm
ΔT_1 in-plane temperature differential of the 1st planar element, K
ΔL_1 length of the 1st planar element, cm

Equating ΔQ_1 from equation (15) with ΔQ_1 from equation (16) yields,

$$\frac{(ktw\Delta T_1)}{\Delta L_1} = q_1 \Delta A_1 \tag{17}$$

Solving for ΔT_1

$$\Delta T_1 = \frac{(q_1 \Delta A_1)\Delta L_1}{ktw} \tag{18}$$

A similar expression can be written for ΔT_2, ΔT_3, and ΔT_N. Assuming $\Delta L_1 = \Delta L_2 = \Delta L_3 = \Delta L_N = \Delta L$, and $\Delta A_1 = \Delta A_2 = \Delta A_3 = \Delta A_N = \Delta A$

$$\Delta T_2 = \frac{(q_1 \Delta A + q_2 \Delta A)\Delta L}{ktw} \tag{19}$$

$$\Delta T_3 = \frac{(q_1 \Delta A + q_2 \Delta A + q_3 \Delta A)\Delta L}{ktw} \tag{20}$$

$$\Delta T_N = \frac{(q_1 \Delta A + q_2 \Delta A + q_3 \Delta A + \cdots + q_N \Delta A)\Delta L}{ktw} \tag{21}$$

where

ΔT_2	in-plane temperature differential of the 2nd planar element, K
ΔT_3	in-plane temperature differential of the 3rd planar element, K
ΔT_N	in-plane temperature differential of the Nth planar element, K
q_2	heat density absorbed by the 2nd planar element, W/cm^2
q_3	heat density absorbed by the 3rd planar element, W/cm^2
q_N	heat density absorbed by the Nth planar element, W/cm^2

Assuming that the heat density absorbed by all the planar elements is uniform,

$$q_1 = q_2 = q_3 = \cdots = q_N = q \tag{22}$$

If equations (19), (20), (21) and all such similar expressions for the temperature differentials of all the individual planar elements ΔT_1 through ΔT_N are added together and factoring out the common factors of q, ΔA, and ΔL

$$\sum_1^N \Delta T_i = \frac{\left(N + (N-1) + (N-2) + \cdots + 1\right)q\Delta A\Delta L}{ktw} \tag{23}$$

It can be recognized that

$$\sum_1^N \Delta T_i = \Delta T \tag{24}$$

$$\Delta A = \Delta Lw \tag{25}$$

$$\Delta L = \frac{L}{N} \tag{26}$$

where

ΔT	total in-plane temperature differential across the cooling plate, K
L	total length of the cooling plate, cm
N	total number of planar elements

Substituting equations (24), (25), and (26) into equation (23)

$$\Delta T = \frac{\left(N + (N-1) + (N-2) + \cdots + 1\right)qL^2}{N^2 kt} \tag{27}$$

Lastly, the infinite series shown in equation (26) can be rewritten as

$$N + (N-1) + (N-2) + \cdots + 1 = \frac{N(N-1)}{2} \tag{28}$$

Substituting equation (28) into equation (27) yields

$$\Delta T = \frac{(N(N-1))qL^2}{2N^2kt} \qquad (29)$$

As N→∞, equation (29) can be rewritten as

$$\Delta T = \frac{qL^2}{2kt} \qquad (30)$$

For fuel cell applications it is ideal to have $\Delta T=0$, but practically speaking, a $\Delta T\leq 3$ °C is acceptable. The reasons are two-fold, first, the fuel cell chemical process kinetics are temperature sensitive. Nonuniformity in the temperature of the fuel cell electrodes means some areas of the electrodes are going to be more active than other areas on the fuel cell electrodes. The second reason is that the water movement within the fuel cell is affected by local variations in the water vapor pressure (which is a function of the water temperature).

The fuel cell heat loads expected from NASA applications is ≤ 0.3 W/cm^2. The heat loads of fuel cells vary depending on their operating current density, but generally speaking these heat loads are small when compared with microelectronics heat loads which can exceed 100 W/cm^2. NASA's fuel cell applications generally optimize at low current densities because the high voltage efficiency that results from operating at low current densities minimizes fuel consumption and overall spacecraft mass. Using the constraints on ΔT and q, a relationship between L, k and t is plotted in figure 5.

Figure 5 shows that for even small fuel cells, where the heat transmission distance is 5 cm or less the conductivity requirements are high. While the thermal conductivity requirements are reduced for thicker plates, thicker plates rapidly increase the mass of the fuel cell stack. The values of the cooling plate thicknesses that are plotted are representative of the cooling compartments currently in fuel cell stacks. Figure 5 shows that copper which has a thermal conductivity of 400 W/m/K would be adequate only for heat transmission distances of 4 cm or less unless cooling plates ≥ 2 mm were used. Diamond, which has a thermal conductivity of 2300 W/m/K, is the most thermally conductive material known, and it would be adequate for heat transmission distances up to about 8 cm. Considering these material constraints, it is understandable why passive thermal systems for fuel cells have not been developed.

Aside from providing a uniform thermal environment for the fuel cell, it is also important that the mass of the cooling system be minimized. A metric used to evaluate the mass properties of a fuel cell system's cooling subsystem is to calculate the ratio of the waste heat handled by the cooling system to the mass of the cooling system components. For a typical liquid-cooled fuel cell system, the mass includes
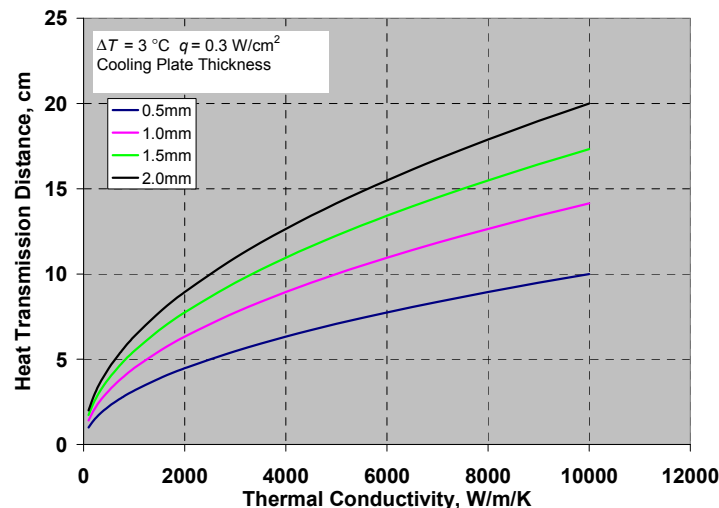
Figure 5.—Cooling plate heat transmission distance, thermal conductivity, and thickness.

the cooling cells within the cell stack as well as the cooling system components outside the cell stack (e.g., tubing, fittings, coolant, sensors, accumulator, etc.). This ratio should be calculated at the maximum heat dissipation since it is the maximum heat dissipation which sizes the cooling system. A cooling system mass metric of 556 W/kg was calculated for a fuel cell system tested at the NASA Glenn Research Center. As a goal for an advanced passive thermal management system a cooling system mass metric of 1000 W/kg was selected. This metric can be incorporated into equation (30) in the following manner.

The fuel cell waste heat density, q can be thought of as the fuel cell waste heat per cell applied to the cooling plate divided by the planar area of the cooling plate. Using the active area of a single cell in the fuel cell stack as the planar area of the cooling plate,

$$q = \frac{Q_{plate}}{A_{cell}}$$

(31)

where
Q_{plate} Fuel cell waste heat per cell absorbed by a single cooling plate, watt
A_{cell} Active area of a single cell in the fuel cell stack, m^2

Substituting equation (31) into equation (30) results in

$$\Delta T = \frac{Q_{plate}L^2}{2kA_{cell}t}$$

(32)

Recognizing that the area times the thickness of the plate is the plate volume, equation (32) can be rewritten as

$$\Delta T = \frac{Q_{plate}L^2}{2kV}$$

(33)

where
V   total volume of the cooling plate, cm^3

The mass of the cooling plate is related to the volume of the cooling plate if an assumption of uniform mass density is made.

$$\rho = \frac{M}{V}$$

(34)

Solving equation (34) for plate volume and substituting this into equation (33) results in

$$\Delta T = \frac{QL^2\rho}{2kM}$$

(35)

Recognizing the ratio of Q/M as the cooling system mass metric

$$\Delta T = \left(\frac{Q}{M}\right)\frac{L^2\rho}{2k}$$
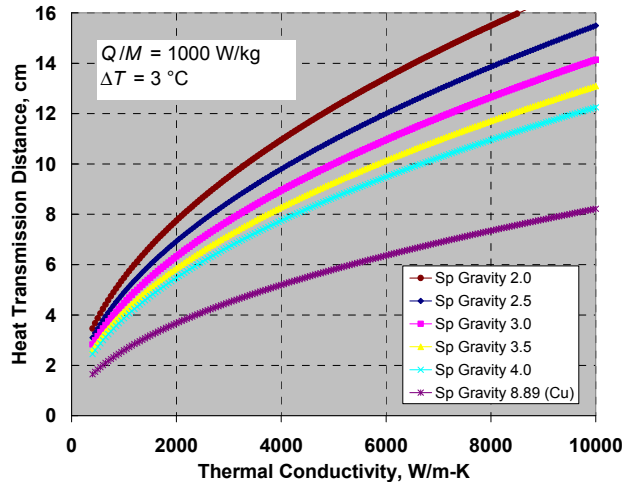
(36)

Figure 6.—Cooling plate heat transmission distance,
thermal conductivity, and plate specific gravity.

Using the 1000 W/kg as the value of the metric, and 3 °C as the ΔT, a relationship between L, ρ, and the average density of the cooling plate is plotted in figure 6.

Figure 6 shows that metals such as copper (specific gravity of 8.89 and thermal conductivity of 400 W/m/K) and aluminum (specific gravity of 2.7 and thermal conductivity of 180 W/m/K) which are used in cooling applications in general, are clearly unsuitable for fuel cell cooling except for very small fuel cells. Table 4 lists alternative high thermally conductive materials (ref. 3). These alternative materials are all carbon based: diamond, diamond composites, pyrolytic graphite, and graphite composites. Highly Oriented Pyrolytic Graphite (HOPG) has the best combination of high thermal conductivity and low specific gravity. HOPG appears to meet the criteria if the heat transmission distance is less than 7 centimeters.

TABLE 4.—ALTERNATE PASSIVE COOLING PLATE MATERIALS (REF. 3)

Material	Thermal conductivity, W/m-K	Specific gravity, g/cm^3
CVD diamond	1100–1800	3.5
HOPG*	1500–1700	2.3
Natural graphite	500	-------
Cont. CF/Cu*	400–420	5.3–8.2
Carbon/carbon*	400 (690)	1.9
Gr flake/Al*	400–600	2.3
Diamond/Cu	600–1200	5.9
Diamond/Al	550–600	3.1

In addition to these materials, heat pipes, which use phase changes to absorb and reject heat are capable of extremely high effective thermal conductivities, and also are candidates for passive cooling plates. Heat pipes are probably the only candidate capable of passively moving the heat for large fuel cells (transmission distances of ≥10 cm).

Conclusions

This analysis of a passive approach to fuel cell thermal management leads to the following conclusions:

1. Passive cooling can be done, but in general, it requires either low heat transmission distances (≤10 cm), very high thermal conductivity (≥1000 W-m/K), or very thick cooling plates. Making thick cooling plates is counter to NASA's goal of reducing the fuel cell stack mass.

2. There are alternative materials whose thermal conductivity is high enough to move the heat ≤10 cm. These materials are diamond, diamond composites or HOPG. Heat pipes are also a potential alternative, and probably the only viable approach for passive heat removal in large fuel cells.

3. The mass of a passive fuel cell thermal management system is potentially about half of that of a conventional fuel cell cooling system.

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2. Calculated from data taken from Kenneth A. Burke, "Small portable PEM Fuel Cell Systems for NASA Exploration Missions", NASA/TM—2005-213994, AIAA–2005–5680 December 2005.
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Appendix—Symbols

A	total active area of the cooling plate, cm^2
A_{cell}	active area of a single cell in the fuel cell stack, m^2
E_a	actual fuel cell voltage, Volt
E_{rev}	reversible cell voltage, Volt
E_{therm}	thermal neutral cell voltage, Volt
F	Faraday's constant (96,487 A-sec/mole of electrons)
I_a	actual fuel cell output current, Ampere
I_f	theoretical fuel cell output current, Ampere
L	total length of the cooling plate, cm
N	total number of planar elements
Q	Waste heat generated by the fuel cell, Watts
Q_{plate}	Fuel cell waste heat per cell absorbed by a single cooling plate, Watts
$\Delta Q1$	Heat transferred through the 1st planar element, Watts
T	reaction temperature, K
V	total volume of the cooling plate, cm^3
W_a	actual electrical energy produced, kJ/mole
i_f	theoretical fuel cell output current density, mA/cm^2
k	thermal Conductivity of the planar material, W/m/K
$\dot{m}_{H_2O}$	fuel consumption, moles of water produced per second
n	number of electrons per mole of water formed (2 moles of electrons per mole of water formed)
q	fuel cell waste heat density, W/cm^2
q_1	heat density absorbed by the 1st planar element, W/cm^2
q_2	heat density absorbed by the 2nd planar element, W/cm^2
q_3	heat density absorbed by the 3rd planar element, W/cm^2
q_n	heat density absorbed by the nth planar element, W/cm^2
t	thickness of the planar material, cm
w	width of the planar elements, cm
ΔA_1	surface area of the 1st planar element, cm^2
ΔA_2	surface area of the 2nd planar element, cm^2
ΔA_3	surface area of the 3rd planar element, cm^2
ΔA_n	surface area of the nth planar element, cm^2
ΔA	surface area of the each planar element, cm^2
ΔG	change in Gibbs free energy, kJ/mole of water formed
ΔH	enthalpy of formation, kJ/mole mole of water formed
ΔL_1	length of the 1st planar element, cm
ΔL_2	length of the 2nd planar element, cm
ΔL_3	length of the 3rd planar element, cm

ΔL_n	length of the nth planar element, cm
ΔL	length of the each planar element, cm
ΔQ_1	heat transferred through the 1st planar element, Watts
ΔS	change in entropy, kJ/K/mole of water formed
ΔT	total in-plane temperature differential across the cooling plate, K
ΔT_1	in-plane temperature differential of the 1st planar element, K
ΔT_2	in-plane temperature differential of the 2nd planar element, K
ΔT_3	in-plane temperature differential of the 3rd planar element, K
ΔT_n	in-plane temperature differential of the nth planar element, K
η_a	actual energy efficiency
η_i	current efficiency
η_t	maximum theoretical energy efficiency
η_v	voltage efficiency

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The NASA Glenn Research Center is developing advanced passive thermal management technology to reduce the mass and improve the reliability of space fuel cell systems for the NASA exploration program. An analysis of a state-of-the-art fuel cell cooling systems was done to benchmark the portion of a fuel cell system's mass that is dedicated to thermal management. Additional analysis was done to determine the key performance targets of the advanced passive thermal management technology that would substantially reduce fuel cell system mass.

15. SUBJECT TERMS
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