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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. The passive thermal management system relies on heat conduction within highly thermally conductive cooling plates to move the heat from the central portion of the cell stack out to the edges of the fuel cell stack. Using the passive approach eliminates the need for a coolant pump and other cooling loop components within the fuel cell system which reduces mass and improves overall system reliability. Previous development demonstrated the performance of suitable highly thermally conductive cooling plates that could conduct the heat, provide a sufficiently uniform temperature heat sink for each cell of the fuel cell stack, and be substantially lighter than the conventional thermal management approach. Tests were run with different materials to evaluate the design approach to a heat exchanger that could interface with the edges of the passive cooling plates. Measurements were made during fuel cell operation to determine the temperature of individual cooling plates and also to determine the temperature uniformity from one cooling plate to another.

Introduction

The purpose of this work was to test different heat exchanger designs, materials, and vacuum grease. The heat exchanger would interface with the edges of the very thermally conductive passive cooling plates of the fuel cell thermal management system. The cooling plates used in these tests were previously developed at NASA and had thermal conductivities of 1400 to 1500 W/m/K (Ref. 1).

Nomenclature

A	Cooling plate cross sectional area, m^2
dT/dx	Temperature gradient, K/m
k	Thermal conductivity, W/m-K
Q	Applied heat, W
T	Cooling plate temperature, K
x	Location of the temperature measurement on the cooling plate, m

Background

The heart of a fuel cell is an electrochemical “cell” where a fuel and an oxidizing agent react, converting 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 under development for future NASA missions 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 is shown in Figure 1.

Heat must be removed from the fuel cell stack to prevent the stack from overheating. Heat is typically removed from the fuel cells via cooling plates within the fuel cell stack that are located between the cells as shown in Figure 1. Typically a liquid coolant is circulated within the plate and heat is removed convectively as the coolant passes through the plate and out of the fuel cell stack to a fuel cell system heat exchanger. 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 exchanger external to the fuel cell stack. Figure 2 shows the difference between a conventional fuel cell thermal management system and a passive fuel cell thermal management system. Potential benefits of the passive approach include reductions in mass, system complexity, and parasitic power as well as improvements in system reliability.

Figure 3 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.

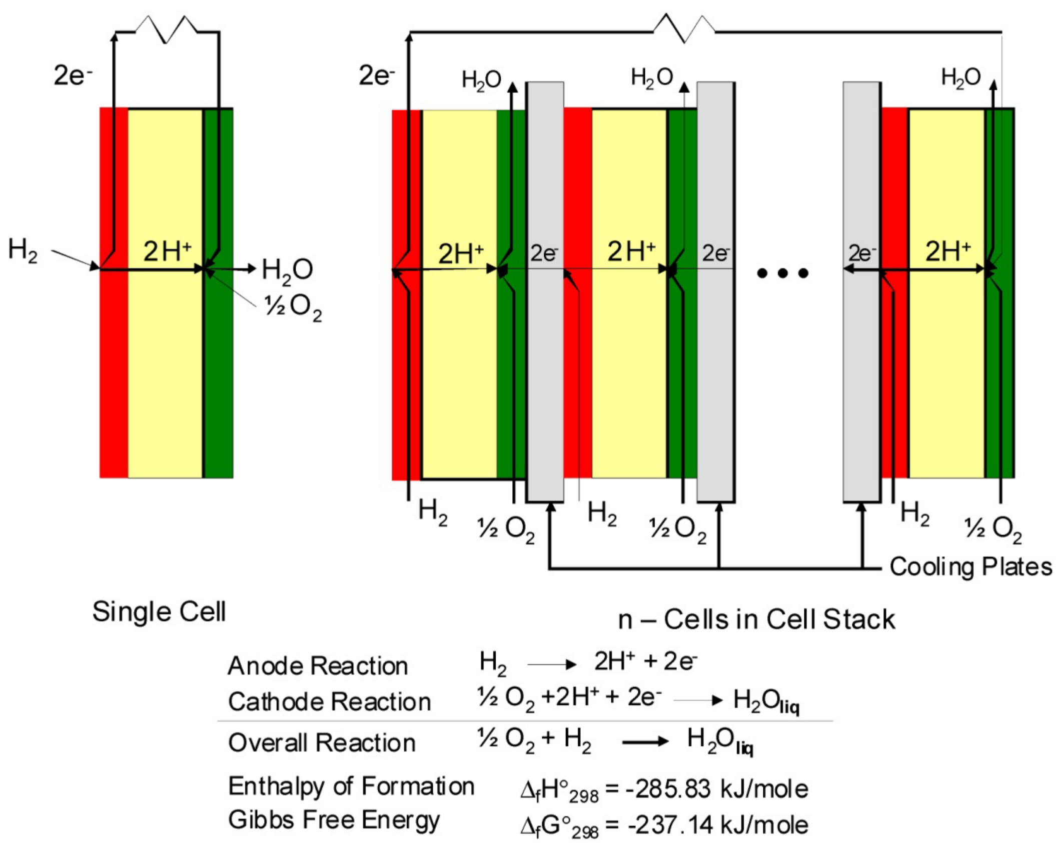

Figure 1.—Proton exchange membrane fuel cell.

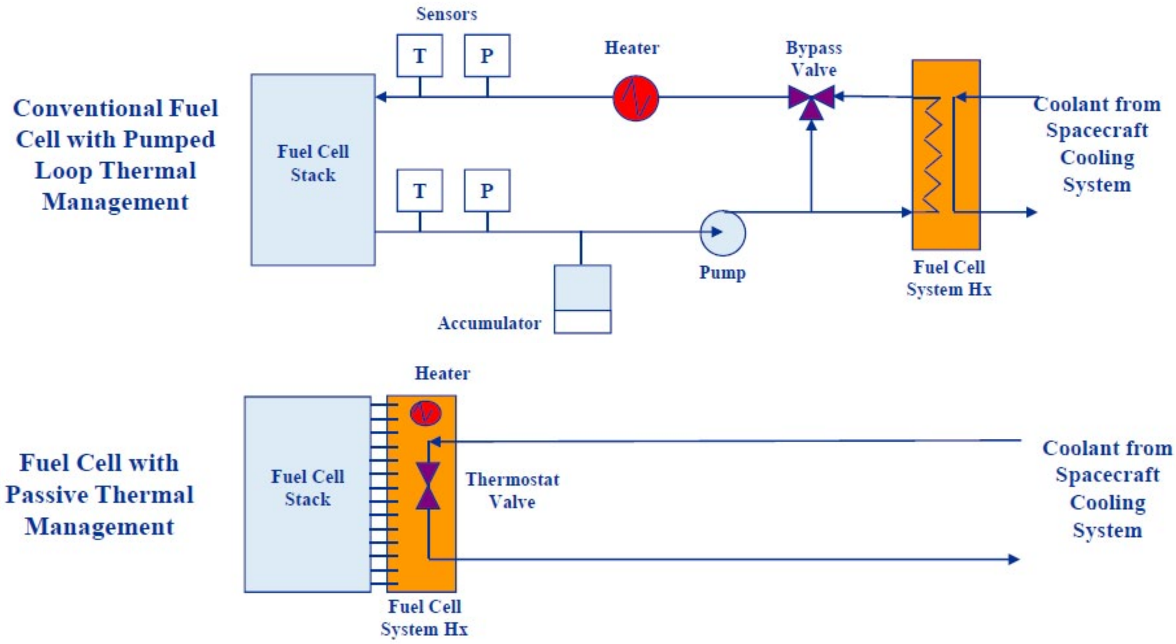

Figure 2.—Fuel cell thermal management systems.

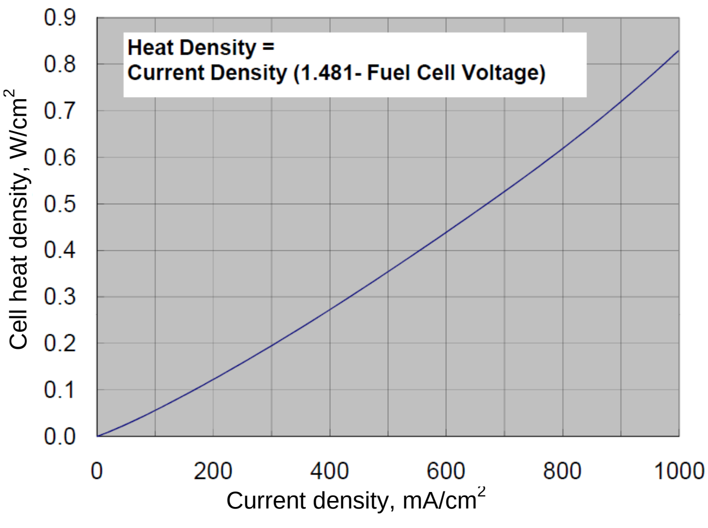

Figure 3.—Fuel cell heat generation

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 were developed (Ref. 2) that relate the thermal performance of a passive cooling plate to its physical characteristics. There are two key metrics used in the evaluation of the thermal management system, the first is the maximum temperature difference, the ΔT, over the chemically active area of each cell in the fuel cell stack. Ideally, a uniform temperature over the active area is desired because this maximizes the electrochemical performance throughout the stack. In practice, a ΔT of zero is never achieved because the process of removing waste heat from the fuel cell always requires a temperature differential. In practice, a ΔT of 3 °C has been acceptable, and therefore was used as a driving requirement. A second key metric is the mass of the thermal management system. The waste heat managed per unit mass of the thermal management system was the defined metric for mass evaluation. The thermal system mass was considered to be the mass of the cooling plates internal to the fuel cell stack and the mass of thermal system components external to the

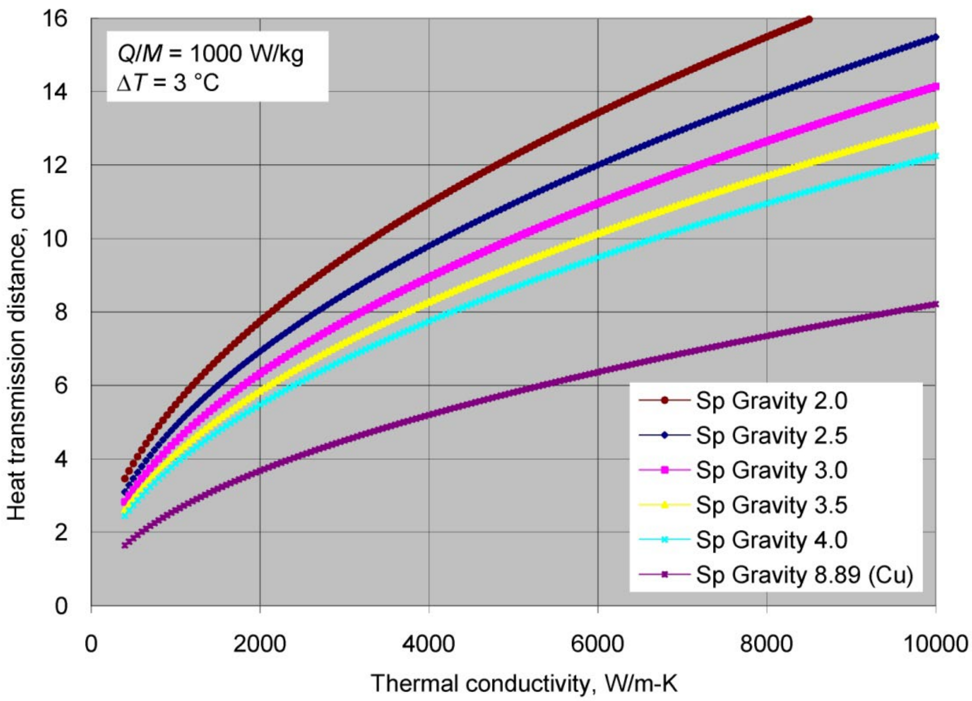

Figure 4.—Cooling plate heat transmission distance, thermal conductivity, and plate specific gravity.

fuel cell stack such as the coolant, plumbing lines, pump, accumulator, sensors, etc. The mass of the fuel cell system heat exchanger common to both approaches was excluded from the mass of the thermal system. The space shuttle fuel cell powerplant has a maximum heat rejection of 7322 W and an overall mass of 115.7 kg (Ref. 3). The fraction of the overall shuttle fuel cell powerplant mass represented by the thermal system was not known but estimated to be 10 percent. This would result in a waste heat per unit mass of 633 W/kg. A value of 1000 W/kg was used as a goal for the passive thermal management system.

Using 1000 W/kg as the value of the metric and 3 °C as the ΔT, the relationship between heat transmission distance L, the specific gravity of the cooling plate ρ, and the thermal conductivity k of the cooling plate is plotted in Figure 4 using the analytical relationships developed (Ref. 2).

From the plot shown in Figure 4, it is apparent that for fuel cells which have to transmit the heat ≥4 cm, a thermal conductivity of ≥ 1000 W/m/K and a specific gravity of ≤4 gm/cc would be required to meet the metric targets.

Interface Heat Exchanger Test Articles

Interface heat exchanger test articles were fabricated from aluminum, stainless steel, copper, thermally conductive plastic supported on aluminum, and anodized aluminum. Table 1 lists the properties of the materials from which the integrated heat exchangers were made (Refs. 4 and 5).

TABLE 1.—INTEGRATED HEAT EXCHANGER MATERIAL PROPERTIES[a]

Material	Density (g/cm^3)	Thermal conductivity (W/mK)	Specific heat capacity (J/g°C)	Coefficient of linear thermal expansion ($\times 10^{-6}$/°C)
C10100 Copper	8.94	391	0.39	17.7
316 Stainless Steel	7.94	15	0.47	16
6061-T6 Aluminum	2.7	180	0.896	23.6
D5506 LCP	1.8	10	0.97	6.4 to 11.3

[a]Properties listed are for approximately room temperature or for an unstated temperature.

Aluminum, Stainless Steel, and Copper Heat Exchangers

Three integrated metal heat exchangers were fabricated with identical geometries. The only difference between the heat exchangers was the material. The heat exchangers were made of aluminum, stainless steel, and copper. A picture of the different heat exchangers is shown in Figure 5.

Two of each type were used in each test. Thermally conductive pyrolytic graphite/copper cooling plates previously developed (Ref. 1) were slide into the slots of the pair of heat exchangers. The cooling plates were approximately 100 mm (4 in.) by 100 mm (4 in) with a thickness of 0.0009 mm (0.23 in) and a thermal conductivity of 1400 W/m/K. Figure 6 shows four cooling plates inserted into one of the pair of heat exchangers. The other heat exchanger was removed so the inserted cooling plates could be more easily seen.

Figure 7 is an illustration of the assembled test article configuration, showing four cooling plates inserted between the two heat exchangers. Each cooling plate was instrumented with twelve thermocouples spaced as shown in Figure 7. A silicone pad heater was adhered to the other side of each plate, so that on one side of each plate were the thermocouples, and on the opposite side of each plate was the silicone pad heater.

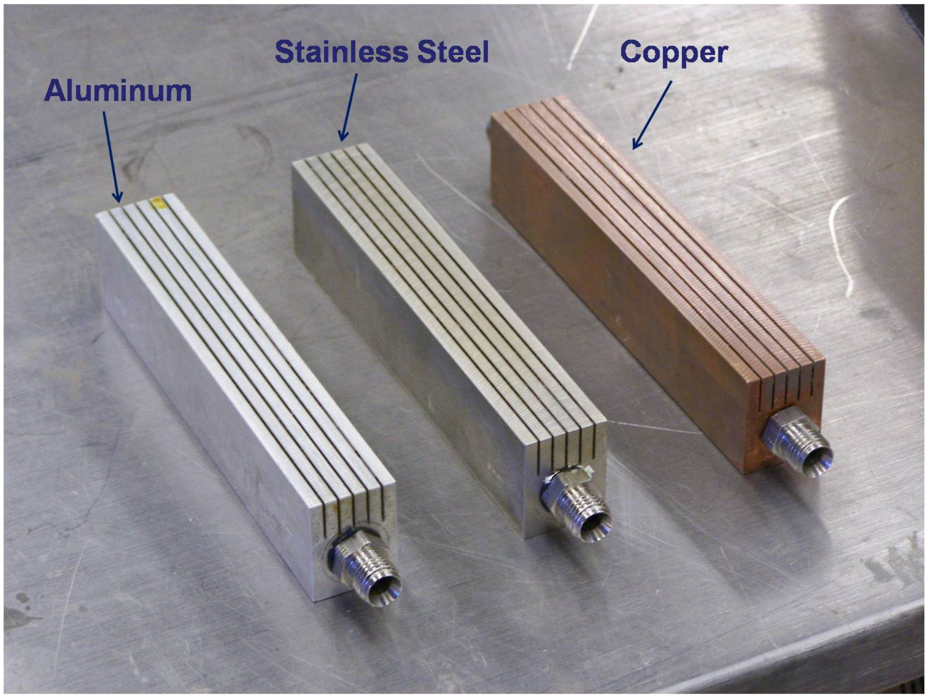

Figure 5.—Aluminum, stainless steel, and copper heat exchangers.

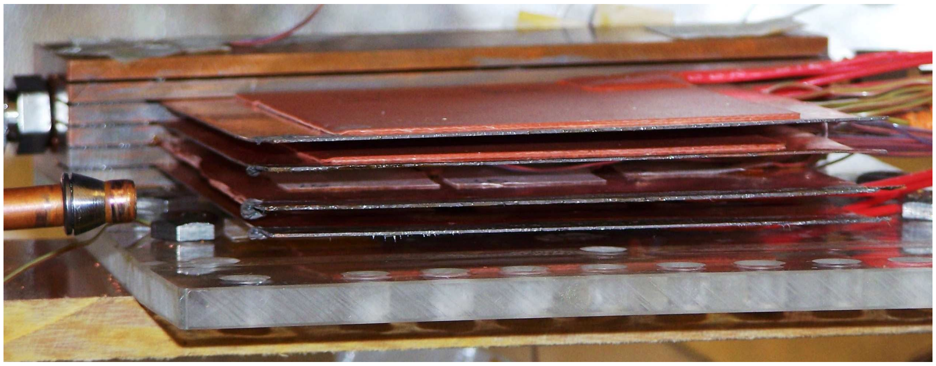
Figure 6.—Heat exchanger with inserted cooling plates.

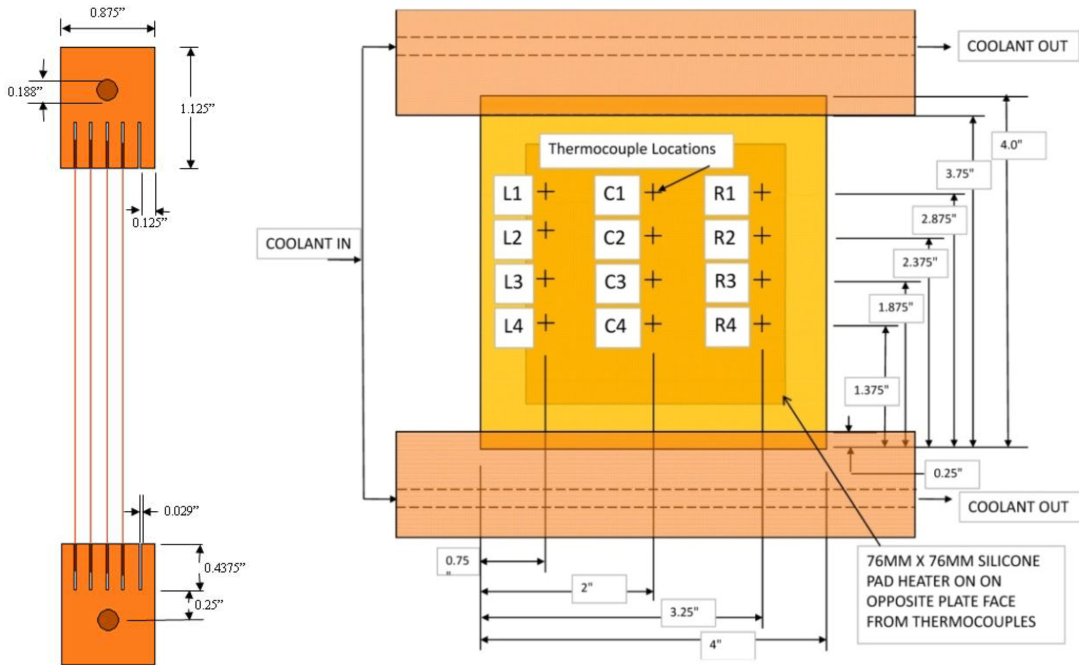

Figure 7.—Aluminum, stainless steel, and copper heat exchanger test article configuration.

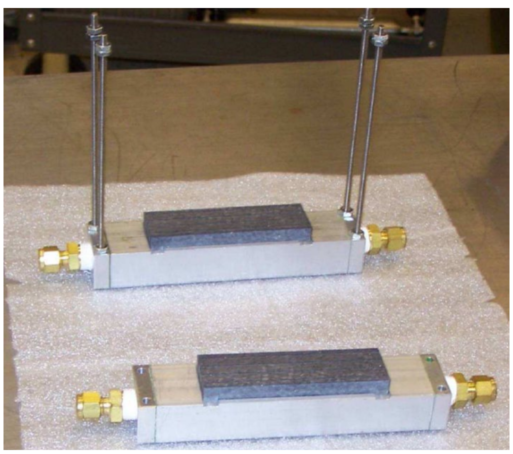

Figure 8.—Plastic/aluminum heat exchangers.

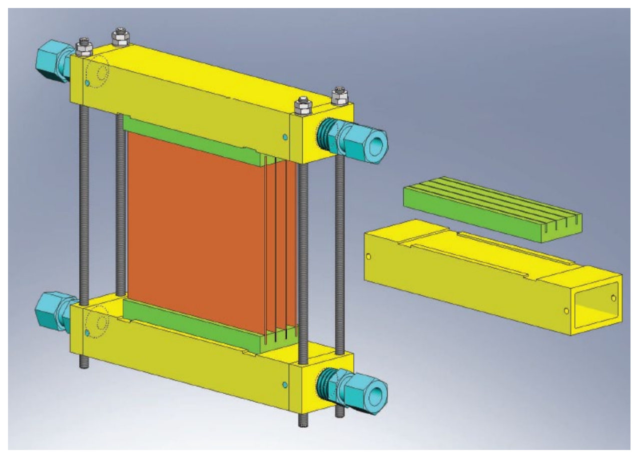

Figure 9.—Assembled plastic/aluminum heat exchanger configuration.

Thermally Conductive Plastic/Aluminum Heat Exchanger

An integrated heat exchanger was made using a thermally conductive plastic from Cool Polymers (Ref. 5). The final configuration of a heat exchanger must not produce an electrical shorting path between cells in a fuel cell stack. The plastic, in this case, provides the necessary insulation between the cooling plates. The properties of this polymer were listed in Table 1. The plastic plate was epoxied onto an aluminum rectangular channel. Aluminum endcaps with tube fittings closed the ends of the rectangular channels. Threaded rods held the two heat exchangers onto the four inserted cooling plates. Figures 8 and 9 show a picture of the fabricated plastic/aluminum heat exchangers and the assembled plastic/aluminum heat exchanger test article configuration.

Figure 10 is an illustration showing the dimensions of the plastic/aluminum heat exchanger test article. The four cooling plates were the same plates as those used in the testing of the metal heat exchangers.

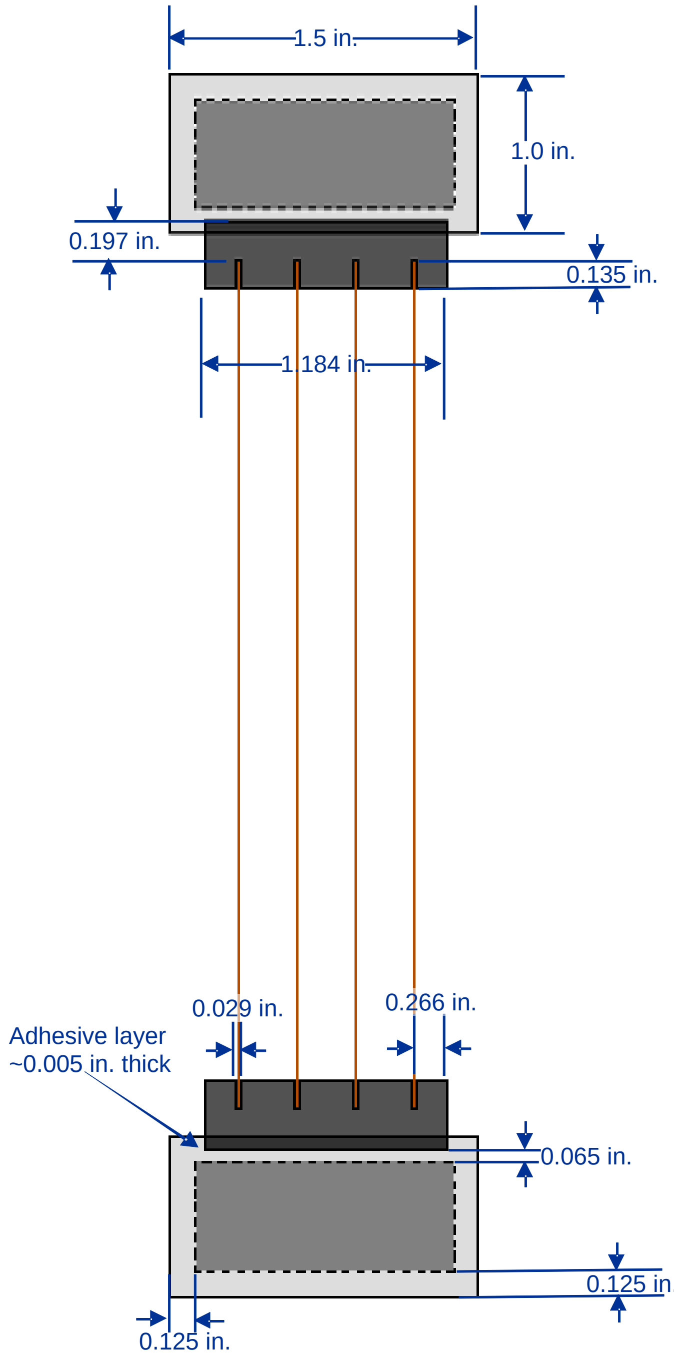

Figure 10.—Plastic/aluminum heat exchanger test article configuration dimensioned.

Single-Sided Thermally Conductive Plastic/Aluminum Heat Exchanger

A single-sided plastic/aluminum heat exchanger was designed and fabricated. The single-sided heat exchanger was designed to be integrated with a functional fuel cell stack. The plastic portion of this heat exchanger used two of the plastic pieces previously used in the construction of the plastic/aluminum heat exchanger shown in Figures 8, 9 and 10. These two plastic pieces were epoxied to a single, rectangular aluminum channel. The cross sectional dimensions of this heat exchanger were identical to the cross sectional dimensions of one side of the double-sided heat exchanger shown in Figure 10. The single-sided heat exchanger is shown in Figure 11.

The cooling plates to be inserted into the fuel cell stack would extend beyond the exterior of the fuel cell stack and fit within the slots machined into the plastic pieces. Pictures of the cooling plate design are shown in Figures 12 and 13. Four of these cooling plates were made. Silicone pad heaters were adhered to one side of each cooling plate. The other side of each cooling plate was instrumented with nine thermocouples.

Figure 14 illustrates the geometry of the cooling plates used with the single sided plastic aluminum heat exchanger. Figure 14 also shows the location of the silicone pad heater. The pad heater mimicked the quantity of heat expected from each cell in the fuel cell stack. The area and placement of the heater similarly mimicked the area and location where the heat would be produced by each cell in the fuel cell stack. Figure 14 also shows the number and placement of the thermocouples used to measure the temperature of each cooling plate. The holes in the cooling plate at the top and bottom of the plate are for the hydrogen and oxygen manifolds within the fuel cell stack, but played no functional role in the experiment of the heat exchangers. Figure 15 shows the assembled singled-sided plastic/aluminum heat exchanger with instrumented cooling plates.

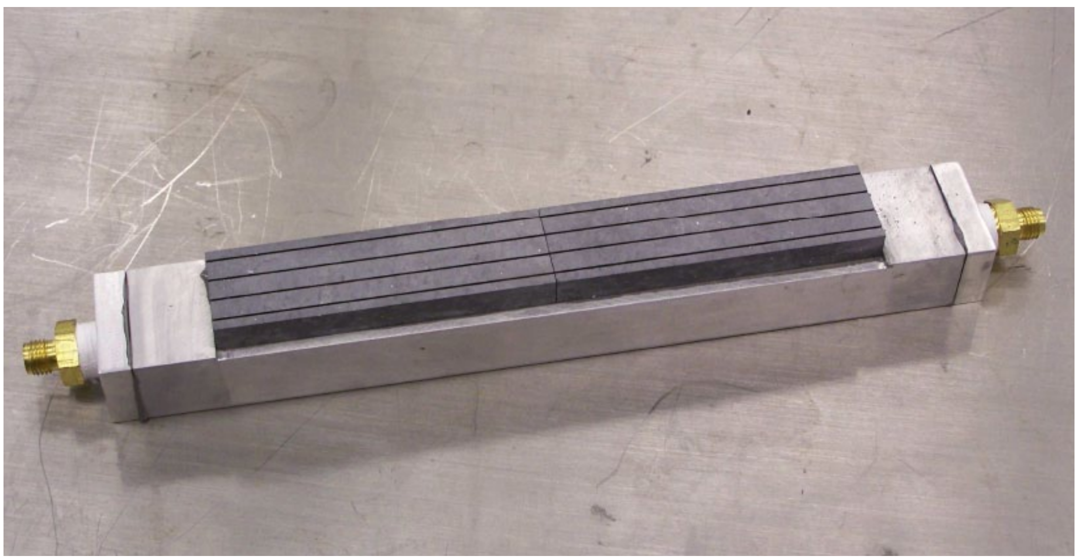

Figure 11.—Single-sided plastic/aluminum heat exchanger.

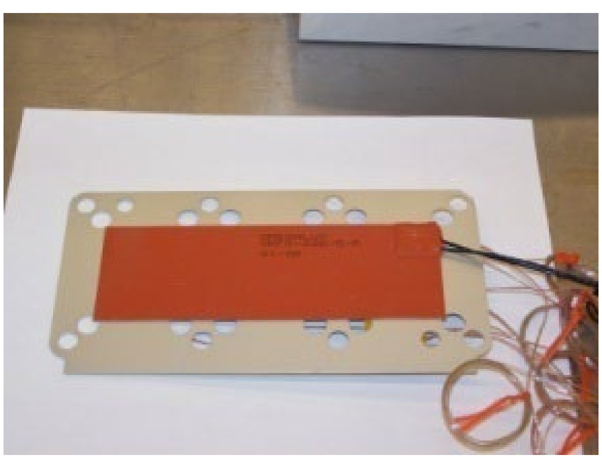

Figure 12.—Fuel cell cooling plate with pad heater.

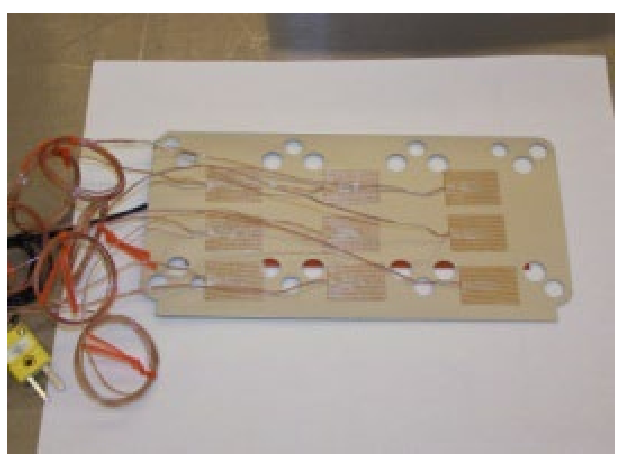

Figure 13.—Fuel cell cooling plate with thermocouples.

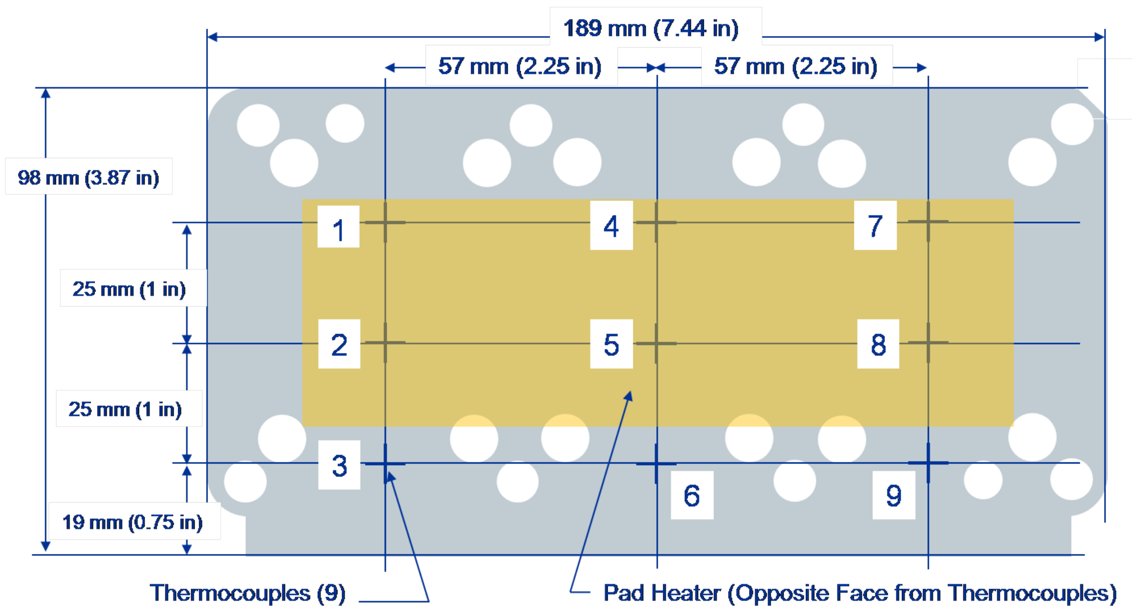

Figure 14.—Fuel cell cooling plate showing location of the pad heater and thermocouples.

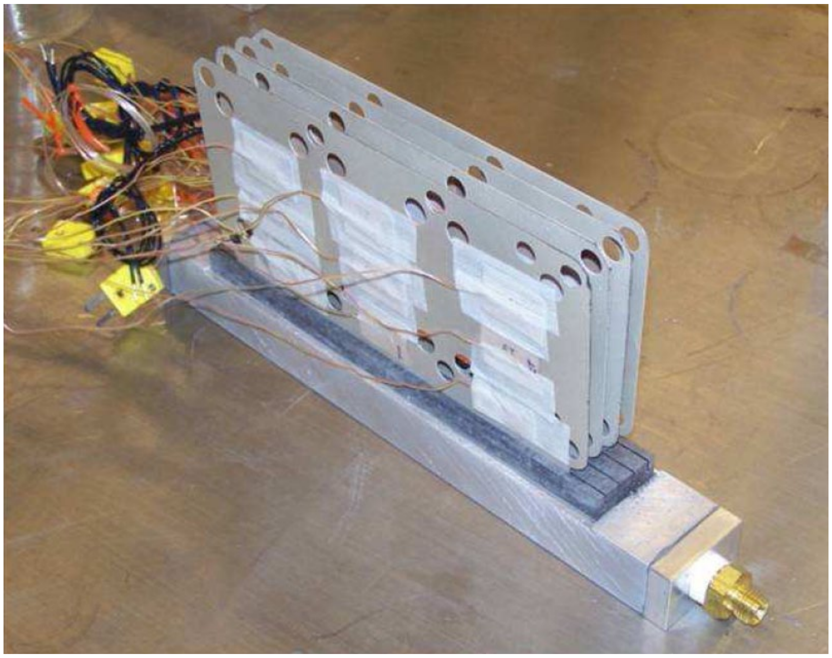
Figure 15.—Single-sided plastic/aluminum heat exchanger assembled with fuel cell cooling plates.

Anodized Aluminum Heat Exchanger

A second single-sided heat exchanger was designed and fabricated. This heat exchanger used an anodized aluminum coating as the electrical insulation layer between the different cooling plates. The cooling plates from the previous single-sided heat exchanger test article were reused with the anodized heat exchanger. Figure 16 shows an illustration of the anodized aluminum heat exchanger with the cooling plates.

Figure 17 shows the fabricated anodized heat exchanger. The cooling plates were inserted into the anodized heat exchanger the same depth as they were into the plastic aluminum heat exchanger. Instead of a single rectangular coolant flow passage, the anodized heat exchanger used five smaller diameter flow channels that carried coolant down the length of the heat exchanger and were connected in parallel to common manifold aluminum blocks.

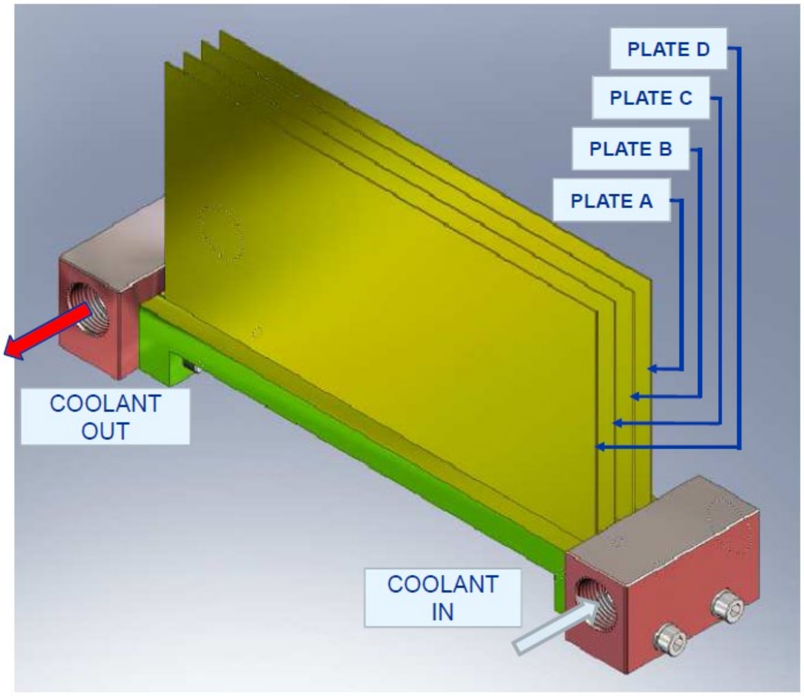

Figure 16.—Single-sided anodized aluminum heat exchanger with fuel cell cooling plates.

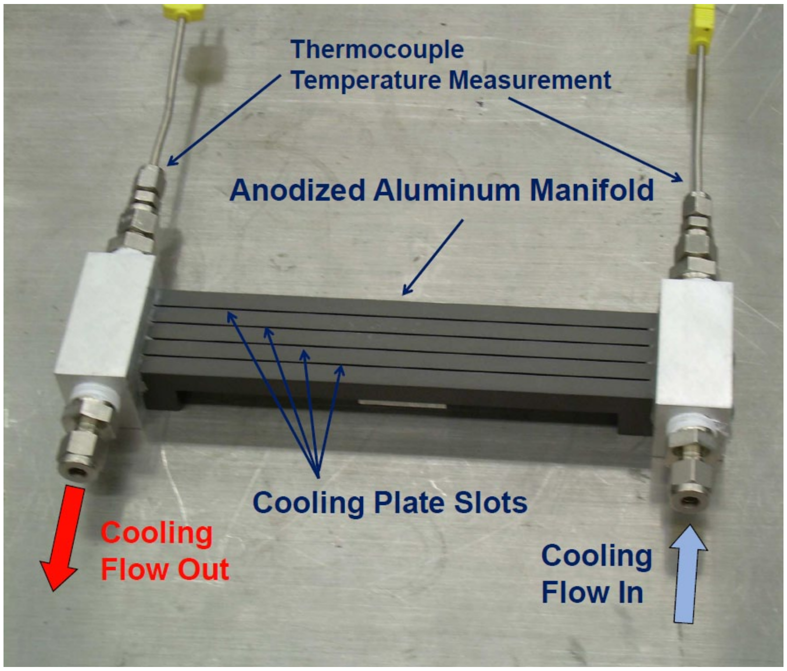

Figure 17.—Fabricated anodized aluminum heat exchanger.

Interface Heat Exchanger Testing

The cooling plates were inserted into each different type of heat exchanger. Tests were run with and without vacuum grease. The vacuum grease was applied to the ends of the cooling plates such that it filled the void spaces between the edges of the cooling plates and the walls of the grooves into which the cooling plates were inserted. The heat exchanger testing consisted of applying different known heat rates to each of the heated pads that were attached to each plate, and removing the heat by flowing coolant through the heat exchanger. Temperature measurements made on the face of each plate gave a measure of the temperature distribution of each plate and how well the heat exchanger was allowing the heat to be transferred to the coolant. These measurements allowed the comparison of the performance of the different heat exchanger designs.

Heat Exchanger Testing Facilities

The heat exchangers and cooling plates were tested in a vacuum chamber shown in Figure 18. Figure 19 shows the interior of the chamber including of the heat exchangers with the inserted cooling plates. The tests were run at vacuum conditions to minimize convective heat transfer from the test article and to ensure that heat conduction from the cooling plates to the heat exchanger was the predominant heat transfer mechanism. This approach simplified the analysis of the data. Radiative heat losses from the samples during the test were negligibly small in comparison to the heat being conducted through the plane of the cooling plate.

Coolant plumbing lines were run from the test article to a feed-through in the vacuum tank wall, and from there to a temperature controlled chiller bath located outside of the vacuum chamber. Power lines from the cartridge heaters were run to a feed-through in the vacuum tank wall and from there to a DC power supply located outside of the vacuum chamber. Leads for thermocouples were similarly run to a feed-through and from there to a computer to record the temperature data. Figure 20 illustrates the overall heat exchanger test rig.

Figure 18.—Heat exchanger vacuum test chamber.

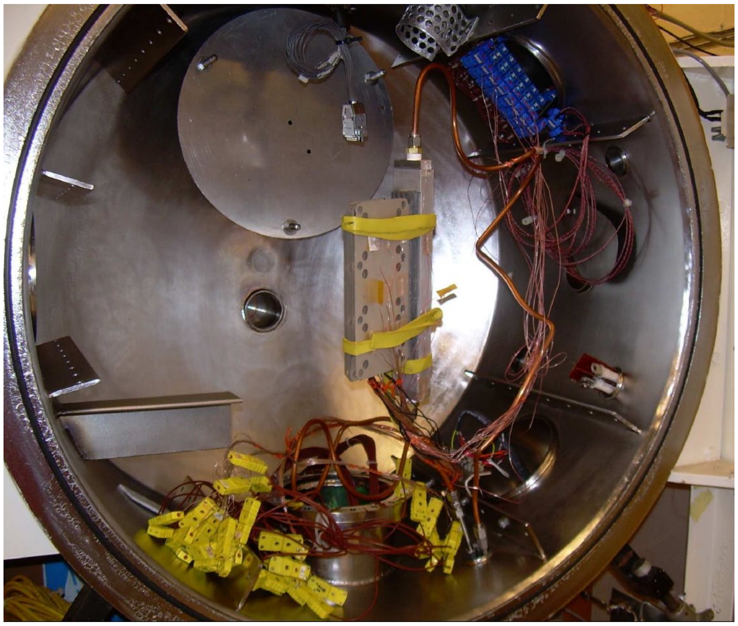

Figure 19.—Vacuum chamber interior with test article.

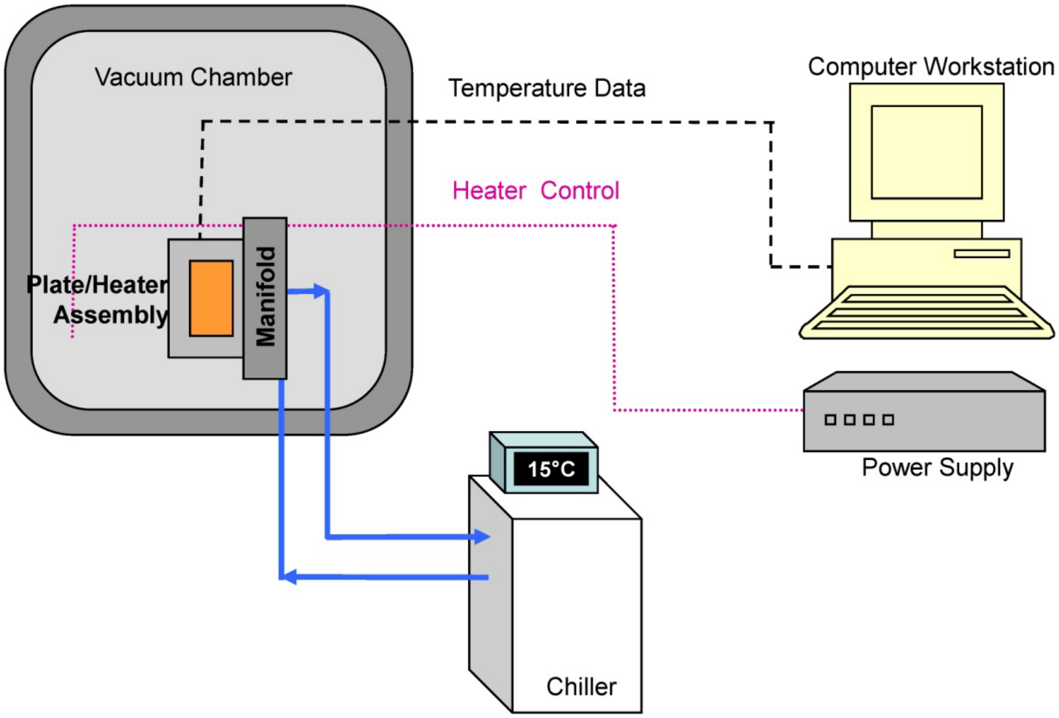

Figure 20.—Overall heat exchanger test rig configuration.

Interface Heat Exchanger Testing Results

Aluminum Heat Exchanger Test Results

The aluminum heat exchanger shown in Figures 5 and 7 was tested in the heat exchanger vacuum chamber. The electrical power applied to the four cooling plates was varied from 2.5 to 22.5 W per plate. The heaters on each plate had an area of 58 cm^2. The heat density was therefore 0.04 to 0.39 W/cm^2. As stated earlier, NASA's fuel cells are expected to operate at current densities that produce < 0.3 W/cm^2. The aluminum heat exchanger was tested with the cooling plates inserted into the heat exchanger without any vacuum grease to fill the clearance space between each cooling plate and the walls of the heat exchanger slot. It was recognized that from a heat transfer perspective, this is a non-ideal situation. The heat exchanger was also tested with the slots filled with a vacuum grease to improve the thermal contact between the cooling plates and the heat exchanger. Figure 21 plots the average plate temperature for each of the four cooling plates at each of the power levels tested. Figure 21 plots both the results from the test done without grease as well as the test done with the vacuum grease. The results show that the vacuum grease substantially improves the heat transfer from the cooling plates to the heat exchanger because when the grease is used, the average plate temperature for all the plates is about 20° cooler than the case where no grease was used. In addition, the uniformity in performance between each of the four plates is much better with the grease than without.

Stainless Steel Heat Exchanger Test Results

The stainless steel heat exchanger shown in Figures 5 and 7 was tested in the heat exchanger vacuum chamber in the same manner that the aluminum heat exchanger was tested. The electrical power applied to the four cooling plates was varied from 2.5 to 22.5 W per plate. Figure 22 plots the average plate temperature for each of the four cooling plates at each of the power levels tested. Figure 22 plots both the results from the test done without grease as well as the test done with the vacuum grease. The results show that the vacuum grease did not substantially improve the heat transfer from the cooling plates to the heat exchanger as was the case with the aluminunm heat exchanger. The grease did improve the heat transfer by about 3°. In addition, the grease did not improve the uniformity in performance between each of the four plates.

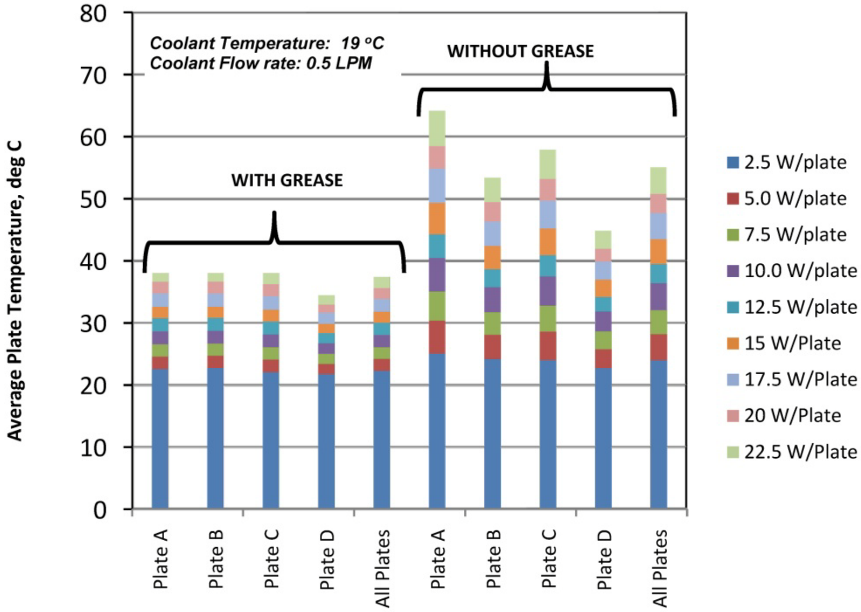

Figure 21.—Aluminum heat exchanger average plate temperature.

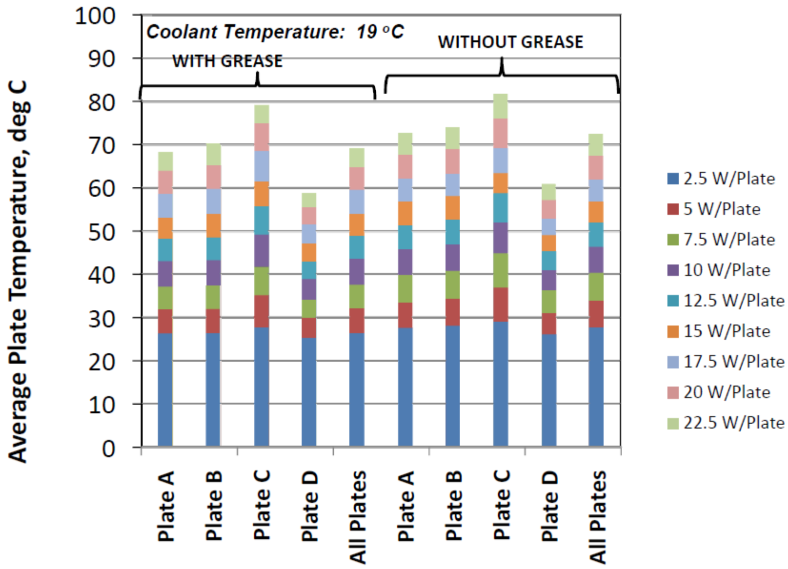

Figure 22.—Stainless steel heat exchanger average plate temperature

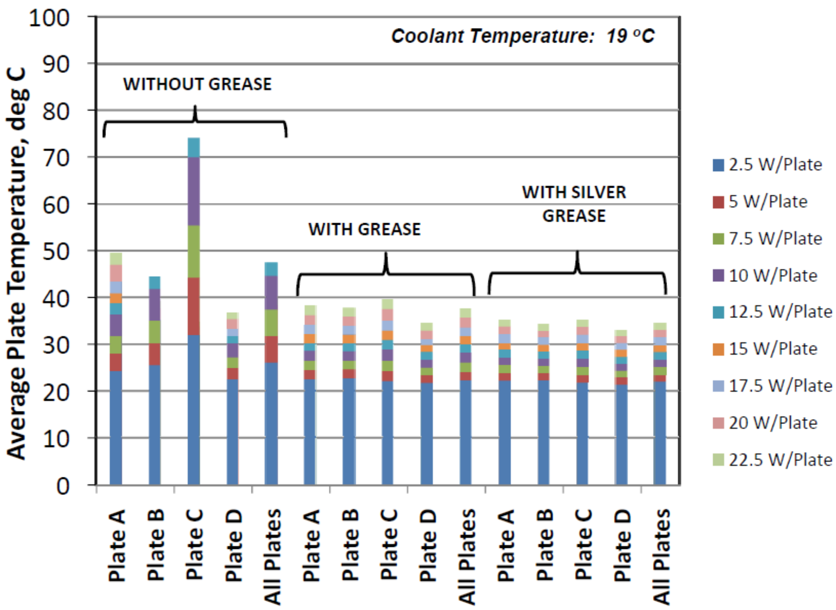

Figure 23.—Copper heat exchanger average plate temperature.

Copper Heat Exchanger Test Results

The copper heat exchanger shown in Figures 5 and 7 was tested in the heat exchanger vacuum chamber in the same manner that the aluminum and stainless steel heat exchangers were tested. The copper heat exchanger was also tested with a silver filled vacuum grease to see if the silver additive improved the thermal performance. The electrical power applied to the four cooling plates was varied from 2.5 to 22.5 W per plate. Figure 23 plots the average plate temperature for each of the four cooling plates at each of the power levels tested. Figure 23 plots both the results from the test done without grease as well as the test done with the two different vacuum greases. The results show that the vacuum grease did substantially improve the heat transfer from the cooling plates to the heat exchanger as was the case with the aluminunm heat exchanger. Both greases did improve the heat transfer by about 10°. In addition, the grease did improve the uniformity in performance between each of the four plates. The silver-filled grease did perform slightly better than the non-filled grease. Based on this data, the grease used on the single-sided heat exchangers was the silver-filled grease.

Plastic/Aluminum Heat Exchanger Test Results

The plastic/aluminum heat exchanger shown in Figures 8, 9, and 10 was tested in the heat exchanger vacuum chamber in the same manner that the aluminum, stainless steel, and copper heat exchangers were tested. The plastic/aluminum heat exchanger was tested with a silver filled vacuum grease. The electrical power applied to the four cooling plates was varied from 2.5 to 22.5 W per plate. The test without the grease was run only up to 7.5 W per plate because the cooling plates were close to their maximum temperature. The test with the grease had power levels up to 22.5 W per plate. Figure 24 plots the average plate temperature for each of the four cooling plates at each of the power levels tested. Figure 24 plots both the results from the test done without grease as well as with the silver-filled grease. The results show that the vacuum grease did substantially improve the heat transfer from the cooling plates to the heat exchanger as was the case with the aluminunm and copper heat exchanger. The grease did lower the temperature of the cooling plates by over 30°. In addition, the grease did improve the uniformity in performance between each of the four plates.

Aluminum, Stainless Steel, Copper, Plastic/Aluminum Heat Exchanger Comparison

The results from the aluminum, stainless steel, copper and plastic/aluminum heat exchanger tests run with grease (silver grease in the case of the copper and plastic/aluminum heat exchangers) are shown side-by-side in Figure 25 for comparison purposes. Figure 25 shows that the aluminum and copper heat exchangers make the cooling plates operate at 20° to 35° lower temperature. The thermal conductivity of the aluminum and copper metals are an order of magnitude greater than the stainless and the plastic, which is the likely reason for the superior performance. The uniformity of the plates in either the aluminum or copper heat exchangers are also much better than when the plates are in the plastic or stainless steel heat exchangers.

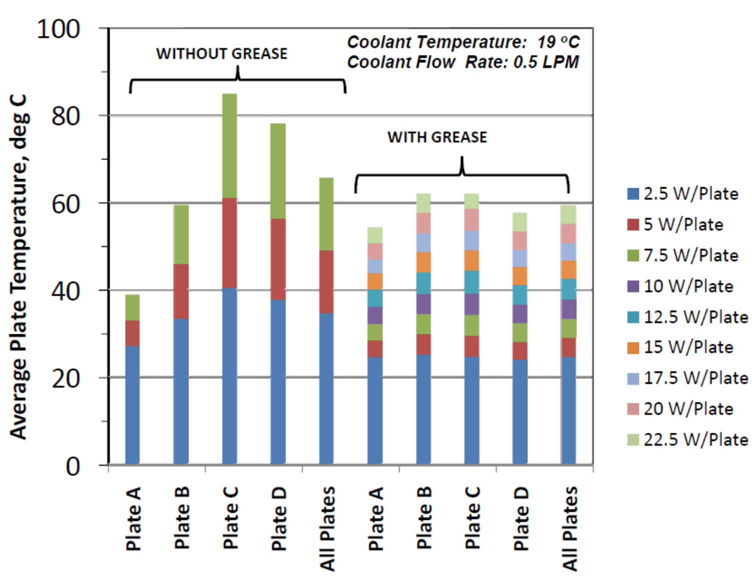

Figure 24.—Plastic/aluminum heat exchanger average plate temperature.

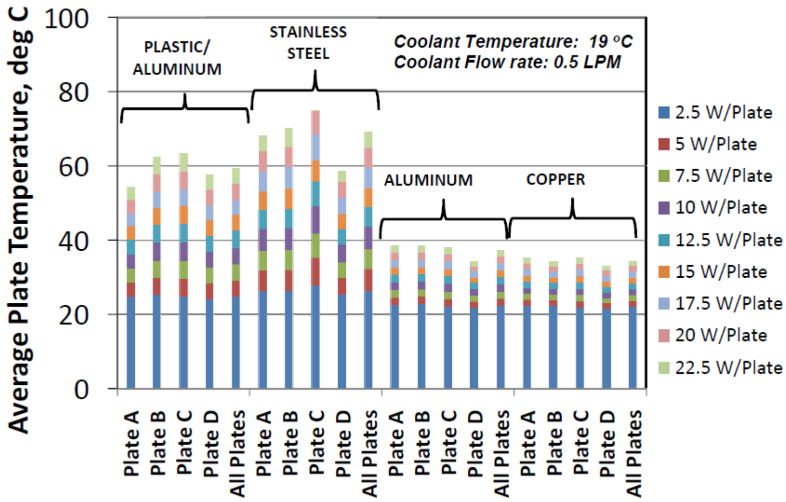

Figure 25.—Heat exchanger average temperature comparison.

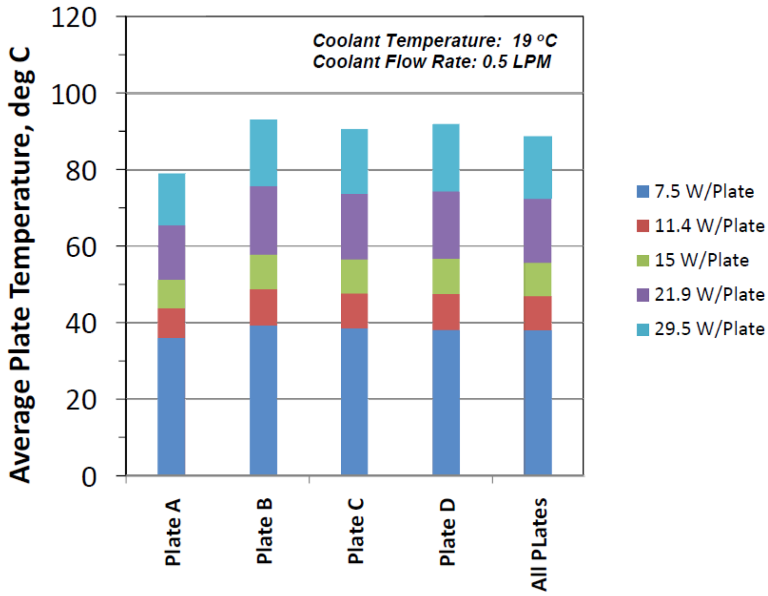

Figure 26.—Single-sided plastic/aluminum heat exchanger average temperature.

Single-Sided Plastic/Aluminum Heat Exchanger Test Results

The heat exchanger and cooling plates shown in Figures 11, 12 and 13 were designed to be integrated with a fuel cell stack. Unlike the previous heat exchangers tested, this heat exchanger attaches to the cooling plates only on one side of the cooling plates. This test verified that the heat exchanger and cooling plates would provide satisfactory cooling of the fuel cell stack since at all but the highest power levels the cooling plates were less than 80 °C (the operating temperature of the fuel cell stack). The heat exchanger and cooling plates were tested in the heat exchanger vacuum chamber in the same manner that the other heat exchangers were tested. The plastic/aluminum heat exchanger was tested with the silver filled vacuum grease. The electrical power applied to the four cooling plates was varied from 7.5 to 29.5 W per plate, which equates to 0.1 to 0.4 W/cm^2. Figure 26 plots the average plate temperature for each of the four cooling plates at each of the power levels tested. The results showed very good cooling and uniform performance among the four plates, even at the high power levels.

Anodized Aluminum Heat Exchanger Test Results

An anodized aluminum heat exchanger was designed to interface with the single-sided cooling plates. The comparison between the performance of the aluminum and plastic/aluminum heat exchangers shown in Figure 25 showed that the aluminum had much better heat transfer performance. Since uncoated aluminum would electrically short the different cooling plates in a fuel cell stack, the heat exchanger was coated with an electrically nonconductive anodized coating. The heat exchanger and cooling plates were tested in the heat exchanger vacuum chamber in the same manner that the other heat exchangers were tested. The anodized aluminum heat exchanger was tested with the silver filled vacuum grease. The electrical power applied to the four cooling plates was varied from 7.5 to 41.5 W per plate, which equates to 0.1 to 0.55 W/cm^2. Figure 27 plots the average plate temperature for each of the four cooling plates at each of the power levels tested. The results showed excellent cooling and uniform performance among the four plates, even at the high power levels.

Single-Sided Heat Exchanger Comparison

Figure 28 shows the comparison of the two single-sided heat exchangers that used the same cooling plates. The anodized aluminum heat exchanger removed the heat from the cooling plates much more effectively than the plastic/aluminum heat exchanger. The applied heat was increased to 41.5 W/cm^2 for the anodized aluminum heat exchanger, but could only be increased to 29.5 W/cm^2 for the plastic/aluminum heat exchanger. Even at 41.5 W/cm^2, the temperature of the cooling plates in the anodized aluminum heat exchanger were over 20 °C cooler. The anodized aluminum heat exchanger allows excellent heat transfer while being electrically non-conductive.

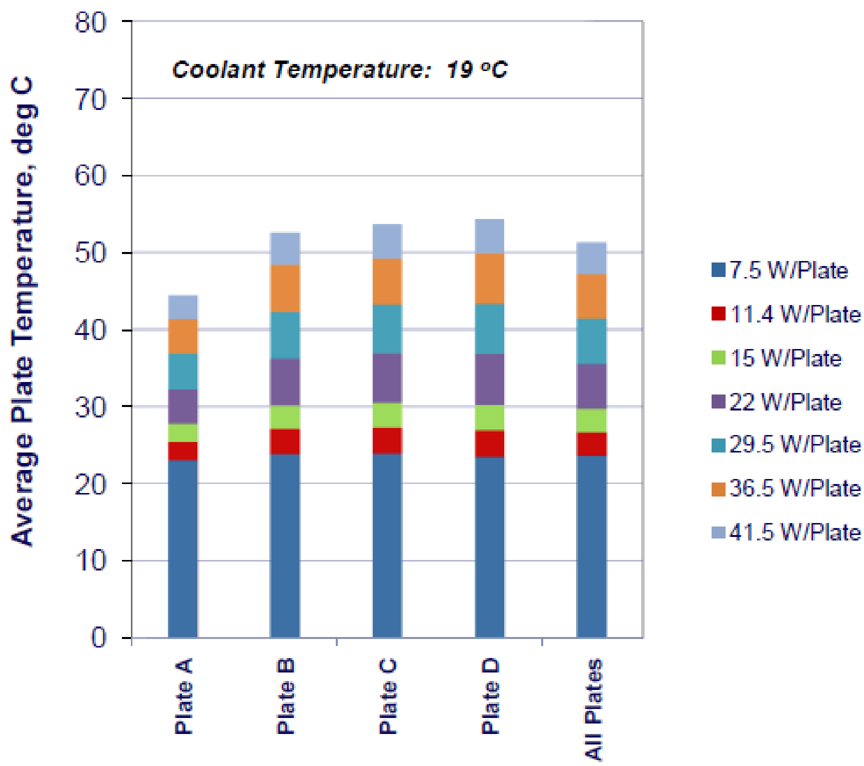

Figure 27.—Anodized aluminum heat exchanger average temperature.

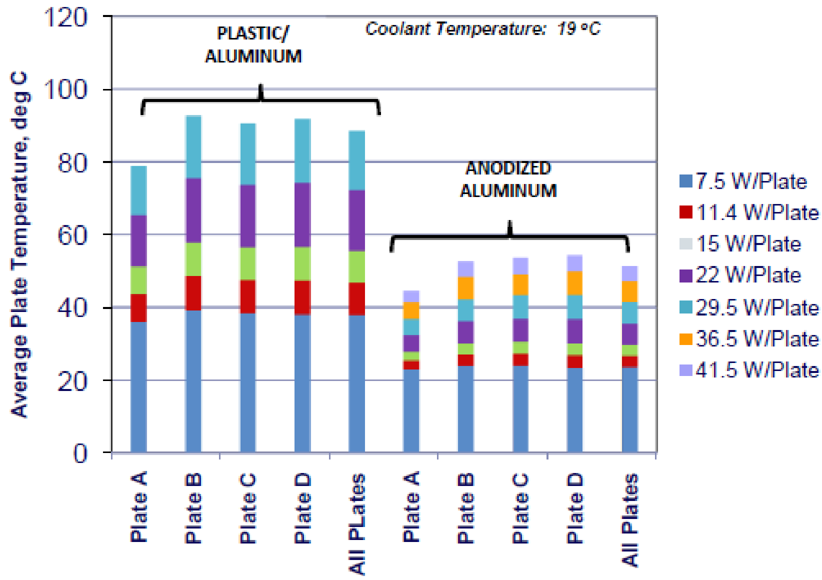

Figure 28.—Single-sided heat exchanger average temperature comparison.

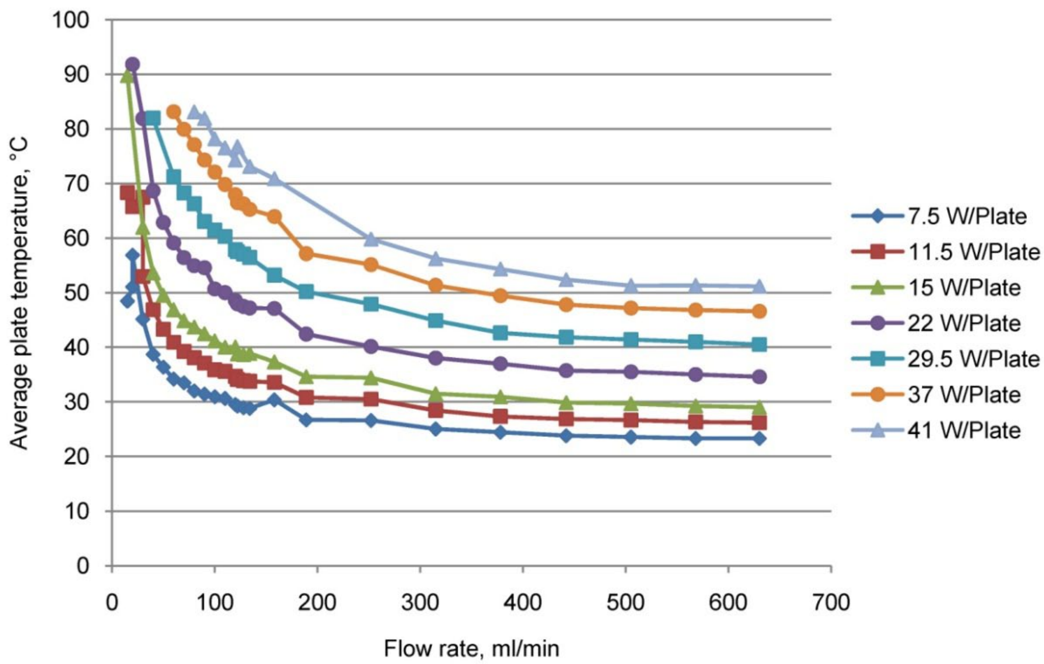

Figure 29.—Average plate temperature versus flow rate for the anodized heat exchanger.

Anodized Aluminum Heat Exchanger Temperature Versus Flow Rate

The anodized aluminum heat exchanger was tested at different coolant flow rates. At each flow rate the power level was varied from 7.5 to 41.5 W per plate. Figure 29 shows the results from the variation in flow rate. As the flow rate was increased, the average temperature of the cooling plates decreased. At higher flow rates the temperature of the cooling plates was not affected by further increases in the coolant flow rate. The data from this test indicates that the cooling plates can be kept within the 60 to 80 °C operating range of a fuel cell stack by varying the flow rate between 0 and 250 ml/min. At 80 °C the controlling flow rate range is 0 to about 100 ml/min.

Conclusions

The efforts to develop a passive fuel cell thermal management heat exchanger have lead to the following conclusions:

1) A passive interface heat exchanger can be fabricated that is capable of removing the heat from cooling plates.

2) The best materials for the heat exchanger are more thermally conductive materials such as aluminum or copper, but the materials must also not electrically short the individual cooling plates. Anodized aluminum was the best material tested.

3) Vacuum grease between the cooling plates and the walls of the heat exchanger grooves substantially improves the ability of the heat exchanger to transfer heat. The vacuum grease also improves the performance uniformity between the different cooling plates. The silver-filled grease is slightly better than the non-silver-filled grease.

4) Controlling the flow rate through the heat exchanger will be effective at maintaining the cooling plate temperature within the operating range of a fuel cell stack.

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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. The passive thermal management system relies on heat conduction within highly thermally conductive cooling plates to move the heat from the central portion of the cell stack out to the edges of the fuel cell stack. Using the passive approach eliminates the need for a coolant pump and other cooling loop components within the fuel cell system which reduces mass and improves overall system reliability. Previous development demonstrated the performance of suitable highly thermally conductive cooling plates that could conduct the heat, provide a sufficiently uniform temperature heat sink for each cell of the fuel cell stack, and be substantially lighter than the conventional thermal management approach. Tests were run with different materials to evaluate the design approach to a heat exchanger that could interface with the edges of the passive cooling plates. Measurements were made during fuel cell operation to determine the temperature of individual cooling plates and also to determine the temperature uniformity from one cooling plate to another.

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