Advanced Thermal Management Technologies for High Power Density Automotive Equipment

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Abstract

Waste heat in military and civilian vehicles continues to rise as more electronics are integrated into these vehicles. High density packaging results in high heat fluxes. Many military vehicles operate in extreme temperature, shock and vibration conditions, imposing additional constraints on the design of thermal management solutions.

Thermal management of a vehicle system requires different technologies at different locations. For example, the high heat fluxes within a semiconductor device package require an effective heat spreader to lower the heat fluxes to a level suitable for further transport and dissipation. Heat transport and dissipation tend to focus more on power consumption, transport line size and system weight. In some cases where the environmental condition fluctuates, thermal control is required to maintain a relative constant temperature for protection of the electronics.

This paper presents several advanced thermal management technologies that address three key categories of electronics thermal management: Heat Spreading, Heat Transport and Temperature Control.

Introduction

A number of trends are coming together in the next generation combat systems and tactical vehicles. One trend is the addition of more mission-critical electronic devices each of which adds to the heat generated within the vehicle. The second trend is the replacement of mechanical and hydraulic devices with smart electrical devices. While this increases overall energy efficiency, it greatly increases the electrical loads and tends to move the thermal loads to locations inside the vehicle. The third trend is the “drive-by-wire” where hydraulic lines and mechanical linkages are replaced by locally powered actuators. Instead of one large hydraulic pump which is relatively easy to cool, it is now necessary to cool a significant number of individual pumps and controller circuits which are located in discrete or inaccessible spaces. These trends greatly increase the heat loads that must be managed within the vehicle while also increasing the number of heat sources and dispersing these sources over most of the vehicle volume.

It is useful to define and understand the electronics cooling thermal architecture in a similar fashion to the “levels of packaging” defined by the interconnection industry to accommodate OEM equipment design, installation and field support requirements for electrical connections. Below is a brief summary of the “levels of cooling”.

- Level 1: Heat spreading within the semiconductor device package. Current technologies include copper, copper-tungsten or copper-moly heat spreaders.
- Level 2: Heat transfer or spreading from the device package to the chassis. Current technologies include copper and aluminum spreaders.
- Level 3: Heat transport from the chassis to the system heat exchanger. Current technologies include forced airflow and pumped liquid loops.
- Level 4: Heat dissipation through the system heat exchanger. Current technologies are air cooled heat sinks and radiators.

For some high power semiconductor devices, a cooling mechanism may directly connect the device package to the system heat exchanger, by passing Level 3. This reduces the number of thermal interfaces and improves the cooling efficiency, often at a price of added costs.

Each level has its unique cooling requirements. For example, Level 1 cooling designs are dominated by high heat flux and miniaturization issues. Levels 2 and 3 both require transport of large amounts of heat with minimal temperature gradients. Level 4 heat exchanger designs are required to sink the most heat with a minimal volume and mass.

In some cases where the temperature of the environment varies greatly, thermal (temperature) control mechanisms are needed to protect the electronics by maintaining a relatively constant temperature. The temperature control may be implemented at different levels. For example, variable speed air blowers or liquid bypass can be added to Level 3 or 4 to adjust the cooling effectiveness to realize temperature control.

This paper presents several advanced thermal management technologies that can be incorporated into a vehicle thermal architecture for improved cooling efficiency and reliability. These advanced technologies fall into three categories: Heat Spreader, Heat Transport, and Temperature Control.

Advanced Heat Spreader Technologies

A heat spreader is often used at Level 1 or 2 to take heat from small heat sources and evenly spread the heat to a larger area for direct heat rejection or further transport toward the system heat exchanger. The performance of a heat spreader is defined by its effective thermal conductivity. A higher thermal conductivity minimizes the temperature gradient and increases the cooling efficiency. As mentioned earlier, current heat spreader technologies are based on solid materials such as Cu, Al, Cu-W and Cu-Mo which have limited thermal conductivities. For example, the highest thermal conductivity of this type of heat spreaders is achieved with copper at around 400W/m-K. This becomes inadequate as the waste heat load and density continue to increase.

Three advanced, higher performance heat spreader technologies are discussed in this section: Hi-K Plates, Vapor Chambers, and Oscillating Flow Heat Spreaders.

Hi-K Plates

Typical Hi-K plates are aluminum heat spreaders that use embedded heat pipes to improve the effective thermal conductivity. Aluminum plates are commonly used to cool military electronics such as radars and sonars, because of their relatively high thermal conductivity, structural strength and overall ruggedness. Embedding heat pipes retains all of the advantages of the aluminum plates and adds the advantage of enhanced thermal conductivity.

Discussed below is an application where a Hi-K plate was used to retrofit an existing aluminum plate. Heat pipes were embedded in the aluminum plate to improve the thermal conductivity. The end product had the same geometry as the original aluminum plate. Figure 1 compares the baseline aluminum plate and the improved Hi-K plate. The aluminum plate has a maximum temperature of 90℃ (shown on the left). The Hi-K plate had a maximum temperature of 69℃. Figure 2 shows a photo of the Hi-K plate.

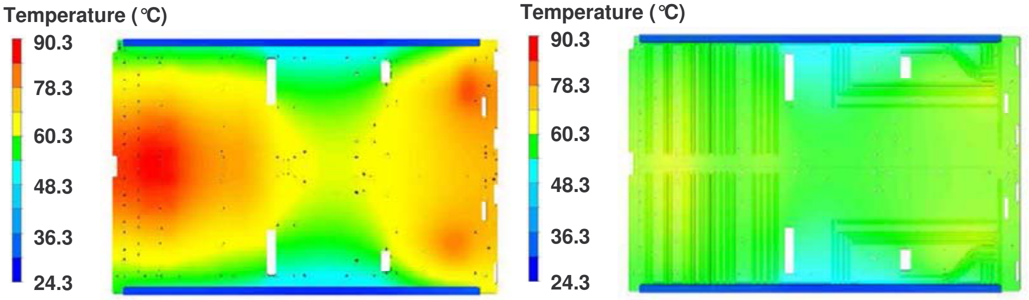


Figure 1 Temperature profiles of a baseline aluminum plate and a Hi-K plate for a military electronics cooling application where the plate was cooled by chilled water on the edges (blue)

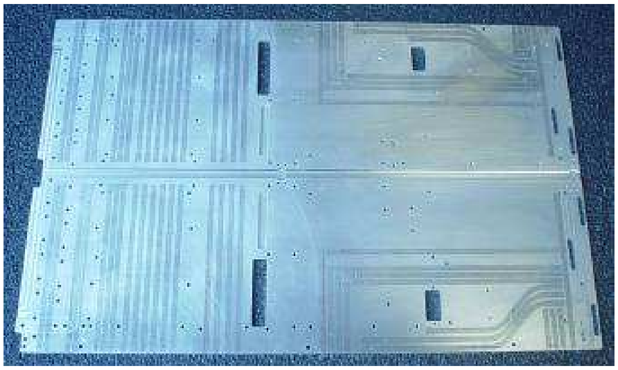


Figure 2 A HiK plate that has embedded heat pipes to increase thermal conductivity

Vapor Chambers

Vapor chambers are planar heat pipes. They are particularly accommodating to multiple heat sources, typical of electronics applications. Vapor chambers tend to produce the best heat spreading due to their ability to spread heat two-dimensionally, rather than axially in one dimension as with tubular heat pipes. Vapor chambers are often compared to Hi-K plates as both provide passive means of heat spreading. Vapor chambers are favored in applications where superior performance is critical while Hi-K plates are favored in applications where overall ruggedness is critical. Figure 3 shows a photo of a vapor chamber. Also shown is an exploded view of a vapor chamber heat sink assembly, showing a vapor chamber top plate, internal support structure and finned heat sink.

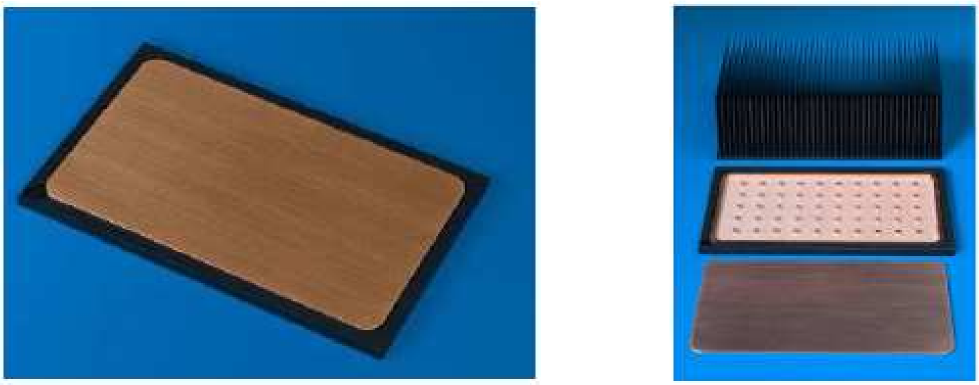


Figure 3 A complete vapor chamber assembly is shown on the left. On the right, an exploded view of a vapor chamber heat sink assembly is shown

Oscillating Flow Heat Spreaders

Oscillating flow heat spreaders remove heat from a concentrated heat source and spread the heat over a larger area by mechanically oscillating fluid in a channel. The oscillating fluid has no net motion but simply oscillates back and forth. Heat diffusion (effective thermal conductivity) is enhanced by the axial fluid mixing caused by rapidly changing velocity profiles in the fluid. Heat transfer coefficients are also enhanced by the disruption of boundary layers near the walls of heat exchanging surfaces.

Oscillating flow heat spreaders offer several benefits. First, they do not need excess fluid reservoirs, and therefore conserve valuable space in electronics packages. Second, they tend to have less thermal gradients across heat sources compared to traditional pumped liquid loops. Pumped liquid accumulates heat as it travels past heat sources causing large temperature gradients across heat sources. Since heat diffuses along oscillating flow, smaller temperature gradients can be maintained across heat sources. Finally, the largest benefit is their ability to absorb heat fluxes in excess of 1,000W/cm^2 because of the elimination of the critical heat flux limit.

Figure 4 shows a photo of a heat sink for a military power electronics module. Oscillating flow channels were integrated into the heat sink base to spread heat from the heat source located at the center of the heat sink. The temperature gradient along the heat sink base was reduced by 70% as compared to the baseline heat sink. The maximum junction temperature was decreased by 30%.

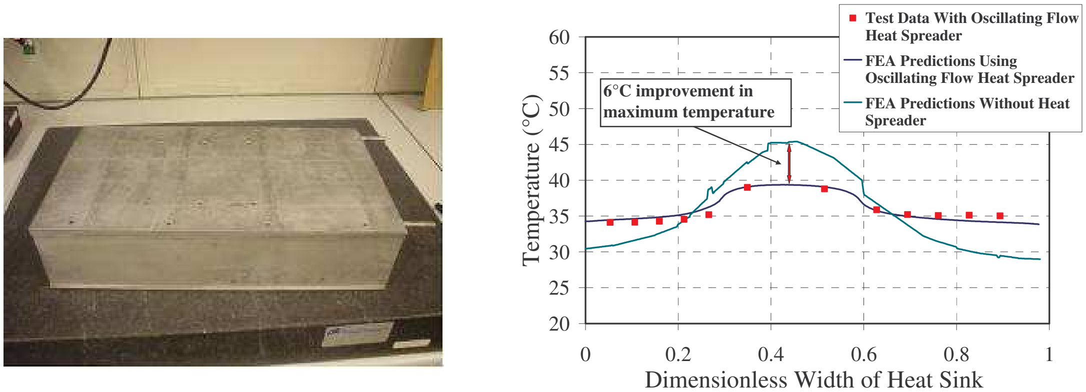


Figure 4 A heat sink incorporated with an oscillating flow heat spreader is shown. Also shown are performance predictions and test data

Advanced Heat Transport Technologies

Current vehicle thermal management relies on pumped liquid cooling loops for heat transport between heat sources and the vehicle radiator. The biggest advantage of a two-phase system over a liquid system is the large heat transfer coefficient in the evaporator. Liquid cold plates have heat transfer coefficients of 1 to 10 kW/m^2-K. Two-phase evaporators have heat transfer coefficients of 10 to 100 kW/ m^2-K. A larger heat transfer coefficient corresponds to a smaller temperature gradient between the heat source and the fluid. Consequently, the two-phase flow operates at much higher temperatures than the liquid flow. This causes an increase in the flow-to-ambient temperature difference in the radiator, reducing the radiator size and mass. Another advantage is that the flow rate in a two-phase system is much less than that in a liquid system. This contributes to a smaller pump and a more compact system. A system analysis on the Environmental Control System (ECS) of the Future Combat System showed that integrating a two-phase loop into the ECS reduces the evaporator and condenser heat loads, compressor power, condenser airflow and cooling fan power by 47%, 9.6%, 47%, 47% and 45%, respectively.

Two advanced two-phase loops, Capillary Two-Phase Loop and Hybrid Two-Phase Loop, are discussed in this section.

Capillary Two-Phase Loops

Figure 5 illustrates the concept of the Capillary Two-Phase Loop (CTPL). Like loop heat pipes, the CTPL is a completely passive heat transport device that uses the capillary force in the evaporator wick to circulate the two-phase flow. Unlike loop heat pipes, the CTPL employs a non-inverted wick design in the evaporator which is inherently inexpensive to make, tolerant to vibration and shock, and capable of high heat fluxes. Figure 6 shows a photo of a CTPL test apparatus.

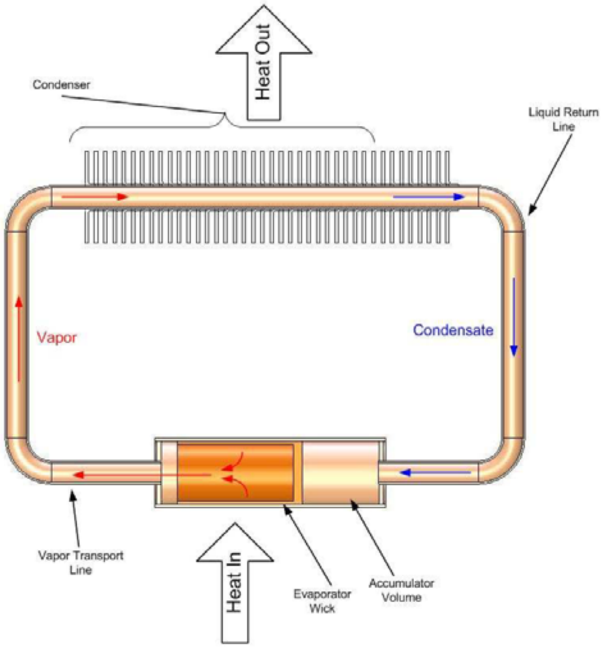


Figure 5 Capillary Two-Phase Loop Schematic

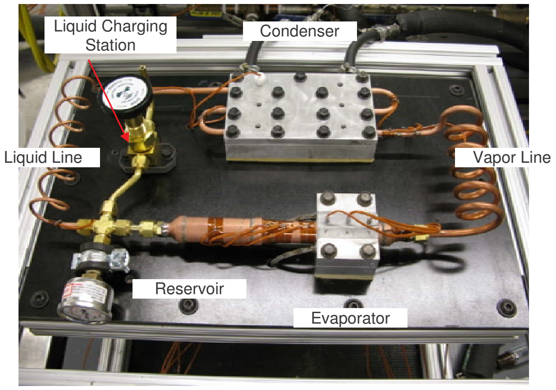


Figure 6 Capillary Two-Phase Loop Test Apparatus

Figure 7 shows the temperature profile of a CTPL that was subject to an increasing heat input from 0 to 200W and a 50℃ heat sink. The total vapor and liquid transport line length is near 1.4m. As shown, the CTPL was able to maintain the maximum heat source temperature within 65℃ (or 15℃ above the heat sink temperature).

Hybrid Two-Phase Loops

The Hybrid Two-Phase Loop (HTPL) combines the robust operation of mechanically pumped liquid loops with the passive flow control of capillary driven two-phase loops. Figure 8 illustrates the concept that consists of two sub loops: the mechanically pumped liquid loop provides robust liquid supply to multiple evaporators and returns any excess liquid to a reservoir; the capillary driven two-phase loop acquires and transports high heat flux heat loads through vaporization (in evaporators) and condensation (in condenser). Capillary wicks inside the evaporators serve as the interface between the two sub loops, providing passive phase separation and excess liquid management.

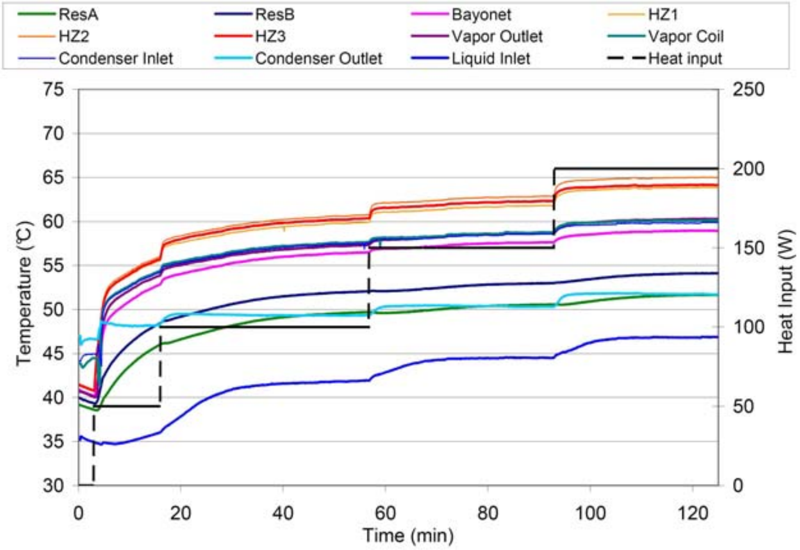


Figure 7 Example of Capillary Two-Phase Loop Test Results

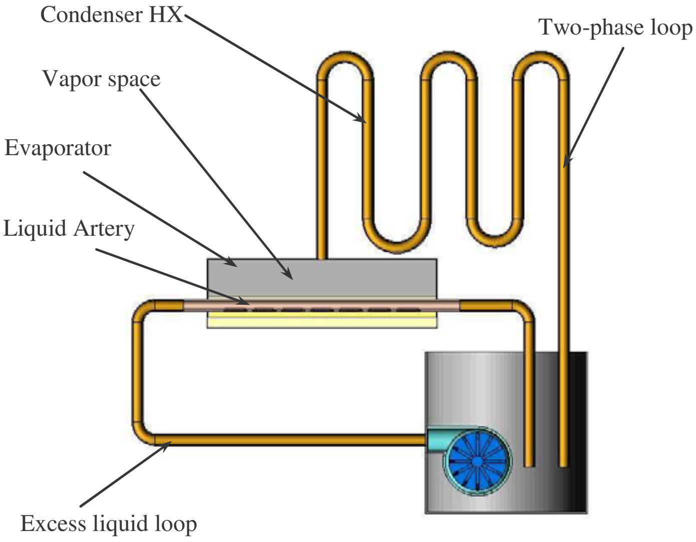


Figure 8 Hybrid Two-Phase Loop Schematic

Compared to other pumped two-phase systems such as evaporative spray and jet impingement, the biggest advantage of the HTPL is the passive control of the liquid supplied to the high heat flux area. The high heat flux area receives only the right amount of liquid, and any excess liquid is returned to the reservoir without entering the high heat flux area. This passive (and self adapting) control eliminates the dry-out or flooding in the high heat flux area that may be caused by varying heat loads and/or orientations in conventional pumped two-phase systems.

The following performance characteristics of the HTPL technology have been demonstrated in laboratory testing:

- Heat flux: 180 to 1,200W/cm².
- Heat transport: >10kW per loop and 4kW per evaporator.
- Large area heat source: 0.5 to 135cm².
- Multiple evaporators: one (1) to seven (7).
- Flow control: No active flow control needed at varying heat loads and orientations.
- Orientation: insensitive to the gravity orientation.
- Shock and vibration: tested to a Mil-Spec vibration/shock.

Figure 9 shows a photo of a full scale HTPL that was designed, fabricated and tested to various military thermal, shock and vibration specs. This HTPL is rated 10kW of heat transport capacity and has four evaporators for discrete heat sources.

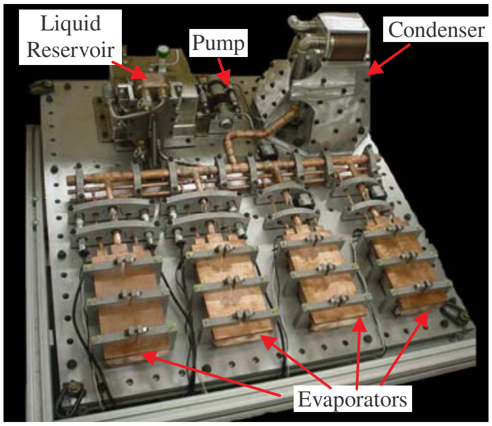


Figure 9 4-Evaporator, 10kW HTPL

Advanced Temperature Control Technologies

Conventional temperature control technologies use variable speed air blowers or liquid bypass to adjust the heat transport or dissipation performances. These technologies rely on active sensing and feedback which are not always reliable. In this section, a passive and therefore more reliable temperature control technology is discussed.

Variable Conductance Heat Pipes

A Variable Conductance Heat Pipe (VCHP) is similar to a conventional heat pipe, but has a reservoir and controlled amount of non-condensable gas (NCG) inside the reservoir. As shown in Figure 10, when the heat pipe is operating, the NCG is swept toward the condenser end of the heat pipe by the flow of the working fluid vapor. The NCG then blocks the vapor from reaching a portion of the condenser. As the evaporator temperature increases, the vapor temperature (and pressure) rises, the NCG compresses (Figure 10 top) and more condenser is exposed to the working fluid. This increases the conductivity of the heat pipe and drives the temperature of the evaporator down. Conversely, if the evaporator cools, the vapor pressure drops and the NCG expands (Figure 10 bottom). This reduces the amount of available condenser, decreases the heat pipe conductivity, and drives the evaporator temperature up.

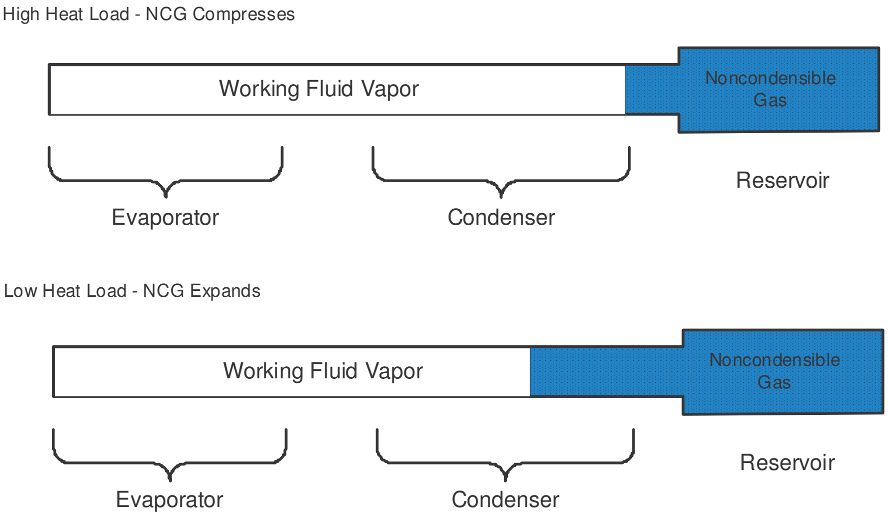


Figure 10 Variable Conductance Heat Pipe Schematic

Figure 11 shows a typical VCHP used to passively control the temperature of spacecraft electronics over varying sink conditions and thermal loads.

Figure 11 VCHP with NCG Reservoir for Spacecraft Thermal Control

Figure 12 shows the thermal performance of a VCHP built and tested for a spacecraft application. The evaporator section of the VCHP was passively controlled to ±1.65ºC as the heat input was doubled from 72W to 150W and as the sink temperature ranged from +15ºC to -65ºC.

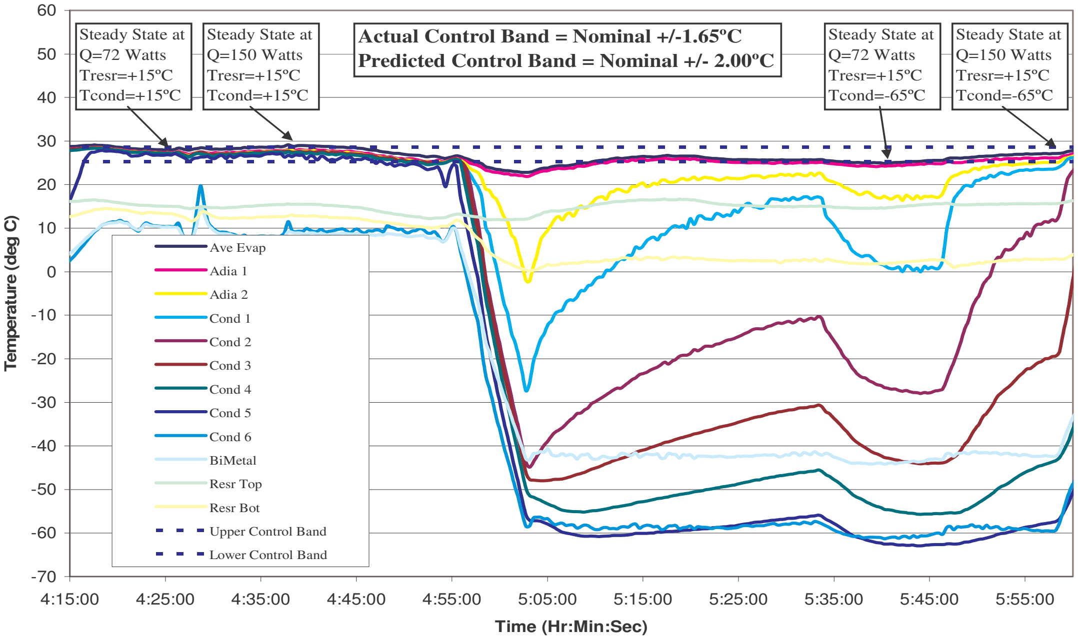
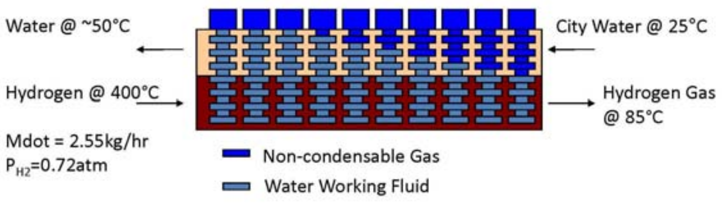


Figure 12 Performance Data for an Aluminum/Ammonia VCHP

VCHP Heat Exchangers

VCHP heat exchangers can provide a passive means (no valves, sensors, actuators, or control algorithms) of regulating process gas temperatures over a wide range of process gas flow rates and temperatures. One application for VCHP heat exchangers is fuel cell reformers, which convert diesel fuel and steam into a hydrogen rich gas supply that feeds the fuel cell stack. The operating temperature of the reactors must be closely controlled to maintain their chemical equilibrium. Temperature control is made more difficult than typical reforming systems because changes in the fuel cell electrical load and the resulting changes in reactant flow rates occur more frequently and drastically. Inlet and outlet temperatures for the reactors must be maintained within ±30℃ despite a turndown ratio of 5:1 in reactant flow rate. The VCHP heat exchanger replaces a bypass valve, which has several drawbacks: (1) requires active control, (2) requires power, and (3) has a large pressure drop. A schematic of the VCHP heat exchanger is shown in Figure 13. At high temperatures or gas flow rates, the NCG is compressed, with maximum heat transfer between the streams. At low flow rates or gas temperatures, the condenser is partially blocked off, lessening the amount of heat transferred.

Figure 14 shows typical test results and predictions for a VCHP heat exchanger for the fuel cell application. The measured outlet temperature of the hydrogen changed 16℃ over an inlet temperature change of 212℃. The temperature variation for a typical heat pipe heat exchanger would be 53℃.



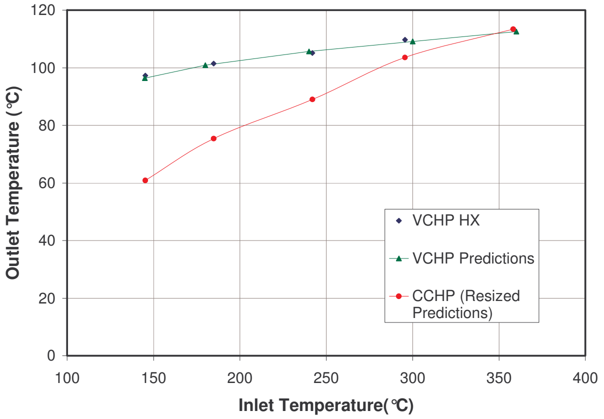


Figure 13 VCHP Heat Exchanger Schematic

Figure 14 Test data and predictions for a VCHP heat exchanger

Conclusions

Using a "levels of cooling" approach, this paper identifies three key categories of cooling technologies required to form an effective vehicle thermal architecture: Heat Spreader, Heat Transport, and Temperature Control. For each category, this paper first briefly analyzes the shortcomings of the current technologies and then discusses advanced technologies that may effectively replace the current technologies. Some specific conclusions can be made in the three categories:

(1) Heat Spreader:
    a. All three advanced heat spreaders, HiK Plates, Vapor Chambers and Oscillating Flow Heat Spreaders, offer superior performances over current Cu, Aluminum, Cu-W and Cu-Mo spreaders.
    b. HiK Plate is the lowest cost and lowest performance of the three advanced heat spreaders.
    c. Oscillating Flow Heat Spreader offers the highest performance at the price of introducing active components.
    d. Vapor chamber offers equivalent performance to oscillating flow heat spreaders. It is probably the most expensive of the three advanced heat spreaders.
(2) Heat Transport:
    a. Capillary Two-Phase Loop and Hybrid Two-Phase Loops are both capable two-phase heat transport devices that offer substantially improved performance and reduced mass and volume compared to conventional pumped liquid loops.
    b. Capillary two-phase loop is most suited for mid-power (less than 1kW) and mid-distance (less than 10ft) heat transport, particularly for Level 3 heat transfer from the circuit board to the chassis.
    c. Hybrid two-phase loop is most suited for high power (> 1kW) and long distance (> 10ft) heat transport, particularly for Level 4 heat transport from chassis to system heat exchanger.
(3) Temperature Control:
    a. Variable Conductance Heat Pipes (VCHP) and related heat exchangers offer passive (and therefore reliable) temperature control for protection of electronics in environments with large temperature swings.

These advanced thermal management technologies have passed laboratory development stages. Some of them (e.g. HiK Plates, VCHPs) have been used in mission critical military and space systems, while others (e.g. oscillating flow heat spreaders, hybrid two-phase loops) require additional system level demonstration before actual deployment.

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