

Hybrid Heat Pipes for Lunar and Martian Surface and High Heat Flux Space Applications

Mohammed T. Ababneh¹, Calin Tarau², and William G. Anderson³

Advanced Cooling Technologies, Inc. 1046 New Holland Ave. Lancaster, PA 17601, USA

Jeffery T. Farmer⁴

NASA Marshall Space Flight Center, Huntsville, AL 35808, USA

Angel R. Alvarez-Hernandez⁵

NASA Johnson Space Center, Houston, TX 77058, USA

Novel hybrid wick heat pipes are developed to operate against gravity on planetary surfaces, operate in space carrying power over long distances and act as thermosyphons on the planetary surface for Lunar and Martian landers and rovers. These hybrid heat pipes will be capable of operating at the higher heat flux requirements expected in NASA's future spacecraft and on the next generation of polar rovers and equatorial landers. In addition, the sintered evaporator wicks mitigate the start-up problems in vertical gravity aided heat pipes because of large number of nucleation sites in wicks which will allow easy boiling initiation. ACT, NASA Marshall Space Flight Center, and NASA Johnson Space Center, are working together on the Advanced Passive Thermal experiment (APT_x) to test and validate the operation of a hybrid wick VCHP with warm reservoir and HiK™ plates in microgravity environment on the ISS.

Nomenclature

| | | |
|------------------|---|---|
| ACT | = | Advanced Cooling Technologies, Inc. |
| APT _x | = | Advanced Passive Thermal experiment |
| CCHPs | = | Constant Conductance Heat Pipes |
| EWHP | = | Electrowetting Heat Pipe |
| ISS | = | International Space Station |
| LHPs | = | Loop Heat Pipes |
| NASA | = | the National Aeronautics and Space Administration |
| NCG | = | Non Condensable Gas |
| VCHPs | = | Variable Conductance Heat Pipes |
| WEB | = | Warm Electronics Box |

I. Introduction

A hybrid wick heat pipe has a porous wick in the evaporator, and a grooved wick in the adiabatic and condenser sections. This paper will discuss two different applications for hybrid wick heat pipes: 1. Adverse evaporator elevations for landers and rovers, and 2. Vertical startup with a liquid column during ground testing. ACT also develops hybrid wick heat pipes for high heat flux applications; this will be discussed in a future paper.

The next generation of polar rovers and equatorial landers is among the near-term NASA applications. A variable conductance heat pipe (VCHP) is required which can operate during large tilts, shut down during the long Lunar night and operate over a wide sink temperature fluctuations on the Lunar surface. The next generation of landers and rovers have a Warm Electronics Box (WEB) and a battery, both of which must be maintained in a fairly narrow temperature range. This requires a variable thermal link between the WEB and the radiator. During the day, the thermal link must transfer heat from the WEB to the radiator as efficiently as possible, to minimize the radiator size. On the other hand, the thermal link must be as thermally isolating as possible during the Lunar night to

¹ R&D Engineer II, Defense/Aerospace Group, Mohammed.Ababneh@1-act.com

² Lead Engineer, Defense/Aerospace Group, Calin.Tarau@1-act.com

³ Chief Engineer, Bill.Anderson@1-act.com

⁴ Project Manager, ES20, MSFC, AIAA Member.

⁵ Passive Thermal Technical Discipline Lead, NASA Johnson Space Center.

preserve the electronics and battery warm with minimal power, even if the sink temperature is very low. This variable thermal link also requires hybrid wick to allow liquid return during operation under unfavorable orientation of the evaporator. After testing on earth, the heat pipes will be tested in micro-gravity environment on the International Space Station (ISS) for two reasons:

1. To make sure that the hybrid wick works in reduced gravity environments because the potentially lander application requires operation in microgravity.
2. To raise the overall TRL level of the hybrid wick heat pipes and HiK™ plates.

Parameters for the considered system are shown in

Table 1.

Table 1. Hybrid wick heat pipe requirements for Lunar landers and rovers.

| Attribute | NASA Requirements |
|--|--|
| Minimum Electronics Temperature | -10 °C |
| Maximum Electronics Temperature | 50 °C |
| Maximum Radiator Load (Moon) | 100 W to 150 W, 150 W preferred |
| Power During Transit (Space) | 100 W to 150 W, 150 W preferred |
| Mission Duration | ~ 6 years |
| WEB/Bus Geometry | 24" (0.61m) x 41" (1.04m) x 14" (0.36m) (height) |
| Maximum Tilt | 14° (lander), 25° (rover), 25 ° preferred |
| Radiator Emissivity | 0.8 |
| Minimum Radiator Sink Temperature (Moon) | 96 K (parasitic heating from lander) |
| Maximum Radiator Sink Temperature (Moon) | 269 K |
| Cruise Sink Temperature (Space) | 168 K |
| Minimum Soil Temperature | 100 K |
| Maximum Soil Temperature | 390 K |
| Condenser Length | 12" (0.30m) |
| Adiabatic Section Length | 18.6" (0.47m) |
| Evaporator Length | 9" (0.23m) |

A second application for hybrid wick heat pipes is to aid in ground testing. Due to their large pore size, VCHPs and CCHPs are typically tested individually with a 0.1 inch (0.254cm) adverse elevation to avoid puddle flow. During thermal vacuum testing, the heat pipes will only operate if they are level, or gravity aided. When the CCHP is gravity aided, all of the working fluid drains into the evaporator, often filling it with liquid. For the heat pipe to startup, pool boiling must occur, with nucleation of a vapor bubble. In some cases, the superheat required is too high, and a startup heater must be added during ground testing. This startup heater can be eliminated with a sintered evaporator wick.

II. Background

It is recognized that CCHPs offer the simplest two-phase capillary-driven heat transport solution. The CCHP needs a wick structure throughout to return liquid from the condenser to the evaporator. As this structure presents a liquid-side pressure drop that competes with the capillary pressure developed by the wick, overall heat transport distance is limited. A LHP overcomes this disadvantage by not using wicked transport lines. This allows for much greater transport distances. In addition, LHP wick design allows for higher developed capillary pressure and greater heat transfer surface area than a CCHP of the similar dimensions. Consequently, a LHP can handle much higher heat fluxes than CCHPs. However, LHP design fabrication and testing is considerably more complex than a standard heat pipe and, as a result, considerably more expensive.

Grooved Aluminum/Ammonia Heat Pipes

Grooved wicks are typically used in spacecraft CCHPs, and VCHPs. Typical aluminum grooved extrusions are shown in Figure 1. These grooves have a very high permeability, allowing very long heat pipes for operation in micro-gravity, typically several meters long. One of their weaknesses is that they are suitable only for space, or for gravity aided sections of a heat pipe. The reason is that the same large pore size responsible for the high permeability results in low pumping capability.

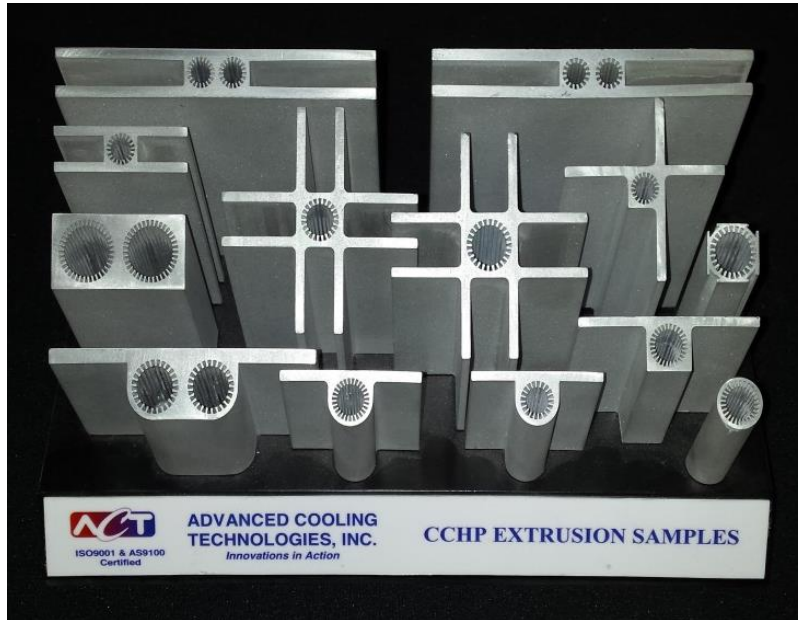


Figure 1. Grooved aluminum extrusions for ammonia heat pipes. Grooves allow long heat pipes for spacecraft applications, but only work about 0.10 inch (0.00254m) against gravity for earth-based testing (ACT Inc.,² 2013).

Grooved aluminum/ammonia heat pipes are designed to work with a 0.10 inch (0.25cm) adverse elevation (evaporator elevated above the condenser). This allows them to be tested on earth prior to insertion in a spacecraft. However, they are very sensitive to adverse elevation. In our previous work, it was shown experimentally that increasing the heat pipe elevation by 0.010 inch (0.0254cm) will significantly decrease the power⁷. For heat pipes operating on the Moon or Mars, grooves can only be used in gravity-aided portions of the heat pipe. Another wick must be found for sections with adverse elevations, e.g. sintered powder, screen mesh, or metal foam wicks.

Variable Conductance Heat Pipe (VCHP)

A VCHP is similar to a conventional heat pipe, but has a reservoir and a controlled amount of non-condensable gas (NCG) inside the reservoir. This NCG is used to regulate the overall thermal conductance of the heat pipe. By regulating the thermal conductance, the temperature at which the VCHP operates can be controlled even with variations in the heat load. Information on VCHPs can be found in (Brennan and Kroliczek³, 1979), and (Marcus⁴, 1971). When the VCHP 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 working fluid from reaching a portion of the condenser. The VCHP works by varying the amount of condenser available to the working fluid for heat transfer. As the evaporator temperature increases, the vapor temperature (and vapor pressure) rises, the NCG compresses (Figure 2, top) and more of the condenser is exposed to the working fluid. This increases the effective 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 2, bottom). As the NCG begins to fill the condenser, the heat pipe effective conductivity decreases, and the evaporator temperature decrease is minimized.

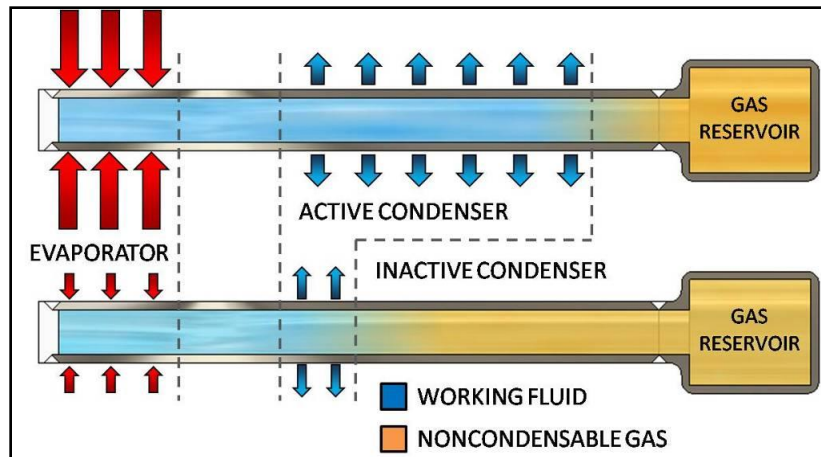


Figure 2. Operation of a VCHP. As heat load increases, the temperature dependent saturation pressure of the working fluid increases and the NCG is compressed into the reservoir (top). As heat input decreases, the working fluid saturation pressure decreases and the non-condensable gas is allowed to expand into the condenser (bottom).

For the simple VCHP illustrated in Figure 2, the reservoir is cold-biased in most spacecraft applications. Electric heaters on the reservoir are then used to control the temperature to within $\pm 2^\circ\text{C}$. During the long Lunar day, the thermal management system must be capable of removing the waste heat from the WEB and ensuring the WEB does not get too warm. During the long Lunar night, the variable thermal link for the WEB must limit the amount of heat that is removed from the WEB and radiated to space. This will keep the electronics and battery warm with minimal power, even with the very low temperature (100 K) environment. A variable thermal link (typically a VCHP) is needed which can operate during large tilts, over a wide sink temperature swings on the Lunar surface and shut down during the long Lunar night.

In contrast to the standard cold, electrically-heated reservoir at the end of the condenser, the hybrid wick VCHP has a warm reservoir located adjacent to the evaporator. This eliminates the 1-2 Watts required to keep the reservoir at the correct temperature. This is a necessity for Lunar applications, where it is estimated that supplying 1 W over the 14 day long Lunar night requires 5 kg of solar cells, batteries, etc. Note that a warm reservoir does not provide the same tight temperature range as an electrically heated reservoir, but this is not a problem for the envisioned applications.

High Conductivity Plates (HiK™ Plates)

The HiK™ plate represents a technology developed at ACT (ACT Inc.⁵, 2013) that consists of heat pipes embedded in a plate as shown in Figure 3, below. The embedded heat pipes are soldered in place, and then the surface is fly-cut to provide a smooth surface. The weight of a HiK™ plate is roughly similar to its solid counterpart; however, effective thermal conductivities range from 500 to 1200 W/m.K (versus ~ 200 W/m.K for aluminum). In some spacecraft applications the effective thermal conductivity can be as high as 2500 W/m.K, equivalent to diamond. For applications with large variations in heat load across a surface, such as electronics boards, the embedded heat pipes can be customized to provide controlled heat transfer across the plate. The addition of HiK™ plates to the electronics enclosure would further decrease the temperature gradient within this device by eliminating hot spots and improving overall heat transfer.

Analysis of a HiK™ Plate is shown in Figure 4 using finite element analysis to compare the performance of a solid aluminum plate and potential improvements using an aluminum plate with embedded copper/water heat pipes. The conventional aluminum plate's highest temperature was 90.3°C whereas the HiK™ aluminum plate is 69.1°C . This is a considerable performance improvement. HiK™ can contain both copper/water and copper/methanol heat pipes. Note that the copper/water heat pipes drop in efficiency below about 20°C , due to the water properties. At 0°C , the water heat pipe will freeze, and will make no contribution to the thermal conductivity until they thaw again. By controlling the water inventory so that no free liquid is available, HiK™ plates have been shown to withstand thousands of freeze/thaw cycles.

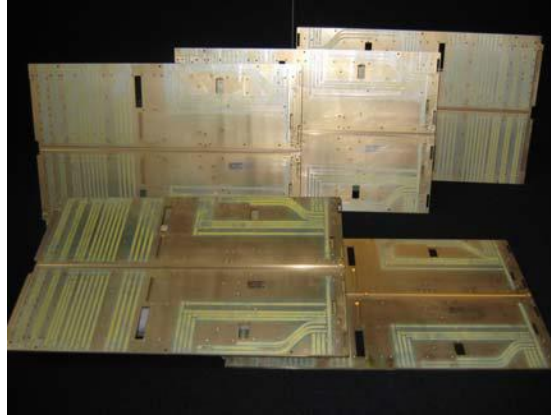


Figure 3. High conductivity aluminum (HiK™ Aluminum) plates with embedded heat pipes.

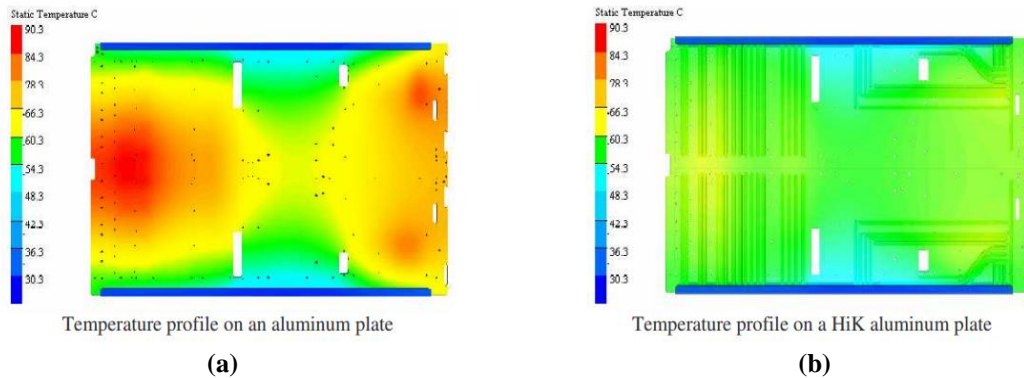


Figure 4. FEA for a particular application with multiple heat sources across the plate. For a) Temperature distribution on the standard aluminum plate b) Temperature distribution on the HiK™ plate. A reduction in peak temperature of 21°C can be observed.

International Space Station (ISS)

The ISS as shown in Figure 5 is the only long-duration platform existing in the relevant space environment with an integrated space systems construction that can be used to validate operations concepts and advanced technologies. The ISS program offers an infrastructure capable of demonstrating and validating prototypes and systems that may advance spaceflight technology readiness. The space station, the in-orbit crew, the launch and return vehicles, and the operation control centers are all supporting the demonstration of advanced systems and operational concepts that will be needed for future exploration missions. (Hornyak⁶, 2013)



Figure 5. The International Space Station as seen from the departing Space Shuttle Atlantis during STS-132.

Hybrid wick VCHP with warm reservoir and HiK™ plate had never been tested in micro-g environment. ACT, NASA Marshall Space Flight Center, and the International Space Station office at NASA's Johnson Space Center will test the hardware on the ISS.

III. Hybrid Wick Heat Pipes Concept

Heat flux limit in axial grooved heat pipe evaporators normally starts at 5-15 W/cm². In order to increase the heat flux limit to more than 50 W/cm², the concept as shown in Figure 6 is to develop heat pipes with a hybrid wick that contains screen mesh or sintered evaporator wicks for the evaporator region, which can sustain high heat fluxes, where the axial grooves in the adiabatic and condenser sections can transfer large amounts of power over long distances due to their high wick permeability and associated low liquid pressure drop.

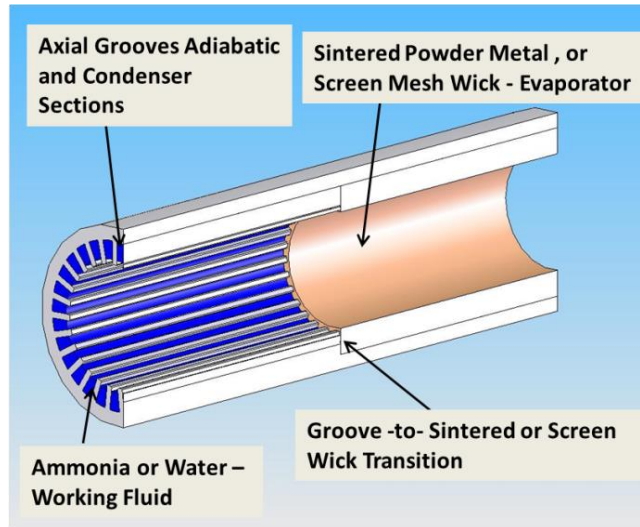


Figure 6. Hybrid CCHPs: axial grooved adiabatic and condenser sections - screen mesh or sintered evaporator wick.

The previous work⁷ shows that the hybrid screen/grooved wicks CCHP did not meet the goal for the program (The total power that will be dissipated for the high heat flux applications is 150 W or higher however the heat flux will be at most 50 W/cm²) so the screen mesh wick was ruled out. Instead, the sintered wicks offer the highest operating heat flux capability and height against gravity compared to screen, foam, and grooved wicks. Hybrid wick heat pipes have the following advantages:

- The sintered-powder-metal evaporator wick is capable of operating at higher heat fluxes in comparison to the axial groove design and can also operate against gravity on the planetary surface.
- The grooved condenser wick in the hybrid CCHPs allows the heat pipe to operate in space, carrying power over long distances.
- The grooved condenser wick in the hybrid CCHPs allows the heat pipe to act as a thermosyphon on the planetary surface for Lunar and Martian landers and rovers. Thus, it is valuable for Lunar/Martian rover and lander applications.
- The combination has a higher transport capability than a porous wick.

Figure 7 depicts the planetary hybrid VCHP evaporator design. The wick design has a cross-sectional flow area over five times larger than that of the standard wick without increasing the ΔT through the wick (i.e., ΔT from evaporator wall to vapor).

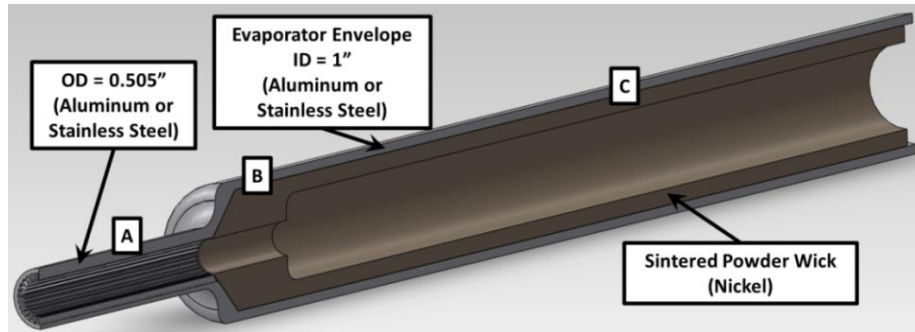


Figure 7. Planetary VCHP evaporator design (sintered wick after insertion into evaporator).

Working fluid returning from the condenser is pumped by the grooves (section A) to the beginning of the sintered wick. A 45° conical interface hydraulically joins the axial grooves to the sintered metal powder wick. There is a 1.25 inch (0.031m) length of adiabatic section (section B) within the sintered wick, which has a vapor core diameter nearly identical to that of the grooves. The evaporator begins at the start of the large diameter cavity (section C) in the sintered wick and has a total length of 9.25 inches (0.23m). Figure 8 contains a cross sectional right view and detail view (inset) of the grooved wick to sintered wick interface. The flow path of the liquid return is shown. This 45° conical interface utilizes a relatively thick amount of sintered powder material to ensure a structurally robust feature (Ababneh et al.⁷, 2015).

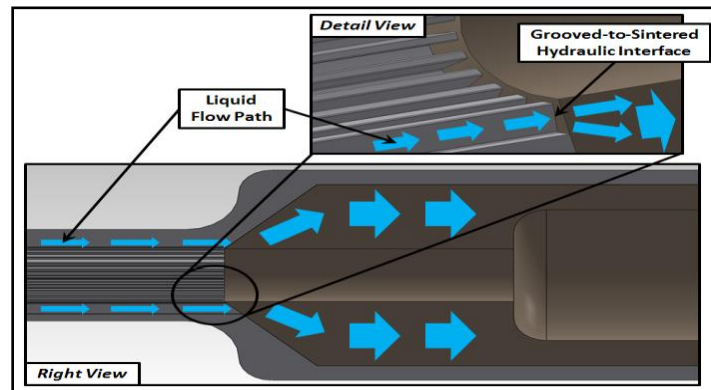


Figure 8. Planetary VCHP evaporator 45° conical interface (cross sectional right view and detail view).

IV. Start-up Difficulties in Vertical Gravity Aided Heat Pipes

For planetary applications, a heat pipe has to operate both in gravity and micro-g environments, thus a conventional, all grooved wick is not appropriate. As an alternative, a hybrid wick is under development as shown in Figure 8. All of the adiabatic and condenser sections have axial grooves for liquid return. The evaporator section uses sintered wick, which has higher capillary pumping pressure than grooves, and which allows the evaporator to be tilted as much as 25° against lunar gravity, accommodating different orientations due to the rough lunar surface.

In addition, sintered evaporator wicks may also eliminate start-up difficulties in vertical gravity aided heat pipes. Swanson and Butler⁸ (2009) have observed start-up difficulties in vertical, grooved aluminum/ammonia heat pipes developed for the Mars SAM (Sample Analysis at Mars) instrument on the Mars Scientific Laboratory (MSL). They believe that start-up was delayed because the heat pipe temperature needed to increase until pool boiling was initiated. A start-up heater was added to solve this problem. ACT theorized that the problem could also be solved with a hybrid wick because of the large number of nucleation sites in wicks which will allow easy boiling initiation in pool boiling systems (Anderson et al.⁹, 1990).

The sintered and grooved evaporator wick heat pipes were tested to verify the hypothesis that the start-up related temperature spikes in vertical gravity aided heat pipes can be eliminated by using sintered evaporator wicks. The

assumption was based on the fact that sintered wicks present a large number of nucleation sites which will allow easy boiling initiation in the sintered wicks evaporator. Therefore, two 12" (0.30m) long heat pipes were fabricated and tested: a conventional axial grooved heat pipe, and a hybrid sintered/grooved heat pipe as shown in Figure 9.

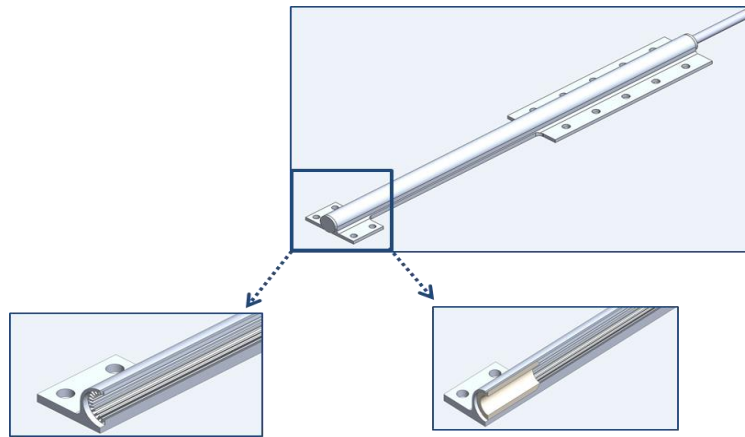


Figure 9. Top: Drawing for the external geometry for the axial grooved and the hybrid CCHP, Bottom left: axial grooved CCHP, Bottom right: hybrid sintered/grooved CCHP.

Figure 10 shows the testing apparatus for the start-up investigation in vertical heat pipes. The testing results for the axial grooved and the hybrid heat pipes at the optimal charged, 10% overcharged, and 20% overcharged with ammonia as a working fluid are shown in Figure 11, Figure 12, and Figure 13. These figures show that the temperature spikes (the temperature spikes are highlighted using the circle) in vertical gravity aided heat pipes are minimized/eliminated by using sintered evaporator wicks.

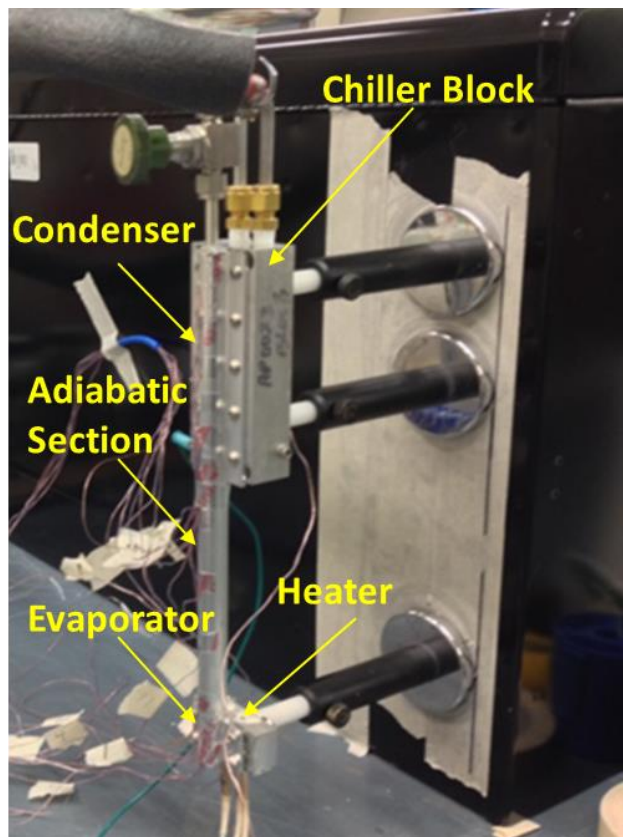
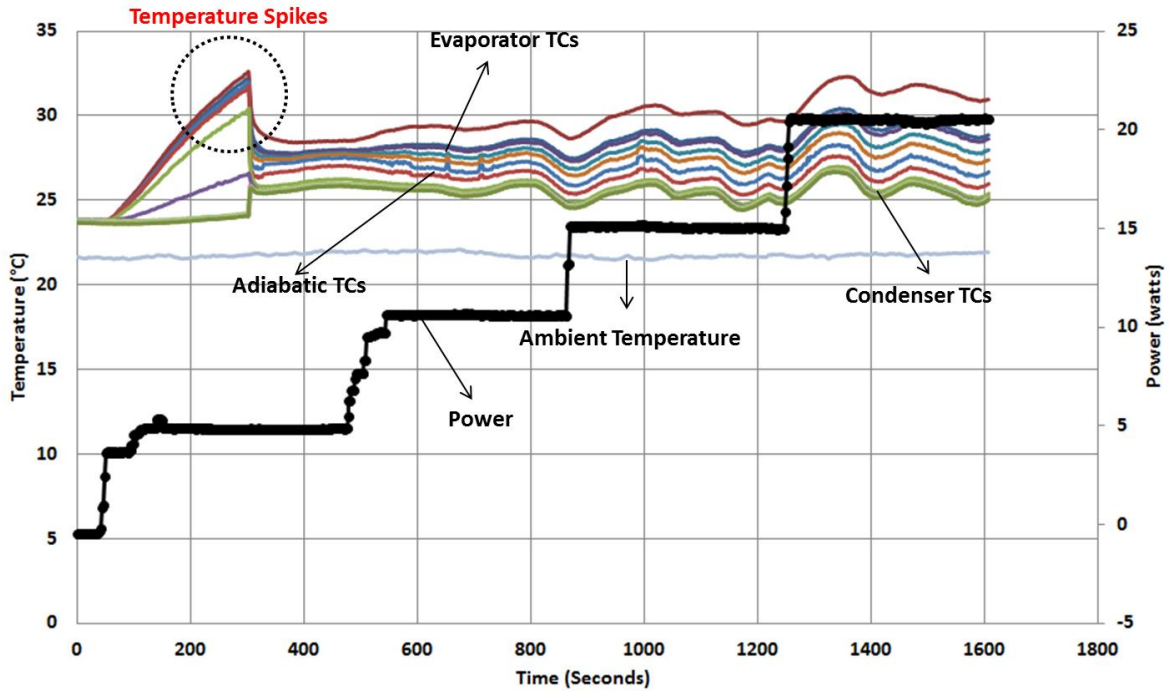
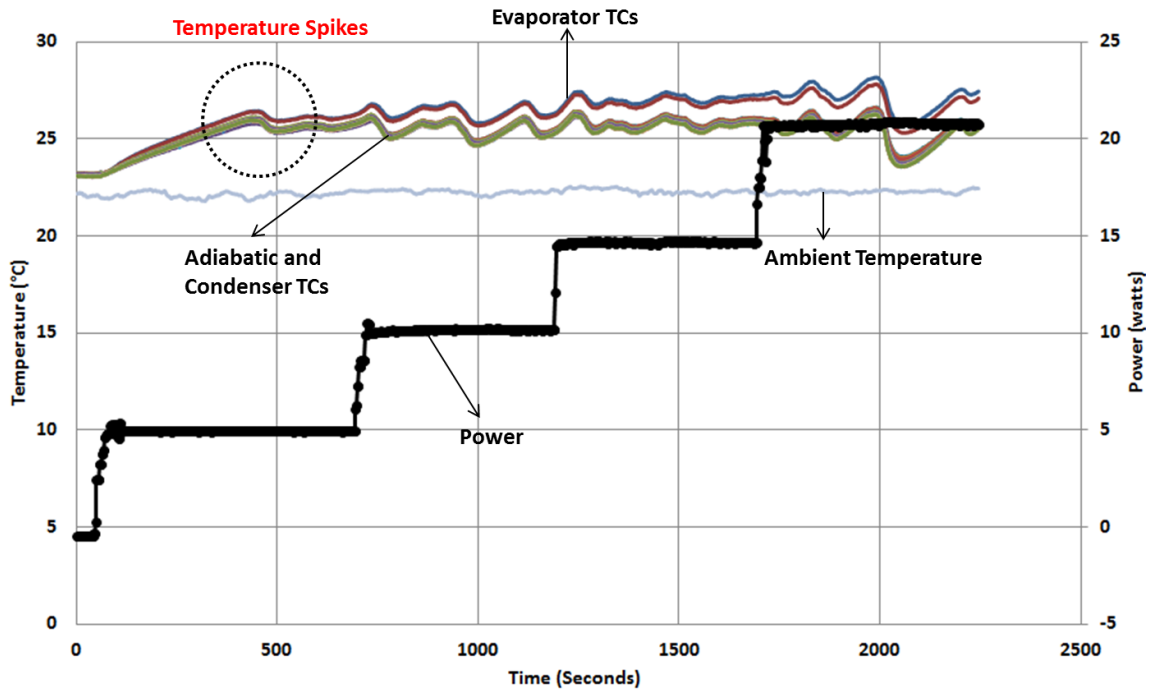


Figure 10. Testing apparatus for the start-up problem in vertical heat pipes.



(a)



(b)

Figure 11. Thermal performance profiles for aluminum CCHP where power was applied in 5 W increments while condenser set-point was maintained at 25°C at the optimal charged amount: (a) grooved, (b) hybrid.

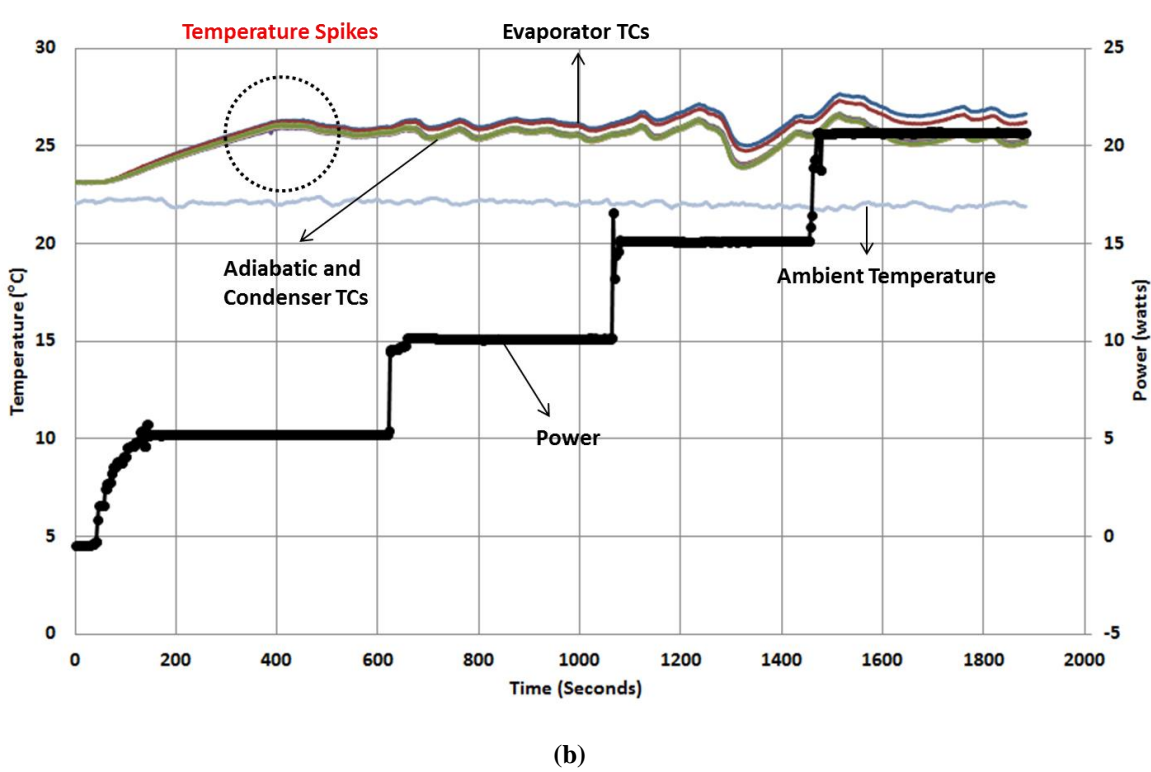
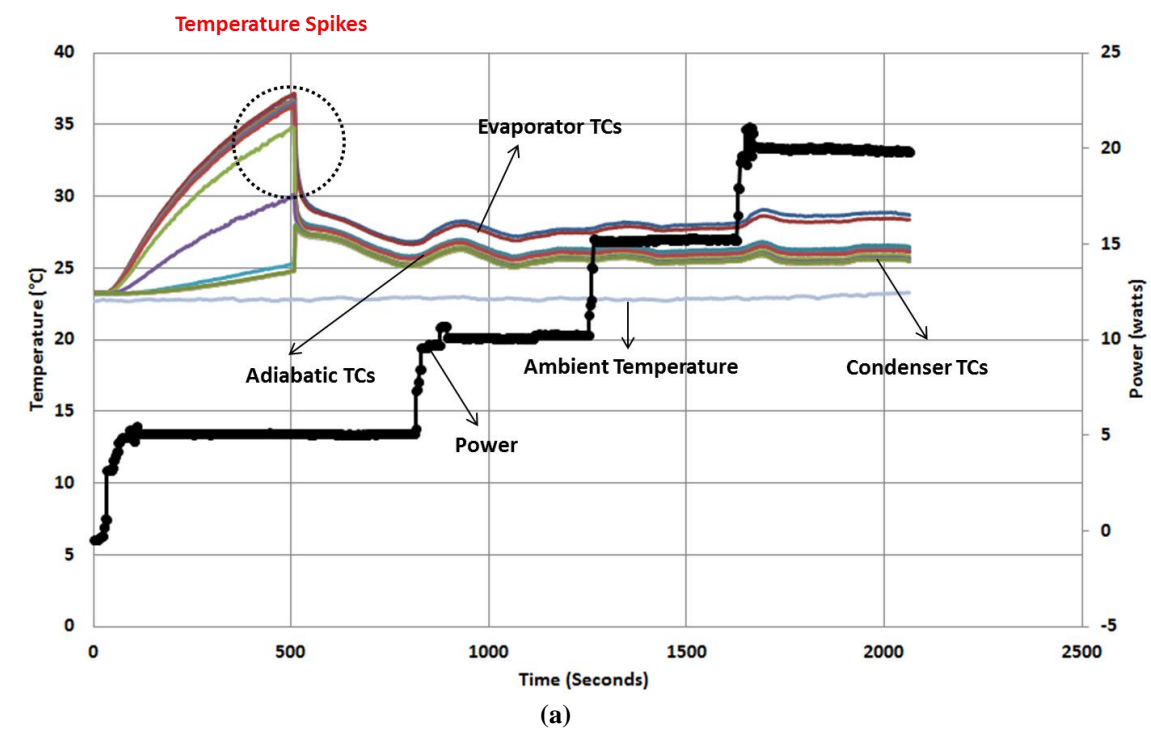
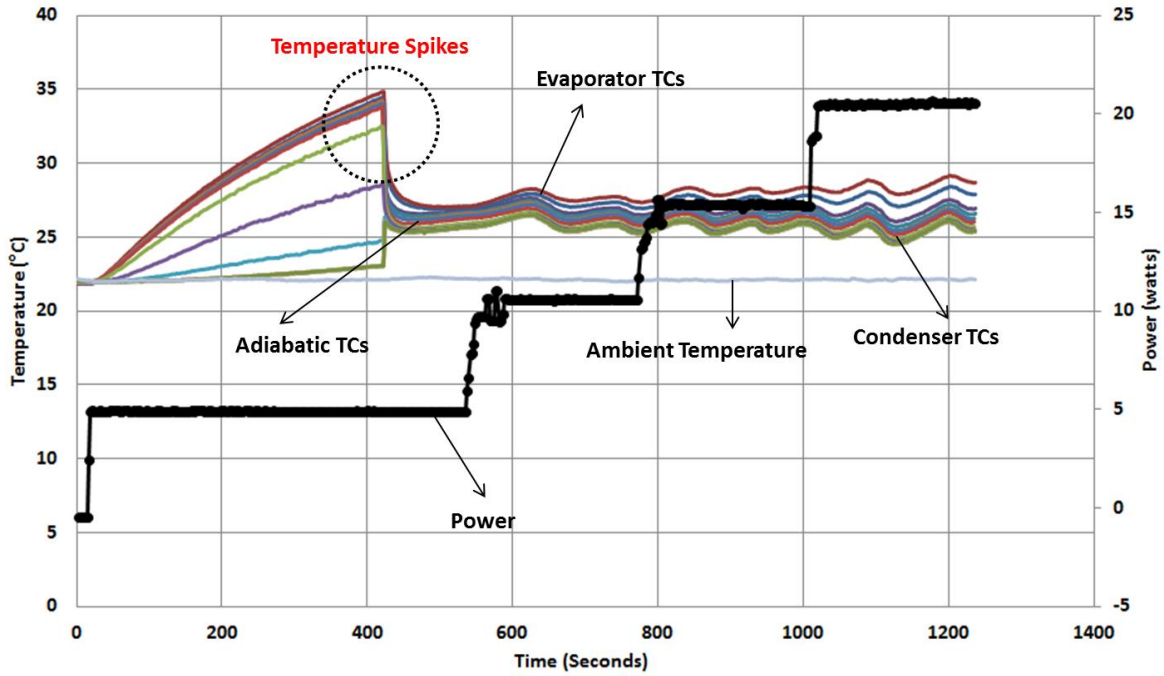
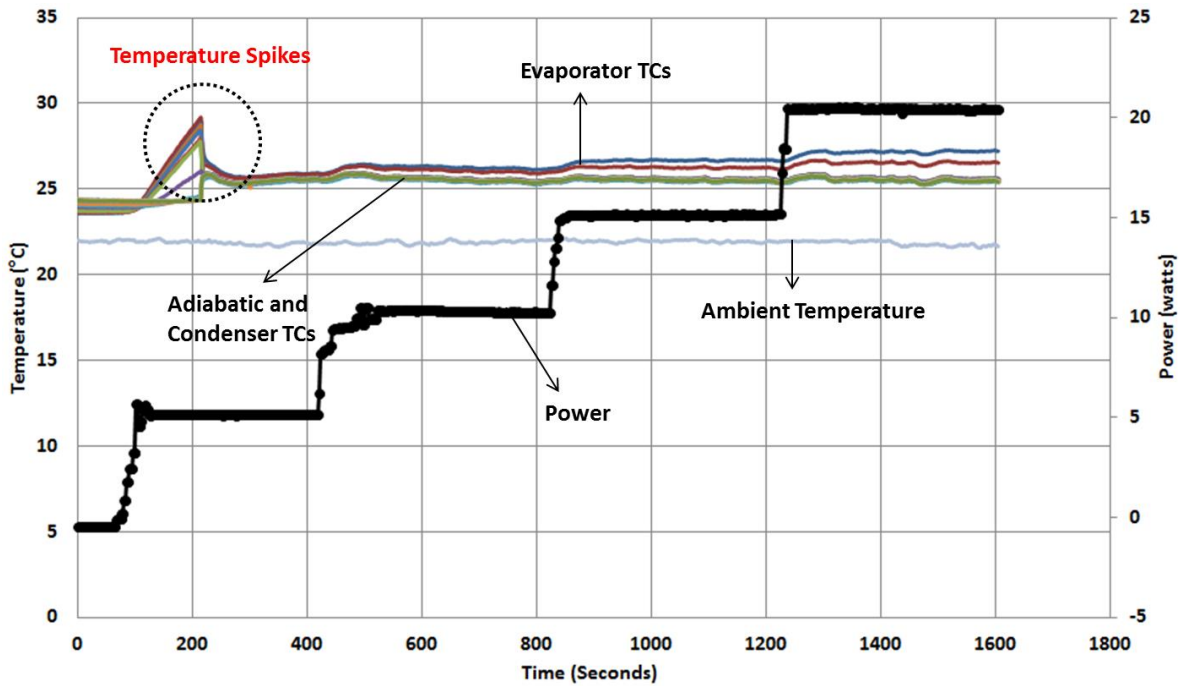


Figure 12. Thermal performance profiles for aluminum CCHP where power was applied in 5 W increments while condenser set-point was maintained at 25°C at the 10 % overcharged amount: (a) grooved, (b) hybrid.



(a)



(b)

Figure 13. Thermal performance profiles for aluminum CCHP where power was applied in 5 W increments while condenser set-point was maintained at 25°C at the 20 % overcharged amount: (a) grooved, (b) hybrid.

Figure 14 shows the maximum temperature on the grooved and hybrid heat pipes with 0, 10 and 20 percent overcharged at a heat input of 5 W. It is observed that the thermal resistances for the grooved heat pipe are higher

than those for the hybrid heat pipe during startup operation. Furthermore, for both heat pipes, as the overcharge amount of ammonia increases, the overall thermal resistances increase.

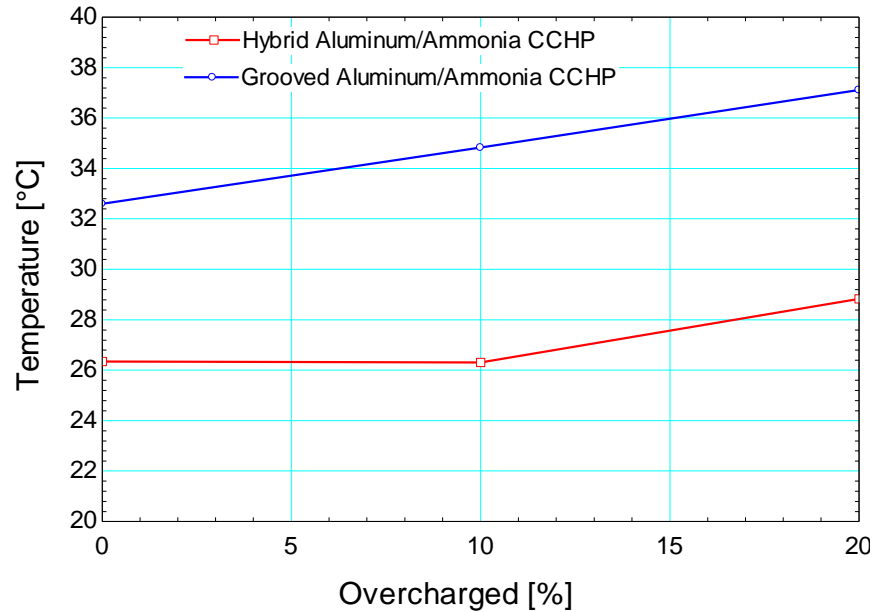


Figure 14. The maximum evaporator temperature during startup (heat input of 5 W) of the grooved and hybrid heat pipes with 0, 10 and 20 percent of overcharge amount of ammonia.

Currently, the hybrid CCHPs and VCHPs for high heat flux space applications and planetary surface are under fabrication at ACT for experimental demonstration in the near future.

V. ISS Flight Hardware

As NASA prepares to further expand human and robotic presence in space, it is well known that spacecraft architectures will be challenged with unprecedented thermal environments in deep space. In addition, there is a need to extend the duration of the missions in both cold and hot environments, including cis-lunar and planetary surface excursions. The heat rejection turn-down ratio of the increased thermal loads in the above mentioned conditions is crucial for minimizing vehicle resources (e.g. power). Therefore, future exploration activities will have the need of thermal management systems that can provide higher reliability and performance, and power and mass reduction. In an effort to start addressing the current technical gaps in thermal management systems, novel new passive thermal technologies have been selected to be included as part of suite of experiments to be tested on the board of the ISS, tentatively in 2017.

ACT Inc., together with NASA Marshall Space Flight Center and NASA Johnson Space Center, are working to test and validate hybrid wick VCHP with warm reservoir and HiK™ plates on the ISS under the Advanced Passive Thermal experiment (APT_x) project. The hybrid wick VCHP is used as a thermal link between Warm Electronics Box (WEB) electronics or avionics and the radiator for landers and rovers (Anderson et al.¹⁰, 2010). The objectives for testing flight hardware on the ISS are:

- Demonstrate VCHP operation at the maximum temperature.
 - Show the gas front dynamics as a function of thermal contexts.
- Demonstrate VCHP shutdown at the shutdown temperature.
 - Show that heat leaks are minimized.
- Demonstrate the operation and flight worthiness of the HiK™ plate.
- Demonstrate the efficiency of the hybrid wick heat pipe in micro-gravity environment.
- Demonstrate startup and capability to address working fluid location anomalies (e.g. in the reservoir).
- Demonstrate turndown ratio for the hybrid VCHP.

The APTx consists of two separate payloads that will be tested sequentially:

- Payload 1 contains a VCHP/HiK™ plate assembly.
- Payload 2 contains a HiK™ plate and the ElectroWetting Heat Pipe (EWHP) experiment, developed by the University of Texas at Austin.

The hybrid wick VCHP design would typically have an aluminum envelope, with ammonia as the working fluid. The HiK™ plate design for aerospace applications would typically include copper/water and copper/methanol heat pipes. All of the heat pipes in the APTx will have water as the working fluid, due both to the short time to develop and test the experiments before they must be flight ready, and the fact that the experiment will be tested inside the ISS. Since water is not compatible with aluminum, the flight test VCHP will have copper and Monel as the envelope.

A hybrid-wick copper-Monel-water VCHP design consists of a copper evaporator (with sintered wick inside), a monel adiabatic section and a condenser both with grooved wick inside and a NCG reservoir thermally and physically attached to the evaporator. In turn, the VCHP evaporator is mounted on an aluminum HiK™ plate. Figure 15 shows the preliminary design and assembly of the hybrid wick VCHP and HiK™ plate for the ISS experiment in payload 1.

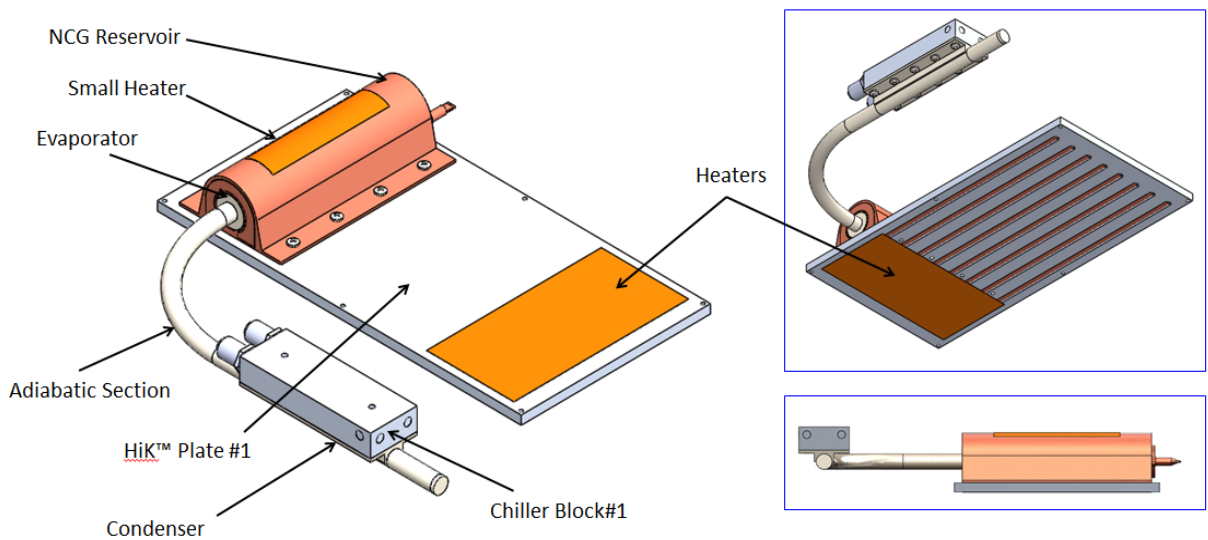


Figure 15. Preliminary design for the hybrid wick VCHP and HiK™ plate for ISS Experiment in payload 1.

For payload 1, a chiller block attached to the VCHP condenser provides the sink temperature that will be varied between -10 to 30°C. Three heaters will be used as heat sources:

- A 50W heater located remotely on the HiK™ plate (to demonstrate operation of both systems)
- A 50W heater located directly below the evaporator (to demonstrate operation of VCHP without HiK™ plate – if needed)
- A 20W maximum heater located on the NCG reservoir.

Temperatures will be monitored using 45 thermocouples (TCs) which will be attached to the VCHP and the HiK™ plate.

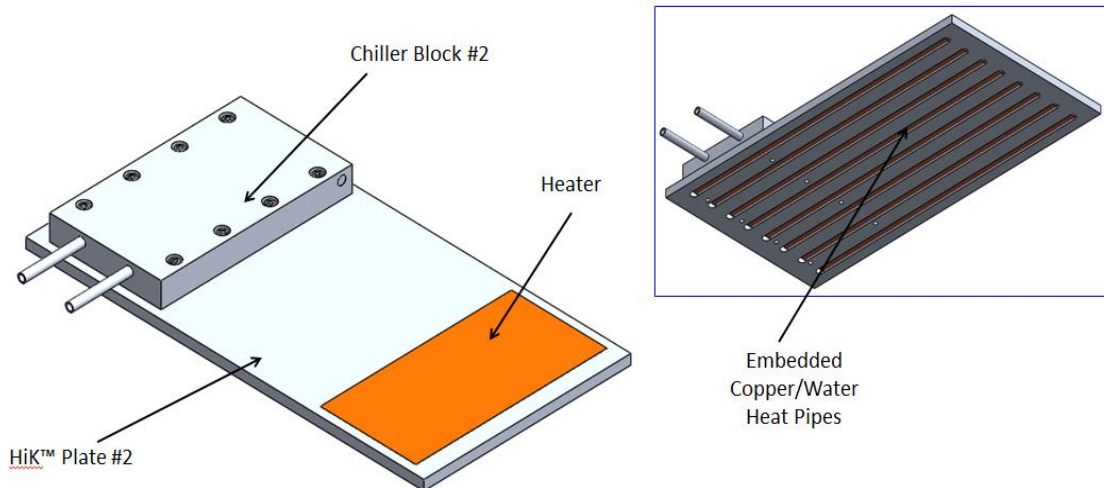


Figure 16. The preliminary design for the HiK™ plate for the ISS experiment in payload 2.

Figure 16 shows the preliminary design of the HiK™ plate for the ISS experiment in payload 2. A 50W heater will be used as a heat source; a chiller block will be used to impose sink temperatures between -10 to 30°C; and about 30 TCs will be used to monitor the temperatures.

The proposed concept of operations for the ISS experiment is:

- After installation, the payloads 1 and 2 will be checked out to ensure power and data connectivity.
- Once checked out the payloads will be commanded from the ground to run through a series of thermal tests.
- Testing of the VCHP and HiK™ plates will not require any crew integration after initial installation.
- Testing will vary both the cold and hot boundary conditions and system performance will be observed.
- Finally, after the experiments are completed the payloads can be discarded.

At this moment, the next step is to fabricate an engineering demonstration unit, followed by the flight article. The flight article will be delivered to NASA by September 1, 2016 for testing and qualification at NASA until the end of the 2016. Eventually, the flight package will be tested on ISS sometime in 2017.

A VCHP model based on flat front theory was used to predict the VCHP performance as a function of the sink temperature. Since the modeling was performed for the prototype to be tested inside ISS, two experimental constraints were considered:

1. Heat sink temperature is relatively high, between -10°C and 30°C.
2. Working fluid can be only water.

Therefore, the entire temperature range of the VCHP operation was shifted upwards. The main reason was that water properties are favorable for two-phase heat transfer at temperatures higher than 30°C. An additional reason was the output of this experiment. Since part of thermal control offered by the VCHP is its capability to maintain the payload warm during low heat sink temperatures and thermal loads, a reasonable difference between the operating temperature and sink temperature had to be considered. As a consequence, a temperature of 70°C was chosen as the high temperature limit of the payload. Figure 17 shows that as sink temperature changes within the limits, vapor temperature will change within a very narrow interval while 50W were rejected and the reservoir volume was ~ 7 in³.

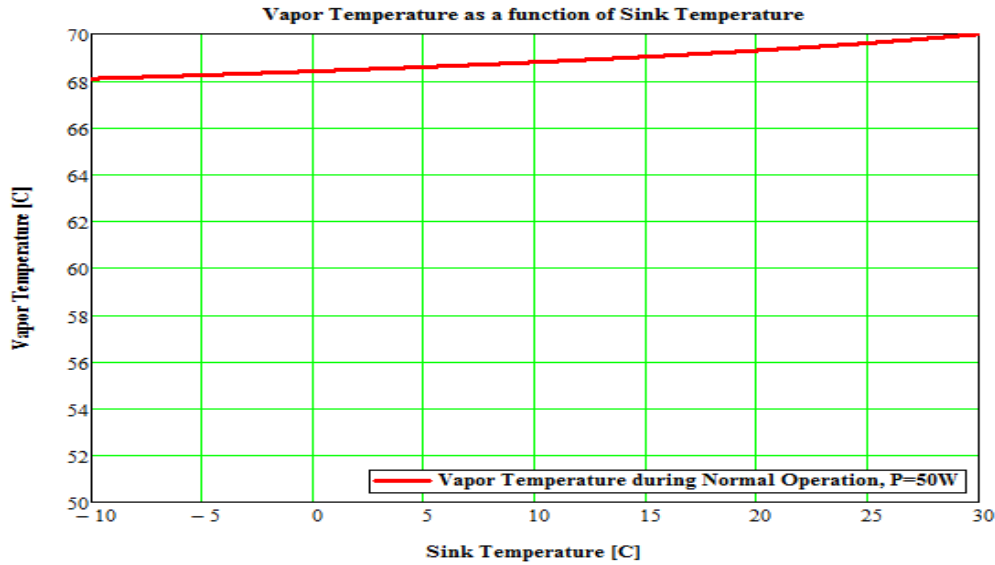


Figure 17. Hybrid VCHP’s vapor temperature as a function of sink temperature while 50 W is rejected.

On the other hand, as sink temperature changes within the limits and only power for survival is applied, the vapor temperature will take the values as shown in Figure 18, assuming that the NCG fills both condenser and the adiabatic region (front is at the exit of the evaporator). Notably, heat leaks (survival power) can be easily calculated from this scenario. The results from the VCHP model will be validated by comparing these predictions with experimental data in the near future.

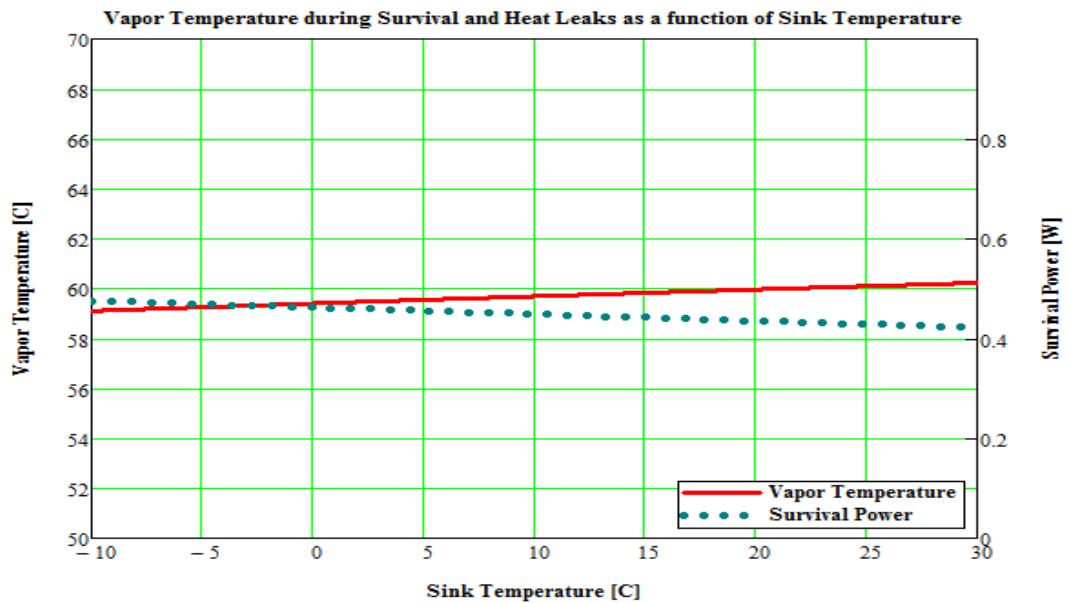


Figure 18. Hybrid VCHP’s vapor temperature as a function of sink temperature and reservoir volume on the survival mode.

VI. Conclusion

The innovation is to develop heat pipes with a hybrid wick sintered in the evaporator section and grooved wick in the adiabatic and condenser sections for planetary surface and high heat flux applications. A hybrid wick heat pipe design allows operating at higher heat fluxes as compared to axial groove design and can also operate against gravity on the planetary surface, operate in space carrying power over long distances, act as a thermosyphon on the

planetary surface for Lunar and Martian landers and rovers, and demonstrate a higher transport capability than an all-porous wick.

In order to solve the vertical startup problem during ground testing, two 12” (0.30m) long heat pipes were fabricated and tested: a conventional axial grooved heat pipe, and a hybrid sintered/grooved heat pipe. The experimental results for the axial grooved and the hybrid heat pipes at the optimal charged, 10% overcharged, and 20% overcharged conditions with ammonia as a working fluid show that the temperature spikes in vertical gravity aided heat pipes are minimized/eliminated by using sintered evaporator wicks.

In order to demonstrate VCHP operation at the maximum and shutdown temperatures, demonstrate the operation of the HiK™ plates, and demonstrate the efficiency of the hybrid wick heat pipe in micro-gravity environment. ACT Inc., NASA Marshall Space Flight Center and NASA Johnson Space Center, are working to test and validate hybrid wick VCHP with warm reservoir and HiK™ plates on the ISS. A VCHP model based on flat front theory was used to predict the VCHP performance as a function of the sink temperature. The model shows that as sink temperature changes within the limits, vapor temperature will change within a very narrow interval when 50W were rejected.

Acknowledgments

This research was sponsored by NASA Marshall Space Flight Center under Contract No. NNX15CM03C. Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration. Dr. Jeffery Farmer is the contract technical monitor. Joel Wells and Corey Wagner were the laboratory technicians responsible for the fabrication and testing of the heat pipes.

References

- ¹Hill, S.A., Kostyk, C., Motil, B., Notardonato, W. Rickman, S., & Swanson T. (2012) “Thermal management systems roadmap.” Technology Area 14.
- ²Advanced Cooling Technologies, Inc., 2013 “Axial Groove Constant Conductance Heat Pipes”, <http://www.1-act.com/wp-content/uploads/2013/01/Axial-Groove-Constant-Conductance-Heat-Pipes-WEB.pdf>
- ³Brennan, P. J., and Krolczek, E. J., “Heat Pipe Design Handbook, NASA Report No. NASA-CR-163661, 1979”. <http://ntrs.nasa.gov/search.jsp>
- ⁴Marcus, B. D., “Theory and Design of Variable Conductance Heat Pipes: Hydrodynamics and Heat Transfer,” NASA Report No. NASA-CR-146195, April 1971.
- ⁵Advanced Cooling Technologies, Inc., “HiK™ Plates”, <http://www.1-act.com/hik-plates/>
- ⁶Hornyak, D. M. (2013) “A Researcher’s Guide To: International Space Station: Technology Demonstration” Published by the NASA ISS Program Science Office.
- ⁷Ababneh, M. T., Tarau C., and Anderson, W.G., "Hybrid Heat Pipes for Planetary Surface and High Heat Flux Applications." 45th International Conference on Environmental Systems, 2015. <http://www.1-act.com/wp-content/uploads/2015/07/Hybrid-Heat-Pipes-for-Planetary-Surfaces-and-High-Heat-Flux-Applications-ICES-paper.pdf>
- ⁸Swanson, T., and Butler, D., NASA/Goddard Thermal Control Technology Overview – 2009, Spacecraft Thermal Control Workshop, El Segundo, CA, March 10 – 12, 2009.
- ⁹Anderson, W. G. et al., Pool Boiler Heat Transport System for a 25 kWe Advanced Stirling Conversion System, Proceedings of the 25th Annual IECEC, Vol. 5, pp. 268-273, Reno, Nevada, August 12-17, 1990.
- ¹⁰Anderson, W. G., Hartenstine, J. R., Walker, K. L., & Farmer, J. T. (2010). “Variable thermal conductance link for lunar landers and rovers.” 8th IECEC, Nashville, TN. <http://www.1-act.com/variable-thermal-conductance-link-for-lunar-landers-and-rovers/>