High-Heat-Flux (> 50 W/cm^2) Hybrid Constant Conductance Heat Pipes

Mohammed T. Ababneh[1], Calin Tarau[2], and William G. Anderson[3]
Advanced Cooling Technologies, Inc. 1046 New Holland Ave. Lancaster, PA 17601, USA

Jesse W. Fisher[4]
Lockheed Martin Coherent Technologies, Louisville, CO 80027, USA

Novel hybrid wick aluminum-ammonia constant conductance heat pipes (CCHPs) are developed to handle heat flux requirements for spacecraft thermal control applications. The 5-10 W/cm^2 heat density limitation of aluminum-ammonia grooved heat pipes has been a fundamental limitation in the current design for space applications. The recently demonstrated > 50W/cm^2 capability of the hybrid high-heat-flux heat pipes provides a realistic mean of managing the high heat density anticipated for the next generation space designs. The hybrid wick high-heat-flux aluminum-ammonia CCHP transported a heat load of 275 Watts with heat flux input of > 50 W/cm^2 and with a thermal resistance of 0.015 ºC/W at 0.1 inch adverse elevation. This demonstrates an improvement in heat flux capability of more than 3 times over the standard axial groove aluminum-ammonia CCHP design.

Nomenclature

ACT	=	Advanced Cooling Technologies, Inc.
CCHPs	=	Constant Conductance Heat Pipes
HHF	=	High-Heat-Flux
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

Future spacecraft and instruments developed for space missions will involve highly integrated electronics, such as for CubeSat/SmallSat and high power laser diode arrays (LDAs). This high density electronics packaging leads to substantial improvement in performance per unit mass, volume and power. However, it also requires sophisticated thermal control technology to dissipate the high heat flux generated by these electronics systems. For example, the current incident heat flux for laser diode applications is on the order of 5-10 W/cm^2, although this is expected to increase towards 50 W/cm^2. This is a severe limitation for the commonly employed axial groove aluminum/ammonia CCHPs (i.e. Boiling limit in axial groove CCHPs typically starts at 5-15 W/cm^2). Hence, high flux heat acquisition and transport devices are required.

[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] Jesse W. Fisher, Lockheed Martin Coherent Technologies, Mechanical Enigneer

Aluminum/ammonia CCHPs are typically used for transferring the thermal loads on-orbit due to their high wick permeability and associated low liquid pressure drop, resulting in the ability to transfer large amounts of power over long distances in micro-gravity. The maximum heat flux in a CCHP is set by the boiling limit, where the working fluid within the evaporator wick structure starts to boil. If the heat flux is high enough, vapor bubbles will form and partially block the liquid return from the condenser to the evaporator, resulting in wick dryout. As the boiling limit is approached, the thermal resistance will continue to increase beyond the design parameters. Film boiling in heat pipe evaporators typically start at 5-15 W/cm^2 for axial groove wicks, and 50-75 W/cm^2 for powder metal wicks. Thus, it can be seen that the flux limit for axial groove designs has been reached. Hence to solve this limiting problem, Advanced Cooling Technologies, Inc. (ACT) is developing novel hybrid wick CCHPs that can manage the high heat flux and carry the heat to long distances[1].

II. Heat Pipe Background

Constant Conductance Heat Pipes (CCHPs)

CCHPs transport heat by two-phase flow of a working fluid as shown in Figure 1. A heat pipe is a vacuum tight device consisting of a working fluid and a wick structure. The heat input vaporizes the liquid working fluid inside the wick in the evaporator section. The saturated vapor, carrying the latent heat of vaporization, flows towards the colder condenser section. In the condenser, the vapor condenses and gives up its latent heat. The condensed liquid returns to the evaporator through the wick structure by capillary action. The phase change processes and two-phase flow circulation continue as long as the temperature difference between the evaporator and condenser are maintained. A CCHP is always on, transferring heat from the evaporator to the condenser.

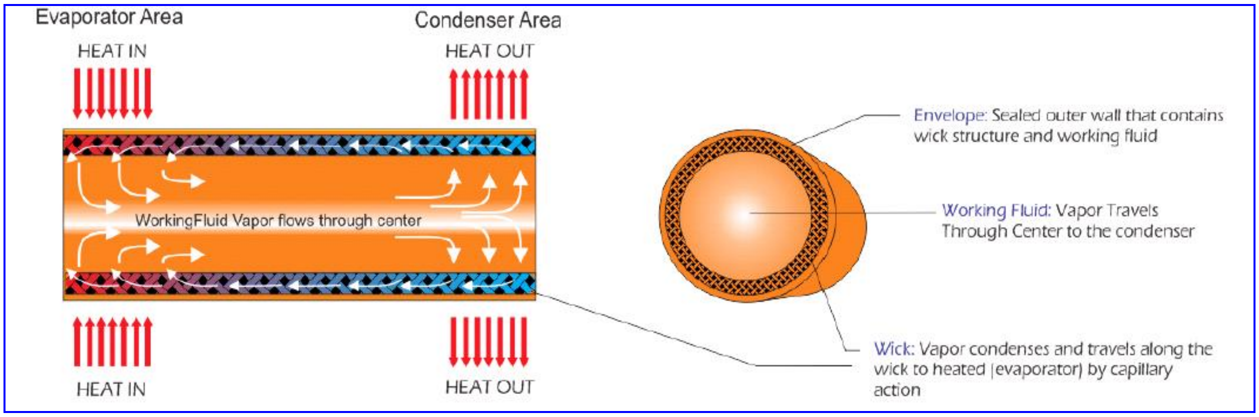


Figure 1. Illustration of Constant Conductance Heat Pipe (CCHP) operation and components.

Grooved Aluminum/Ammonia Heat Pipes

Grooved wicks are typically used in spacecraft CCHPs and VCHPs. Typical aluminum grooved extrusions are shown in Figure 2. 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.

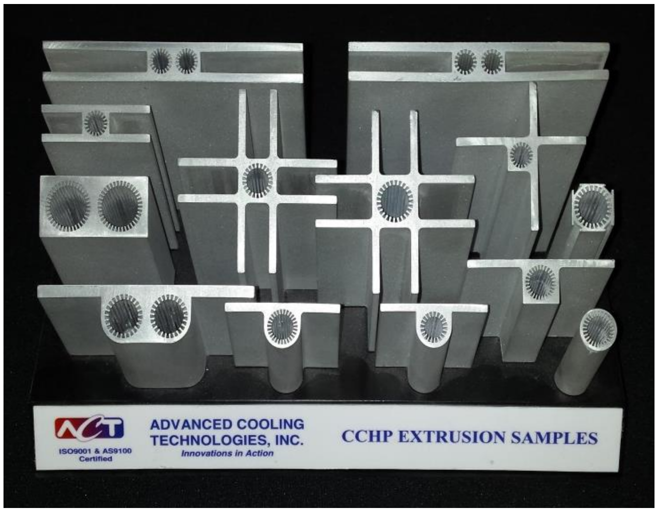


Figure 2. Grooved aluminum extrusions for ammonia heat pipes. Grooves allow long heat pipes for spacecraft applications, but only work about 0.10 inch (0.00254m) against gravity for earth-based testing (ACT Inc., 2013[2]).

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 inches (0.0254cm) will significantly decrease the power[2]. 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.

III. Hybrid Heat Pipes

Heat flux limit in axial grooved heat pipe evaporators normally starts at 5-15 W/cm^2. In order to increase the heat flux limit to more than 50 W/cm^2, the concept as shown in Figure 3 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.

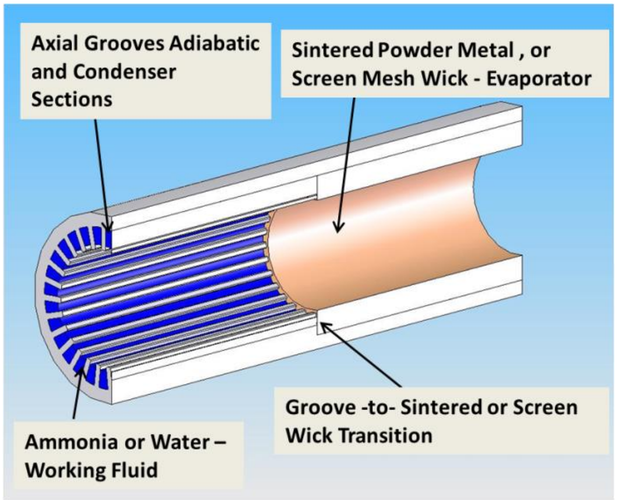


Figure 3. Hybrid CCHPs: axial grooved adiabatic and condenser sections - screen mesh or sintered evaporator wick.

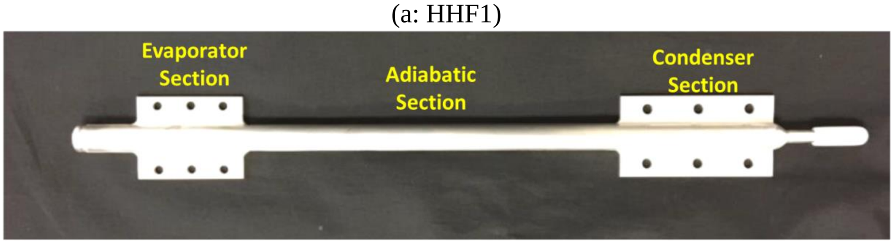
The previous work[1] showed that the hybrid sintered/grooved wicks in the CCHPs offer the highest operating heat flux capability and height against gravity compared to screen, foam, and grooved wicks. Hybrid wick heat pipes have the following advantages:

- 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.

IV. Hybrid High-Heat-Flux Heat Pipes Fabrication and Testing

Two aluminum/ammonia hybrid high-heat-flux (HHF) heat pipes were designed and fabricated as shown in Figure 4. These heat pipes (bended (HHF1) and straight (HHF2)) represent the high heat flux design with sintered powder metal in the evaporator and axial grooves in the condenser and adiabatic sections. The grooves in the evaporator section were removed by machining, and an annular sintered metal powder wick was inserted in place of the grooves.

(a: HHF1)



(b: HHF2)

Figure 4. ACT high-heat-flux (HHF) heat pipes based on hybrid wick technology: (a) the bended HHF1 heat pipe, (b) the straight HHF2 heat pipe.

Both high-heat- flux heat pipes had ~ 12” long and charged with ~ 5 grams of ammonia, and then tested.

HHF1:

Testing for the hybrid HHF1 CCHP was performed between 0° - 14.5° adverse elevation between the evaporator and the condenser as shown in Figure 5. An aluminum heater block (for aluminum/ammonia hybrid CCHP) with 2 (200 Watts) cartridge heaters as the heat input source. For the hybrid CCHP, the heat input area is 5.08 cm (2.0 inch) x 1.27 cm (0.50 inch), or 6.45 cm^2. The condenser sink condition was established using an aluminum block connected with a Liquid Nitrogen (LN) source for the hybrid CCHPs. The LN flow was adjusted to the condenser via a temperature controller. The pipe was instrumented with type T thermocouples. A thermal cutoff switch set to 85°C was added to the evaporator block and wired in series with the heaters. An over-temp controller set to 85°C with a TC attached to the evaporator block was also be used. Figure 5 shows overall test assembly. The test procedure was as follows:

- The CCHP was instrumented, insulated and oriented between 0° - 14.5° adverse elevation between the evaporator and the condenser
- The sink conditions was adjusted to maintain a 10 °C condenser temperature by keeping the averaged temperatures TC23, TC24, TC25 and TC26 (as shown in Figure 6) around 10 °C.
- The power was input as a step function and the temperature was monitored.
- The heat input was increased until a dry out condition was observed. Dry out is signaled by a pronounced spike in temperatures within the evaporator section as vapor bubbles begin to interfere with liquid return in the wick. Temperatures and powers were recorded.

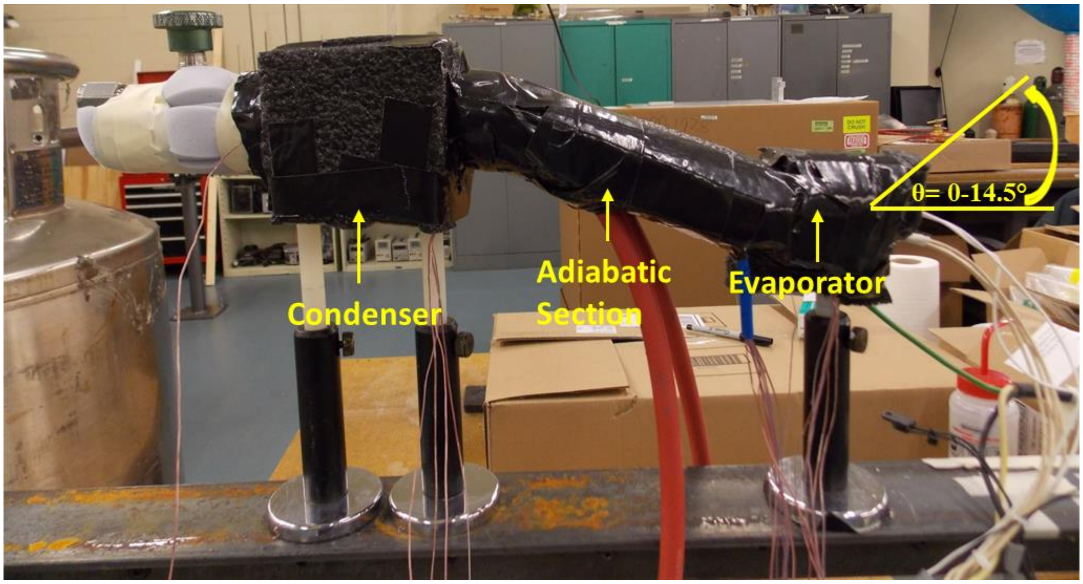


Figure 5. The overall test assembly for the bended aluminum/ammonia HHF1 CCHP testing set up.

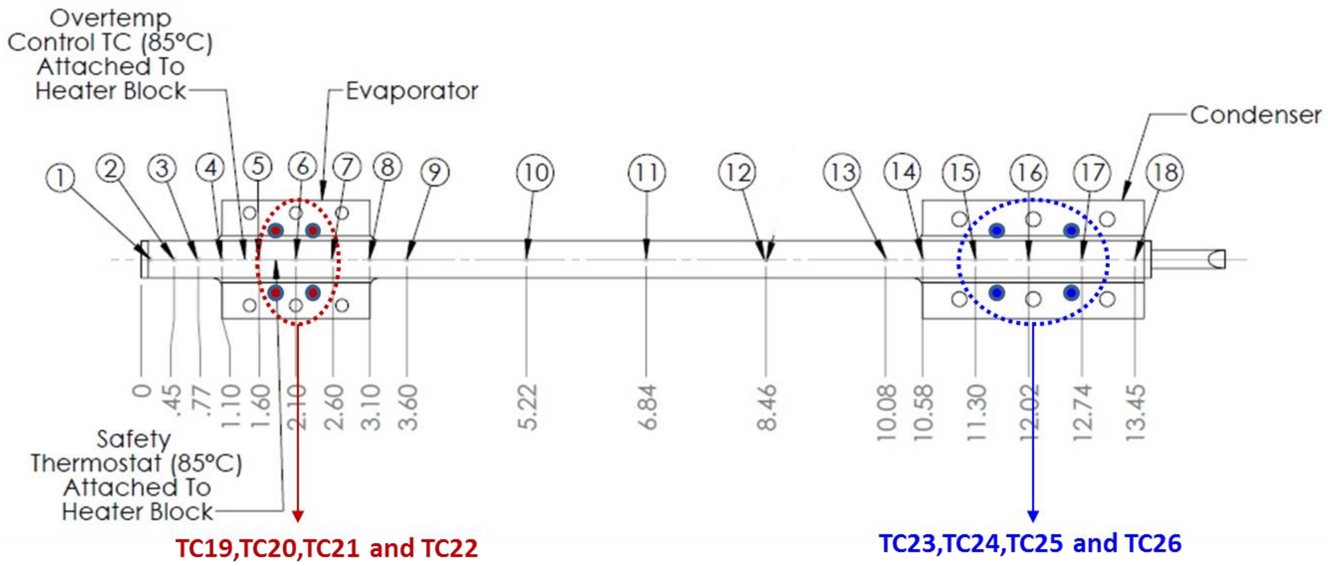


Figure 6. Thermocouples and control locations for the aluminum/ammonia HHF1 CCHPs testing set up.

The HHF1 pipe transported a heat load of ~ 350 W up to 8.2° adverse elevation respectively before complete dry-out. The thermal resistance as a function of power for the bended hybrid HHF1 heat pipe in horizontal positions (between 0.1° to 14.5° adverse elevation) is shown in Figure 7.

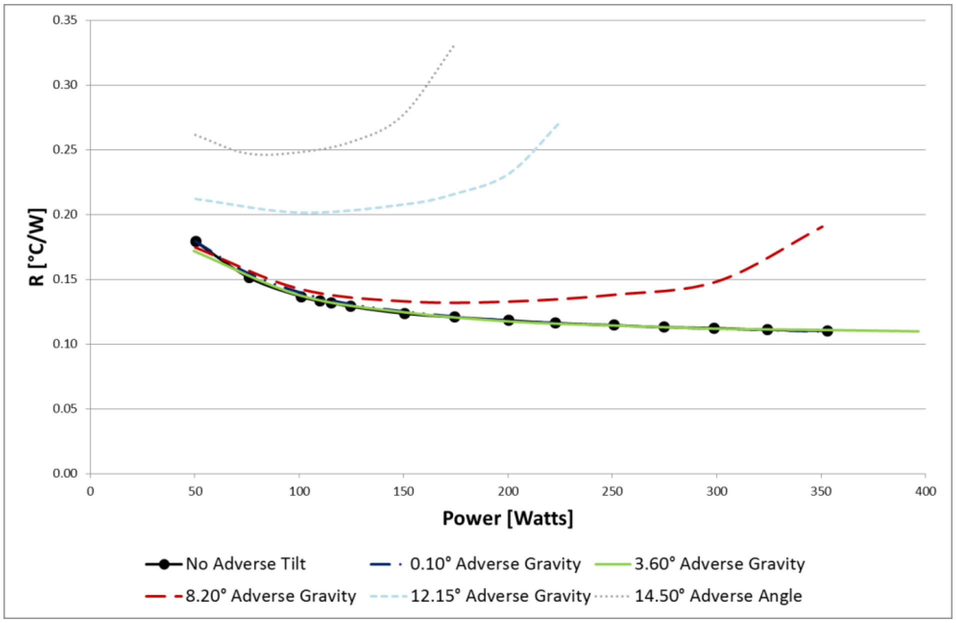


Figure 7. The thermal resistance as a function of power for the hybrid HHF1 heat pipe between 0° - 14.5° adverse elevation.

The bended HHF1 hybrid heat pipe was shipped to Lockheed Martin Coherent Technologies, Inc. for validating the testing results. The testing results from Lockheed Martin as shown in Figure 8.

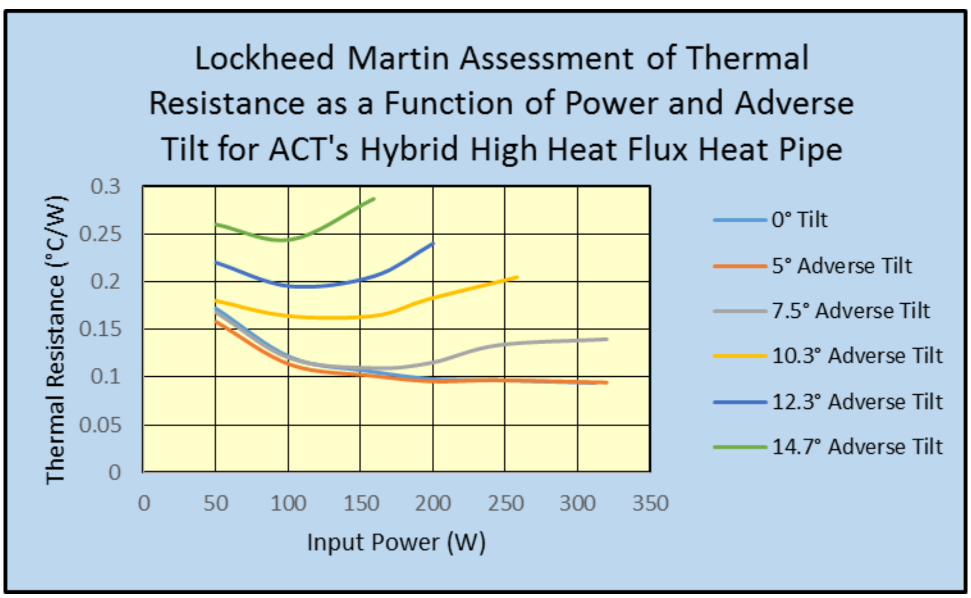


Figure 8. Lockheed Martin Assessment of Thermal Resistance as a Function of Power and Adverse Tilt for ACT's Hybrid High Heat Flux Heat Pipe.

Figure 9 shows the comparison of the thermal resistance as a function of power for the high heat flux heat pipe at ~ 5º adverse tilt that performed at ACT and Lockheed Martin and a standard grooved CCHP. The high-heat-flux (HHF1) aluminum/ammonia CCHP transported a heat load of > 320 Watts with heat flux input of > 50 W/cm^2 and thermal resistance < 0.012 ºC/W. This demonstrates an improvement in heat flux capability of more than 3 times over the standard axial groove aluminum-ammonia CCHP design. Note the differences in the results for the high-heat-flux heat pipe as shown in Figure 9 are related to differences in testing methodologies between ACT and Lockheed Martin.

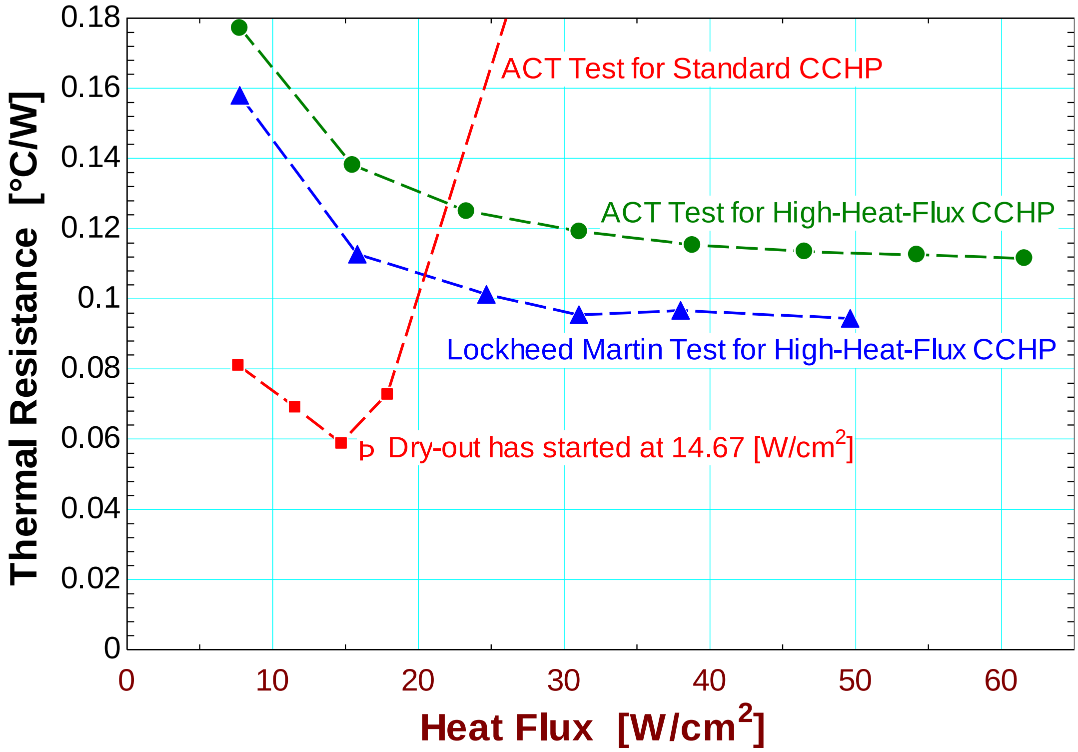


Figure 9. Comparison of the thermal resistance as a function of heat flux for the bended HHF1 at 5º adverse tilt that performed at ACT and Lockheed Martin and a standard grooved CCHP.

HHF2:

The second straight high-heat-flux (HHF2) heat pipe was fabricated as shown in Figure 4-b. Figure 10 shows the second high heat flux heat pipe under performance test with similar TC map that shown in Figure 6.

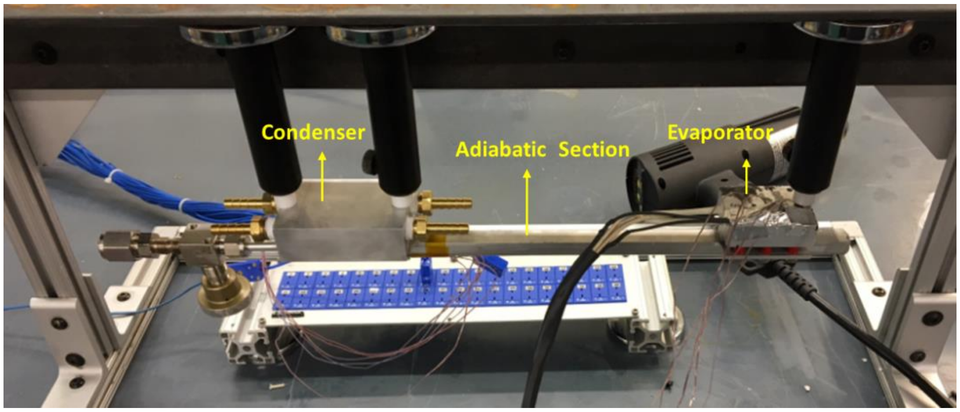


Figure 10. The second hybrid aluminum-nickel-ammonia high heat flux CCHP under performance test.

The hybrid HHF2 heat pipe was tested in horizontal non-inverted “standard orientation” positions (between 0.1” to 0.3” adverse elevation). Figure 11 shows the thermal performance results for the pipe at 0.1” adverse elevation as a function of time respectively.

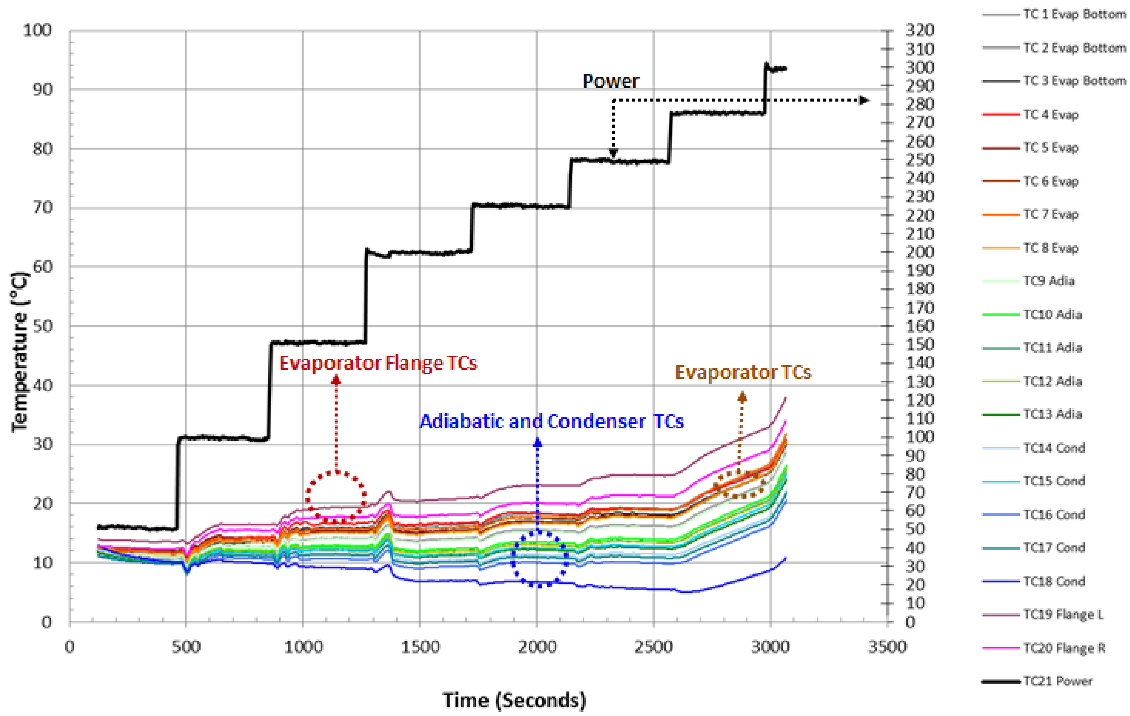


Figure 11. Thermal performance profile for the second hybrid aluminum/ammonia HHF2 heat pipe, 10 °C condenser set point at 0.1" adverse elevation.

The hybrid wick high heat flux aluminum/ammonia CCHP transported a heat load of 275 Watts with heat flux input of **54 W/cm^2** and R=0.015 ºC/W at 0.1 inch adverse elevation. This demonstrates an improvement in heat flux capability of more than **3 times** over the standard axial groove CCHP design.
The thermal resistance as a function of power for the second hybrid heat pipe in horizontal positions (between 0.1" to 0.3" adverse elevation) is shown in Figure 12.

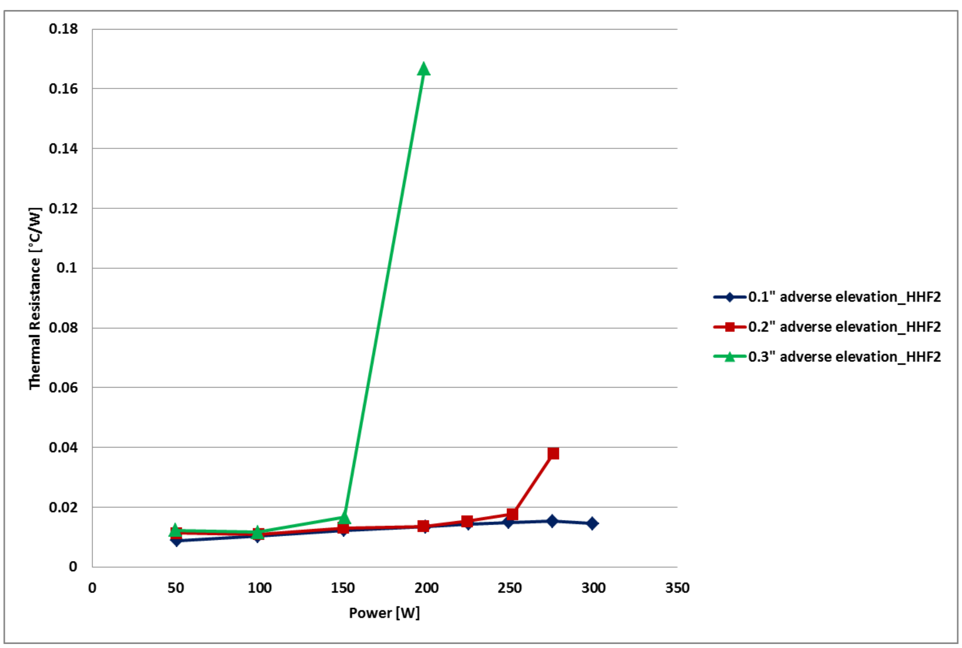


Figure 12. The thermal resistance as a function of power for the hybrid heat pipe in horizontal non-inverted positions (0.1, 0.2, and 0.3 inch adverse elevation).

V. Conclusion

ACT develops new generation of high-heat-flux CCHPs based on hybrid wick technology. The 5-10 W/cm^2 heat density limitation of aluminum-ammonia grooved heat pipes has been a fundamental limitation in the current design for space applications. Two high-heat-flux hybrid CCHPs were developed and tested. The first bended hybrid CCHP (HHF1) transported a heat load of > 320 Watts with heat flux input of > 50 W/cm^2 and thermal resistance < 0.012 ºC/W and the results were validated by Lockheed Martin. The second hybrid CCHP (HHF2) transported a heat load of 275 Watts with heat flux input of > 50 W/cm^2 and with a thermal resistance of 0.015 ºC/W at 0.1 inch adverse elevation. This demonstrates an improvement in heat flux capability of more than 3 times over the standard axial groove aluminum-ammonia CCHP design. The results show that the heat pipe performs efficiently, consistently and reliably and can adapt to many high heat flux applications.

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, Chris Jarmoski, and Corey Wagner were the laboratory technicians responsible for the fabrication and testing of the heat pipes.

References

[1] Ababneh, Mohammed T., Calin Tarau, and William G. Anderson. "Hybrid Heat Pipes for Planetary Surface and High Heat Flux Applications." *45th International Conference on Environmental Systems*, 2015.

[2] Advanced 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