Hybrid Heat Pipes for Planetary Surface and High Heat Flux Applications

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Novel hybrid wick Constant Conductance Heat Pipes (CCHPs) were developed to solve the high heat flux limitation for future highly integrated electronics. In addition to carrying power over long distances in space, the hybrid CCHP evaporator can also operate against an adverse tilt 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 instruments such as on the next generation of polar rovers and equatorial landers. The thermal transport requirements for future spacecraft missions continue to increase, while at the same time the heat acquisition areas have trended downward, thereby increasing the incident heat flux from 5-10W/cm^2 to the projected > 50W/cm^2. This exceeds the performance of standard axial groove CCHPs and loop heat pipes (LHPs). Aluminum/ammonia and stainless steel/ammonia hybrid CCHPs to demonstrate high heat flux capability and for planetary (Lunar and Martian) rovers and landers were designed, fabricated and tested. The CCHPs had a sintered powder metal wick in the evaporator and axial grooves in the adiabatic and condenser regions The hybrid wick high heat flux aluminum/ammonia CCHP transported a heat load of 175 watts with heat flux input of 53W/cm^2 at 0.1 inch adverse elevation. This demonstrates an improvement in heat flux capability of 3 times over the standard axial groove CCHP design. The hybrid wick high heat flux stainless steel/ammonia CCHP transported a heat load of 165 watts with heat flux input of 51W/cm^2 at 0.1 inch adverse elevation. The Thermal Link planetary aluminum/ammonia CCHP transported approximately 202 watts at a 4.2° adverse inclination before dryout, exceeding the 150W target. Also the Thermal Link planetary aluminum/ammonia CCHP was tested for maximum transport power at three different adverse elevations to extrapolate zero-g power. The maximum power at zero-g is 288 watts, exceeding the 150W target. The X-ray micrographs for the interface between the sintered powder metal wick and the axial grooves in the stainless steel hybrid CCHP shows much better contact in comparison to the aluminum CCHP because of the successful internal sintering technique developed during this project.

Nomenclature

ACT	=	Advanced Cooling Technologies, Inc.
CCHPs	=	Constant conductance heat pipes
g	=	Gravitational acceleration
K	=	Permeability
LHPs	=	Loop heat pipes
NASA	=	the National Aeronautics and Space Administration
r_c	=	Pore radius
VCHPs	=	Variable Conductance Heat Pipes
W	=	Watts
WEB	=	Warm Electronics Box
$\Delta P_{capillary,max}$	=	the maximum pumping pressure of the wick system
$\Delta P_{gravity}$	=	the pressure drop as a result of gravity
ΔP_{liquid}	=	the pressure drop of the liquid flow
ΔP_{vapor}	=	the pressure drop of the vapor flow

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I. Introduction

Future spacecraft and instruments developed for NASA's Science Mission Directorate will involve highly integrated electronics, such as for CubeSat/SmallSat. This high density electronics packaging leads to substantial improvement in performance per unit, mass, volume and power. However, it also results in requirement of 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 constant conductance heat pipes (CCHPs). Hence, high flux heat acquisition and transport devices are required.

Typically, aluminum/ammonia CCHPs are 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. So hybrid grooved and sintered wick CCHPs/VCHPs have been developed, which 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 surfaces.
- 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 surfaces 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 an all-sintered wick.

Table 1. Hybrid Wick CCHP Requirements.

Attribute	NASA Requirements
Min. Electronics Temp.	-10 °C
Max. Electronics Temp.	50 °C
Max. 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” x 41” x 14” (height)
Max. Tilt	14° (lander), 25° (rover), 25 ° preferred
Radiator Emissivity	0.8
Min. Radiator Sink Temp. (Moon)	96 K (parasitic heating from lander)
Max. Radiator Sink Temp. (Moon)	269 K
Cruise Sink Temp. (Space)	168 K
Min. Soil Temp.	100 K
Max. Soil Temp.	390 K
Condenser Length	12”
Adiabatic Section Length	18.6”
Evaporator Length	9”

The hybrid wick heat pipes will be capable of operating at the higher heat flux requirements expected in NASA’s future spacecraft and instruments such as on the next generation of polar rovers and equatorial landers (Hill et al.[1], 2012). In many higher powered spacecraft, CCHPs are used to collect the heat and transfer the heat to a loop heat pipe, which in turn carries the power to a radiator. Loop heat pipes have a higher boiling limit than grooved CCHPs.

With a moderate heat flux, an LHP could be used to collect the heat instead of a CCHP. However, LHPs are roughly 50 times more expensive than CCHPs. For cases with higher heat fluxes than a LHP can handle, as well as cases when there is more than one high heat flux area, it makes more sense to use hybrid CCHPs to collect the high heat flux heat and deliver it to a single LHP, which in turn can carry the power to the radiator. Parameters for the system are shown in Table 1.

II. Background

It is well known that CCHPs provide the simplest capillary-driven, two-phase heat transport solution. The CCHP requires a wick structure throughout to return liquid from the condenser to the evaporator. As this structure introduces 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. As a result, a LHP can handle much higher heat fluxes than CCHPs. However, LHP design and fabrication is considerably more complex than a standard heat pipe and, as a result, significantly more expensive.

Grooved Aluminum/Ammonia Heat Pipes

Grooved wicks are the standard wick used in spacecraft CCHPs, Diode Heat Pipes, and Variable Conductance Heat Pipes (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. Axial grooves CCHPs also have a relatively low heat flux limitation.

Figure 1. Grooved aluminum extrusions for ammonia heat pipes. Grooves allow long heat pipes for spacecraft applications, but only work about 0.10 inch against gravity for earth-based testing.

Grooved aluminum/ammonia heat pipes are designed to work with a 0.10 inch 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. Increasing the heat pipe elevation by 0.010 inch will significantly decrease the power. 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. Design of Hybrid Wick Heat Pipes

Heat flux limit in axial grooves heat pipe evaporators normally start at 5-15 W/cm^2 for axial groove wicks. In order to increase the heat flux limit to more than 50 W/cm^2, the concept as shown in Figure 2 is to develop heat pipes with a hybrid wick that contains screen mesh, metal foam 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.

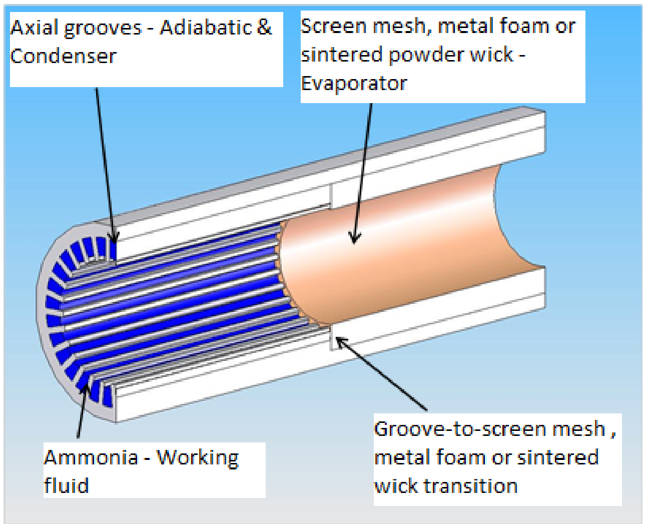


Figure 2. Hybrid CCHPs for high heat flux applications: axial grooved adiabatic and condenser sections - screen mesh, metal foam or sintered evaporator wick.

A. Wick Structure

Figure 3 shows a comparison of the microstructure of three candidate wicks that were investigated during this work: screen mesh wick (Figure 3-A) open-cell metal foam wick (Figure 3-B), and sintered metal wick (Figure 3-C). Screen mesh wicks (Figure 3-A) are designated by their mesh number, which is an indication of the number of pores per unit surface area. By the tightness of the wrapping, the liquid flow resistance can be controlled. The relatively easy fabrication steps make screen wicks attractive, but compared to sintered wick they have higher pore size (lower pumping capability) and lower thermal conductivity. The availability of screens in particular mesh numbers restricts the possible range of pore size, porosity and permeability. The remarkable characteristic of metal foams is the existence of many voids within the material (see Figure 3-B). Metal foams with a cellular structure are known to have many favorable combinations of mechanical and physical properties (for example, low weight and high permeability, strength and toughness). Currently, metal foams are incompletely characterized, and the methods used to fabricate them are poorly controlled, resulting in some inconsistency in properties (Ashby[2], 2000). However, the sintered metal wick is more easily to produce, and there is a wide range of pore sizes, porosities and permeability that can be tuned by choosing the starting powder size (to be sintered). In addition, mixture of powder sizes provides the capability to develop biporous wicks that have shown enhanced capillary performance. Hence, sintered wicks (see Figure 3-C) offer the highest operating heat flux capability and operation against gravity compared to screen, foam, and grooved wicks.

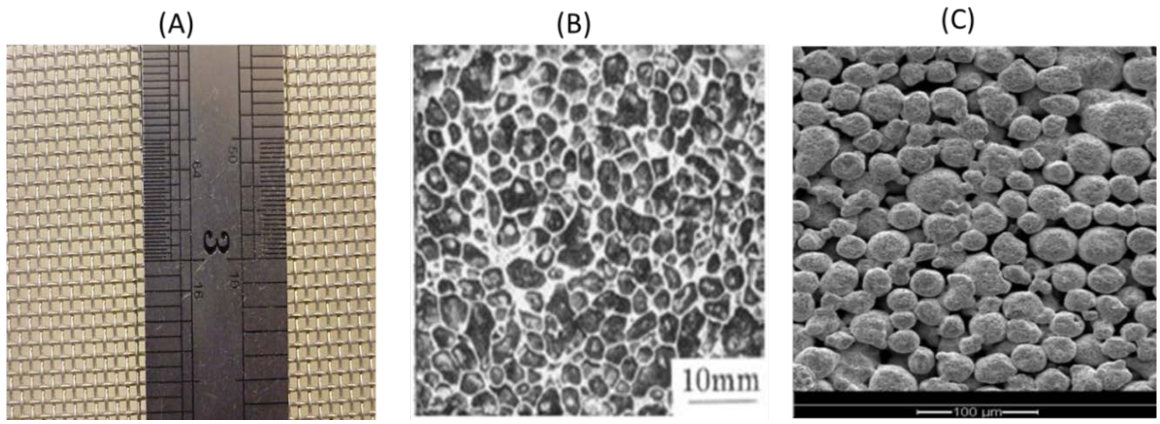


Figure 3. Micrograph of typical: (a) standard screen mesh wick, (b) open-cell metal foam wick and (c) sintered metal wick (A- ESPI Metals, B- Foamtech Corporation, C- (Ababneh[3], 2012)).

In order for a heat pipe to work properly, the capillary pumping capability must be greater than the sum of pressure losses in the system. Heat pipe performance is typically constrained by the flow resistance of the wick, which limits mass flow rate of the liquid return and, as a consequence, the total heat load the system is able to transport. If the heat load on a heat pipe is increased, the mass flow inside the device increases. As the axial pressure gradient of the liquid within the wick structure increases, a point is reached where the maximum permissible capillary pressure difference across the vapor–liquid interface in the evaporator equals the total pressure losses in the system. The maximum heat transport of the device is reached at this point. So if the heat load exceeds this point, the wick will dry-out in the evaporator region and the heat pipe will not work (Ababneh[4], 2013). This point is called the capillary limit. In addition to the capillary limit, other operating limits like sonic, entrainment, viscous, and boiling can affect pipe's performance.

The performance of the hybrid wick CCHP was predicted using ACT's proprietary heat pipe design code. The program works by balancing the two sides of the heat pipe capillary limit equation:

$$\boldsymbol{\Delta P_{capillary,max} \geq \Delta P_{liquid} + \Delta P_{vapor} \pm \Delta P_{gravity}} \qquad \textbf{Eq. 1}$$

Where $\Delta P_{capillary,max}$ indicates the maximum pumping pressure of the wick system, ΔP_{liquid} signifies the pressure drop of the liquid flow through the wick structure, ΔP_{vapor} represents the pressure drop of the vapor flow as a result of friction and momentum changes, $\Delta P_{gravity}$ denotes the pressure drop (positive or negative) within the liquid flow caused by gravity. Capillary pumping pressure is fixed by the choice of wicking structure. The pressure drops depend upon a number of heat pipe operating parameters such as geometry, wicking structure, transport power, operating temperature, adverse elevation, etc. The design code was set up such that transport power, adverse elevation/inclination and wick permeability functioned as inputs and maximum evaporator length was the output. Results are shown in Figure 4. The gravity pressure drops were based on a 0.1" adverse elevation for the simulated space case and a 25° adverse inclination (3.8" adverse elevation) for the lunar case. Earth based heat pipe testing can only be performed in earth's gravitational field; therefore, the gravity pressure drop terms are included. Testing of the heat pipe is done at adverse elevations of 0.1 inch, 0.2 inch and 0.3 inch. Data collected at these three elevations allows for extrapolation of performance at 0.0 inch, which corresponds to zero gravity. Puddle flow, which would produce overly optimistic results, prevents direct testing of the heat pipe at 0.0 inch elevation. For this reason, the heat pipe code includes a 0.1" adverse elevation term for the simulated space case.

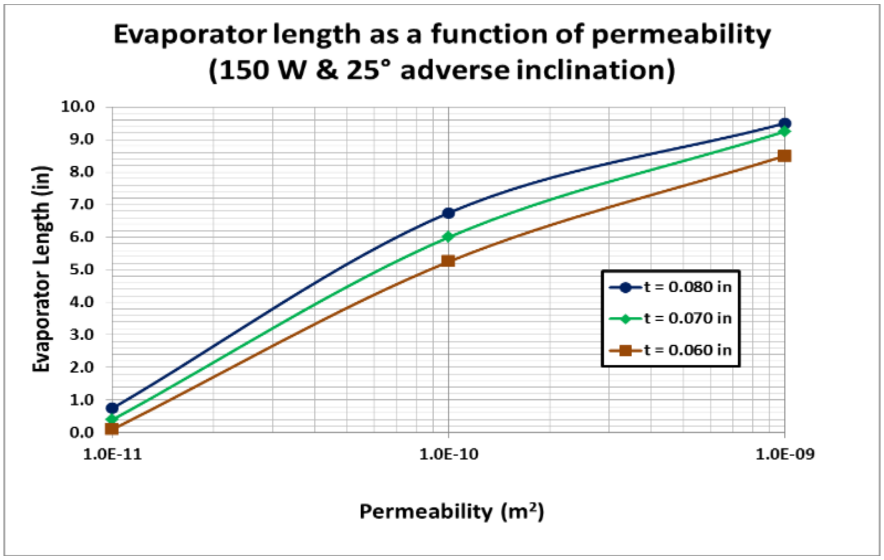


Figure 4. Maximum evaporator length for high heat flux hybrid wick CCHP (0.5" OD sintered wick evaporator).

According to Figure 4, the permeability of the wick will need to be approximately 1×10^{-9} m^2 or better to achieve the desired 9 inch long evaporator (See Table 1). Observe that small changes in evaporator wick thickness, which increases flow cross-sectional area and thus reduces hydraulic resistance, do not significantly increase the maximum length especially at the lower permeabilities. The theoretical performance of the planetary evaporator design is shown in Figure 5. Evident from the figure, the planetary design permits a 9 inch evaporator with permeabilities as low $\approx 6\times10^{-12}$ m^2.

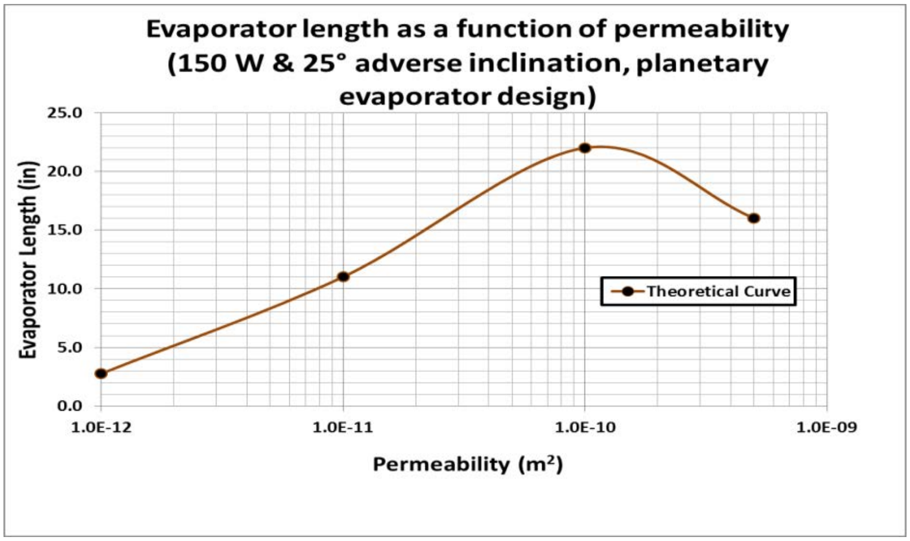


Figure 5. Maximum evaporator length for planetary hybrid wick CCHP (1" OD sintered wick evaporator).

The heat flux or boiling limit is related to the bubble formation and the subsequent collapse of the bubbles and it occurs when the applied heat flux at the evaporator section is enough to cause nucleate boiling in the evaporator wick. This generates bubbles that partially block the liquid return and can lead to dryout in the evaporator wick. By applying a pressure balance on any given bubble (Chi[5], 1976). The boiling limit (q_b) can be written as:

$$q_b = \left(\frac{2\pi L_e k_{eff} T_v}{h_{fg}\rho_v \ln({}^{ri}/_{rv})}\right)\left(\frac{2\sigma}{r_n} - \Delta P_c\right) \qquad \text{Eq. 2}$$

Where L_e is the evaporator length, k_{eff} is the effective thermal conductivity of the liquid/wick combination, T_v is the vapor temperature, r_n is the nucleation site radius, and ΔP_c is the capillary pressure.
For the current hybrid heat pipe, the capillary and the boiling limits are expected to be the most constraining operating limits. For the metal foam or screen hybrid wick (grooved adiabatic and condenser) CCHP, the modeling effort shows that the grooved wick in the condenser and adiabatic sections cannot sustain flow rate governed by metal foam or screen mesh wick in the evaporator (i.e. liquid and vapor pressure drop from frictional losses in grooves which is function of mass flow rate governed by metal foam or screen mesh in the evaporator is less than the capillary limit for grooves). Therefore, the hybrid metal foam and screen mesh evaporator CCHPs did not meet the goal for the program. So the offered metal foam (50 PPI) and screen mesh (stainless steel mesh # 635) were ruled out as shown in Figure 6. On the other hand, the sintered nickel wicks offer the highest operating heat flux capability compared to screen, foam, and grooved wicks. The green line in Figure 6 shows the power requirements for the CCHPs.

Also, the modeling effort determined the effect of the evaporator's wick thickness in the CCHPs performance as shown in Figure 7. The boiling limit can be improved by minimizing the wick thickness in the evaporator but the capillary limit will be reduced. Since the boiling limit is more sensitive and important than the capillary limit in our hybrid CCHPs the 0.06" thickness was selected.

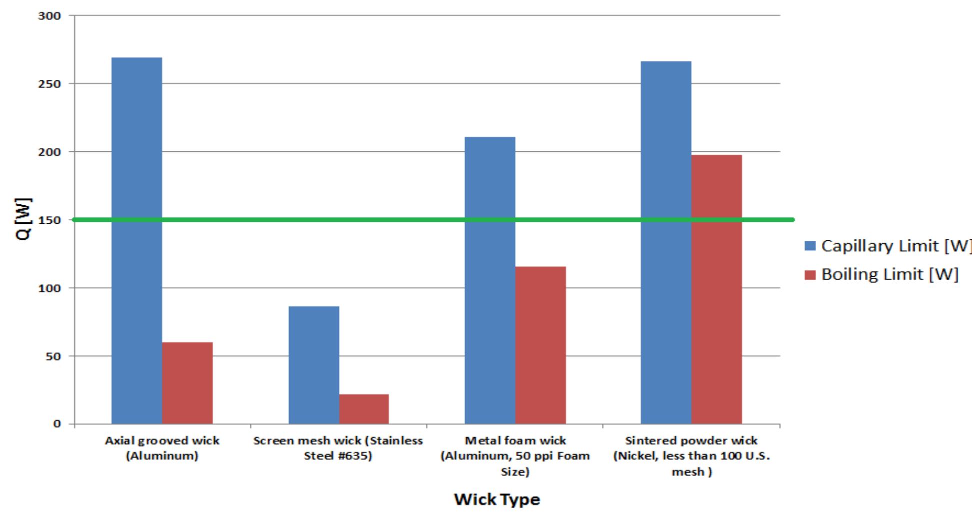


Figure 6. Theoretical capillary and boiling limits for different wick types at 20^0 C.

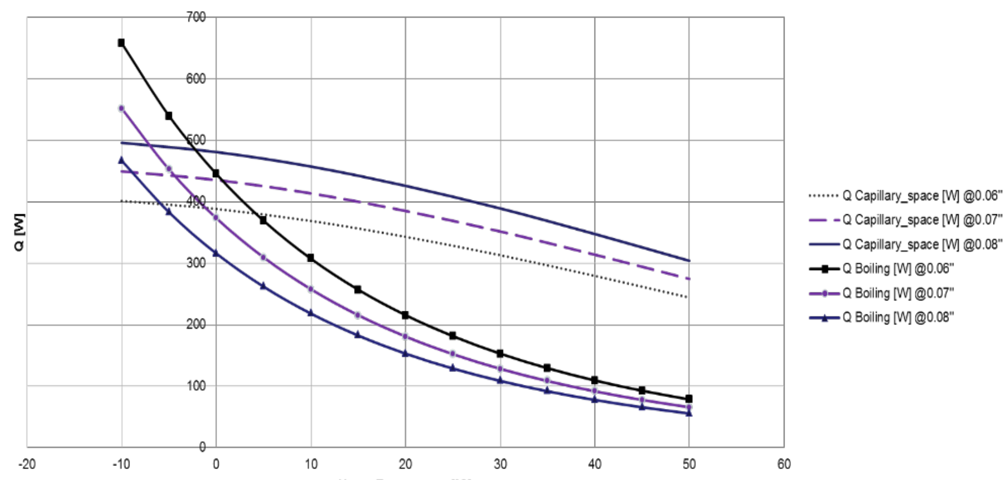


Figure 7. The effect of the evaporator wick thickness on the CCHPs performance as a function of vapor temperature.

B. Sintered Wick

Sintering is frequently utilized to create metallic filters, and many parts of machines are nowadays created by this method as opposed to molding or die casting. The process includes bonding a large number of particles together in the arrangement of a packed metal powder. The powder, which is usually spherical, is placed in containers giving the shape needed and then either sintered with or without applying pressure. Sintering is typically accomplished at a temperature of 100 – 200 ^{0}C below the melting point of the sintering material (Ababneh[6], 2012).

A specification of pore radius and permeability defines the wicking characteristics of a sintered metal powder. It was desired to have permeability serve as the independent variable since it was the limiting property. A pore radius was still needed in order to calculate capillary pumping pressure; therefore, Figure 8 shows the 36 samples experimental trials, at different furnace conditions (temperature and duration of exposure), packing pressure, and different particle size. Less than 100 U.S. mesh size is finalized and used inside the hybrid CCHPs after the sintering process. For sintered powder wicks, the permeability and the pore radius can be related by the Anderson curve shown in Equation 3 (Zuo and North[7], 2000)

$$\boldsymbol{r_c} = (\boldsymbol{8K})^{\frac{1}{2.207}} \qquad \textbf{Eq. 3}$$

Where r_c is the pore radius (m), and K is the permeability (m^2). This relation is based on test data from numerous sintered metal powder wicks. Figure 9 shows an example picture for one of these sintered nickel powder wick.

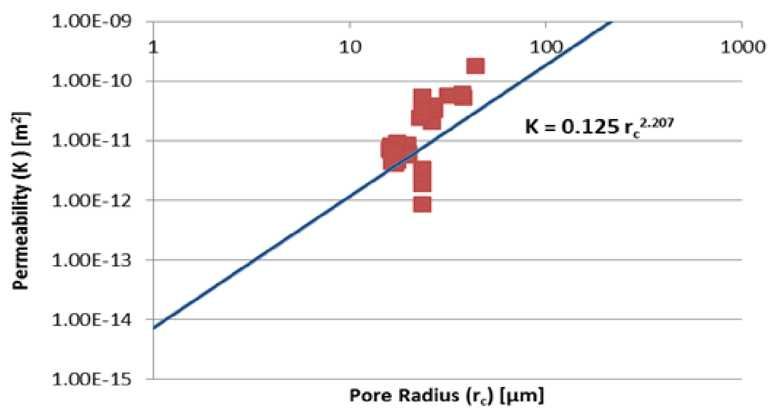


Figure 8: Permeability as a function of the pore radius for nickel powder.

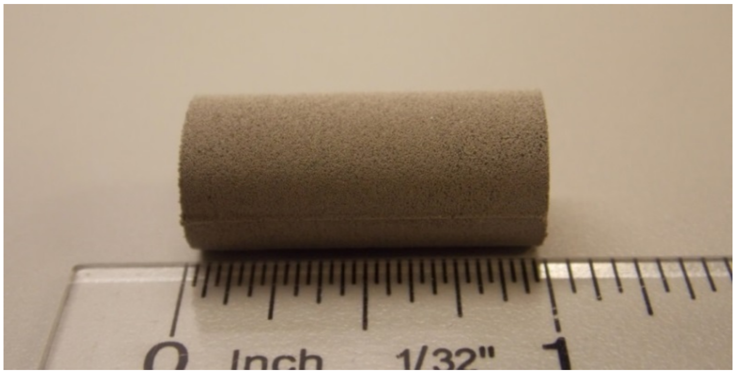


Figure 9. Sintered nickel powder (-100 US sieve size, OD = 0.5”, length = 1”).

C. Evaporator Design

Two types of constant conductance heat pipes (CCHPs) were fabricated:

- CCHPs to demonstrate high heat flux operation, the evaporator has the same cross-sectional profile as the adiabatic and condenser sections of the heat pipe.
- CCHPs to demonstrate operation against gravity, the evaporator has larger cross-sectional profile than the adiabatic and condenser sections of the heat pipe to minimize the liquid pressure drop. These CCHPs are described in more detail in the following sections:

i. <u>High Heat Flux Hybrid CCHP</u>

a) Sintered Wick to Axial Groove Design and Wick Insertion for Aluminum/Ammonia Hybrid CCHP

The evaporator has the same cross-sectional profile as the adiabatic and condenser sections of the heat pipe (~ 0.5” OD), except that the grooves would be removed to make room for the sintered wick. A number of interface designs between the sintered powder metal wick and the axial grooves were evaluated; see Figure 10. The design criteria were to assure adequate fluid connection with the grooved wick and good thermal connection with the evaporator wall. The 45° angled (Figure 10-d) cone was selected for the test articles in this effort, where the evaporator with its sintered metal powder wick is located on the left half of the heat pipe. Benefits of this design are: 1) standard aerospace CCHP grooved aluminum extrusion, which is TRL 9 rated, can be used throughout the entire length of the heat pipe and 2) the heat pipe can have a completely contiguous envelope without seams to enhance reliability.

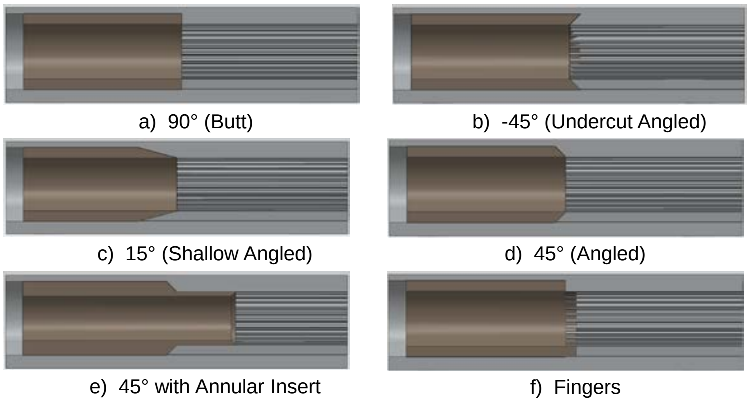


Figure 10: Potential interface designs between the sintered wick and axial grooves.

b) Sintered Wick to Axial Groove Design for Stainless Steel /Ammonia Hybrid CCHP

The metal powder wick for the stainless steel heat pipes was sintered internally with the optimum sintering characteristics (packing pressure and furnace schedule). Figure 11 shows the interface between the sintered powder metal wick and the axial grooves in the stainless steel hybrid CCHP.

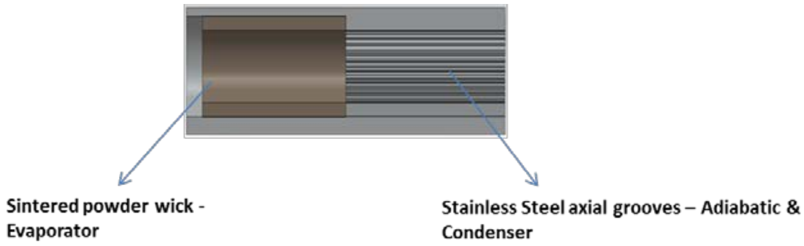


Figure 11 : Interface between the sintered wick and axial grooves in the stainless steel hybrid CCHP.

ii. *Planetary surfaces hybrid CCHP*

However, the high heat flux evaporator design is not valid for the planetary hybrid CCHP. The disadvantages of the design all relate to the relatively small inside diameter (~ 0.5" ID) of the extrusion; the liquid pressure drop in the evaporator is greatly exacerbated by the relatively small cross-sectional flow area through the wick. The primary impetus for the planetary evaporator design was to minimize the liquid pressure drop by increasing the cross-sectional flow area. Slight increases (e.g., +0.010", +0.020") in wick thickness were not effectively reducing the pressure drop; therefore, a larger diameter evaporator was chosen. Figure 12 depicts the planetary hybrid CCHP 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).

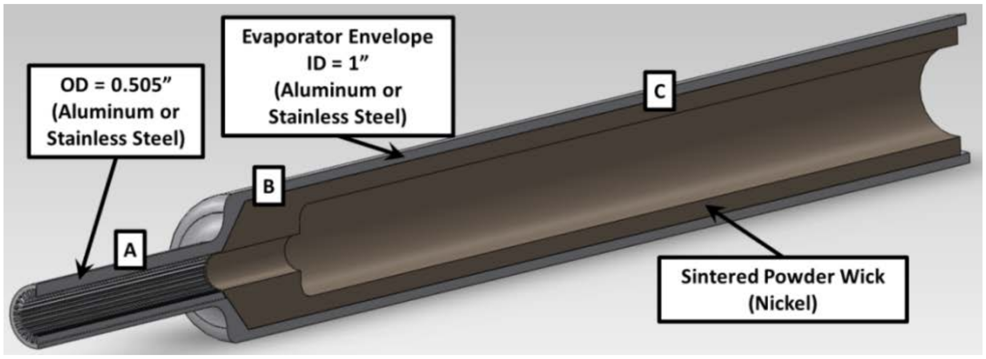


Figure 12. Planetary CCHP evaporator design (sintered wick after insertion into evaporator).

Working fluid returning from the condenser is pumped by the grooves (section A) to the beginning of the sintered wick. A 45° conical interface (it is the same interface as the design shown in Figure 10-d) hydraulically joins the axial grooves to the sintered metal powder wick. There is a 1.25 inch 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. Figure 13 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.

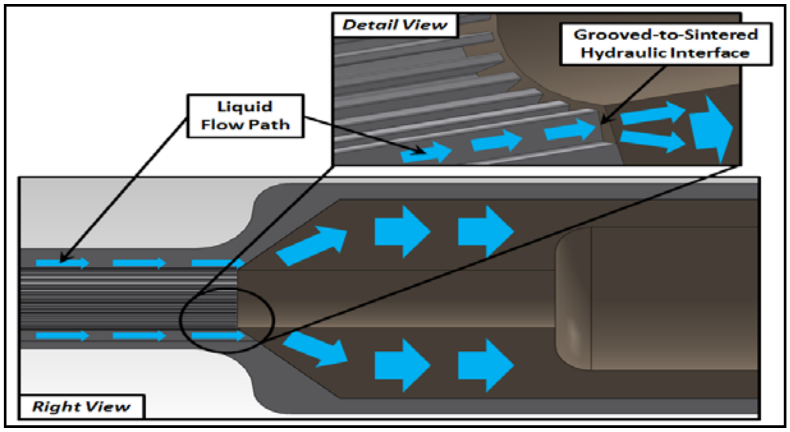


Figure 13. Planetary CCHP evaporator 45° conical interface (cross sectional right view and detail view).

IV. Hybrid Heat Pipe Fabrication

Five constant conductance heat pipes were fabricated: two CCHPs to demonstrate high heat flux operation, two CCHPs to demonstrate operation against gravity, and a standard axial groove CCHP. These CCHPs are described in more detail in the following sections:

A. Standard Axial Grooves CCHP

This heat pipe represents the baseline design and has axial grooves throughout its entire length, which is typical of CCHPs for satellite thermal control (Advanced Cooling Technologies[8], 2013). The maximum heat flux capability was determined at the industry standard 0.1 inch adverse elevation. This heat pipe was fabricated and tested in the previous program, so the performance results are used to compare them with the new hybrid CCHPs.

B. Hybrid High Heat Flux CCHPs with Sintered Wick Evaporator

These heat pipes represent the high heat flux design with sintered powder metal in the evaporator and axial grooves in the condenser and adiabatic sections. For aluminum/ammonia hybrid CCHP, the grooves in the evaporator section were removed by machining, and an annular sintered metal powder wick was inserted in place of the grooves. Conversely, the metal powder wick is sintered inside the evaporator section for the stainless steel/ammonia hybrid CCHP. Standard thermal performance testing at 0.1" adverse elevation was performed to determine the maximum heat flux capability. The design parameters and drawing for both the standard axial groove CCHP and the CCHP with the sintered wick evaporator are shown in Table 2 and Figure 14, respectively.

The hybrid wick stainless steel/ammonia CCHP is shorter than the aluminum/ammonia hybrid CCHP due to the time and high cost required for building stainless steel grooved CCHPs.

Table 2. Design parameters for the high heat flux CCHPs and the standard axial groove CCHP.

Design Parameter	Hybrid Wick Aluminum/Ammonia CCHP Design	Hybrid Wick Stainless Steel/Ammonia CCHP Design	Standard CCHP Design
Overall Length	22 inches (55.9 cm)	11.25 inches (28.6 cm)	22 inches (55.9 cm)
Evaporator Length	1 inch (2.54 cm)	1 inch (2.54 cm)	1 inch (2.54 cm)
Condenser Length	5 inches (12.7cm)	5 inches (12.7cm)	5 inches (12.7cm)
Heat Input Area	3.26cm^2	3.26cm^2	3.26cm^2
Wick Structure – Condenser and Adiabatic	Axial Grooves	Axial Grooves	Axial Grooves
Wick Structure – Evaporator	Sintered Nickel Powder	Sintered Nickel Powder	Axial Grooves
End Detail in Evaporator	45° Angled	90° Angled	NA
Envelope Material	6063 Aluminum	304 Stainless Steel	6063 Aluminum
Ammonia Fluid Charge	9.1 grams	4.8 grams	8.5 grams

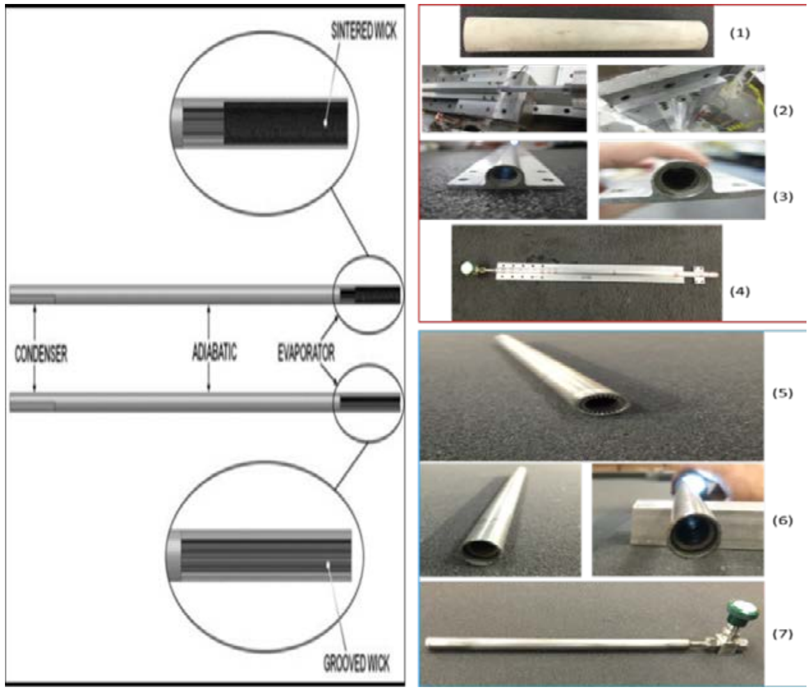


Figure 14. Bottom left: Drawing of the standard axial groove CCHP. Top left: the hybrid CCHP with the evaporator grooves removed and replaced with a sintered powder metal wick. Top right (1-4): Hybrid aluminum/ammonia heat pipe assembly. (1) Shows the sintered powder metal wick. (2) Shows the sintered wick insertion into the aluminum extrusion (3) sintered wick after insertion and machined to establish the wick and vapor space design parameters. (4) Shows the completed heat pipe assembly. Bottom right (5-7): Hybrid stainless steel/ammonia heat pipe assembly. (5) Shows the stainless steel axial grooved pipe. (6) Shows the machined sintered wick after internal sintering. (7) Shows the completed heat pipe assembly.

C. Hybrid Planetary CCHPs

These pipes represent a thermal link between Warm Electronics Box (WEB) electronics or avionics and the radiator for landers and rovers (Anderson et al.[9], 2010). These CCHPs have a sintered wick in evaporator and a grooved wick in adiabatic and condenser regions. The evaporator section was formed separately from the rest of the CCHP and included the length for the sintered evaporator wick a 3 cm diameter and a short length of axial grooves a 1.27 cm (0.5 inch) diameter, for direct interface to the axial grooves in the adiabatic and condenser regions. The design parameters, drawing and assembly for Thermal Link CCHP are shown in Table 3 and Figure 15, respectively.

Table 3. Design Parameters for the Hybrid Planetary CCHPs.

Design Parameter	Planetary CCHPs
Overall Length	40 inches (101.6 cm)
Evaporator Length	9 inches (22.9 cm)
Condenser Length	12 inches (30.5cm)
Wick Structure – Condenser and Adiabatic	Axial Grooves
Outside Diameter – Condenser and Adiabatic	0.5 inch (1.27 cm)
Wick Structure - Evaporator	Sintered Nickel Powder
Outside Diameter - Evaporator	1.18 inch (3.0 cm)
End Detail in Evaporator	45° Angled
Envelope Material	6063 Aluminum and 304 Stainless Steel
Ammonia Fluid Charge	27.7grams

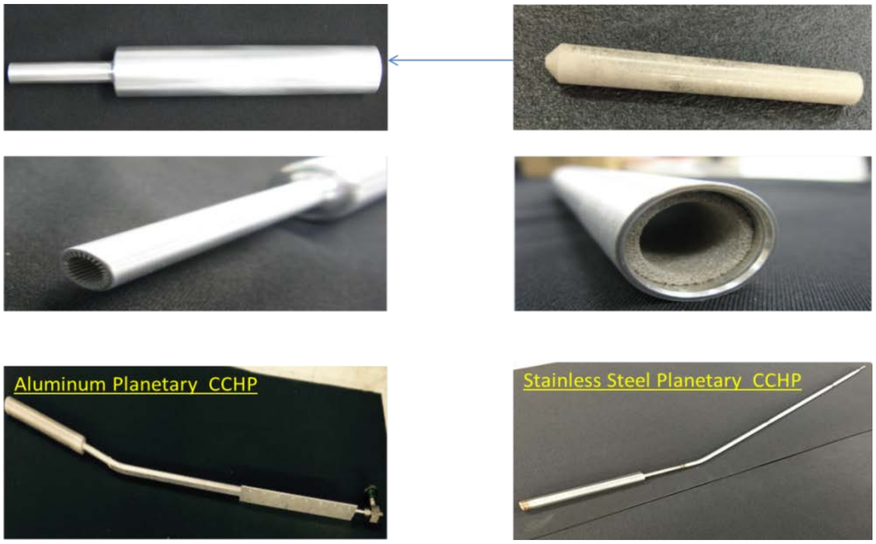


Figure 15. Planetary CCHPs assembly: The top right view shows the sintered powder metal wick with end detail design (45°) to interface with the axial grooves. The middle right view shows the sintered wick after insertion into the aluminum extrusion and machined to establish the wick and vapor space design parameters. The lower views show the completed pipes assembly before final bending as shown in Figures 22 and 24.

D. X-ray Inspection

In-house X-ray inspection at ACT is utilized for identifying the quality of interface between the sintered powder metal wick and the axial grooves. Figure 16-A shows the disconnection between the sintered wick and axial grooves in the aluminum hybrid CCHP in one of the failed CCHPs because of improper insertion. The insertion procedure was revised to produce successful connection between the sintered powder metal wick and the axial grooves as shown in Figure 16-B.

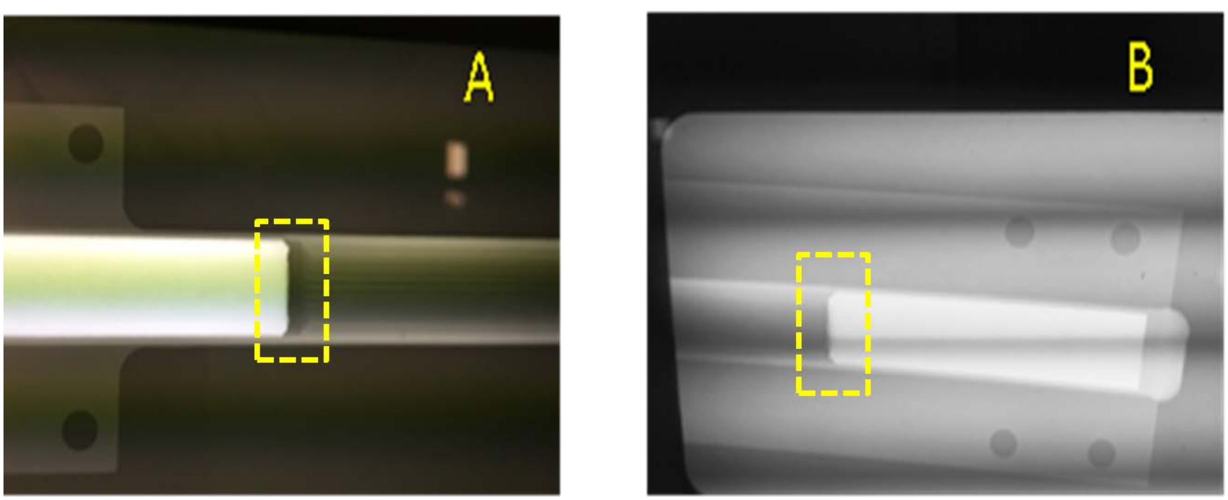


Figure 16. X-ray inspection is utilized for identifying the quality of interface between the sintered powder metal wick and the axial grooves in the aluminum hybrid CCHPs. A) The disconnection between the sintered wick and axial grooves, B) The successful connection between the sintered powder metal wick and the axial grooves.

The X-ray for the interface between the sintered powder metal wick and the axial grooves in the stainless steel hybrid CCHPs shows improvement over the aluminum CCHPs because of the internal sintering technique as shown in Figure 17.

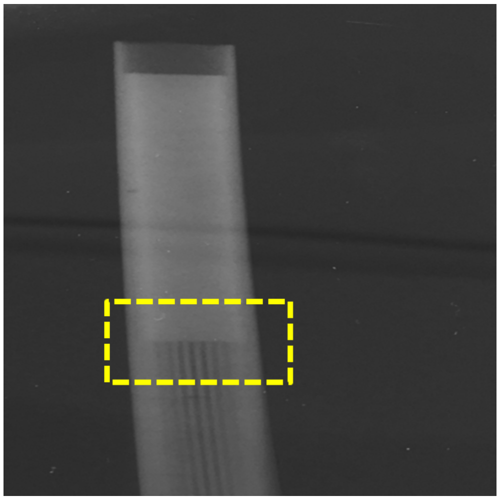


Figure 17. X-ray for the successful connection between the sintered powder metal wick and the axial grooves in the stainless steel hybrid CCHPs.

V. Performance Testing

A summary of the thermal performance test plan is shown in Table 4.

Table 4. Hybrid Heat Pipe Thermal Performance Test Plan.

Hybrid Heat Pipes Description	Lunar Application		Space Application	
	Operating Temperature	Adverse Orientation	Operating Temperature	Adverse Orientation
Hybrid Wick CCHPs Sintered Wick Evaporator	–	–	25°C	0.1 inch
Hybrid Planetary CCHPs	25°C	4.2°	25°C	0.1, 0.2, 0.3 inch

A. Hybrid High Heat Flux CCHPs

Testing for the hybrid high heat flux CCHPs was performed at a 0.1 inch adverse elevation between the evaporator and the condenser, with the evaporator above the condenser. An aluminum heater block (for aluminum/ammonia hybrid CCHP) and a copper heater block (for stainless steel/ammonia hybrid CCHP) with cartridge heaters is the heat input source. To be noted is that although the stainless steel hybrid CCHP does not have a flange similar to the aluminum hybrid CCHP, the heat input area is 3.26 cm^2 for both hybrid CCHPs. The condenser sink conditions were established using an aluminum block connected with a Liquid Nitrogen (LN2) source for both hybrid CCHPs. The LN2 flow to the condenser is adjusted via a temperature controller, based on the adiabatic temperature. The pipes were instrumented with type T thermocouples. Figure 18 and Figure 19 show overall test assembly. The test procedure, that is similar for all thermal performance testing, is described below:

- The test CCHPs were instrumented, insulated and oriented at 0.1 inch adverse elevation.
- The sink conditions were adjusted to maintain a 25°C adiabatic temperature.
- The power was input as a step function and the temperatures were 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.

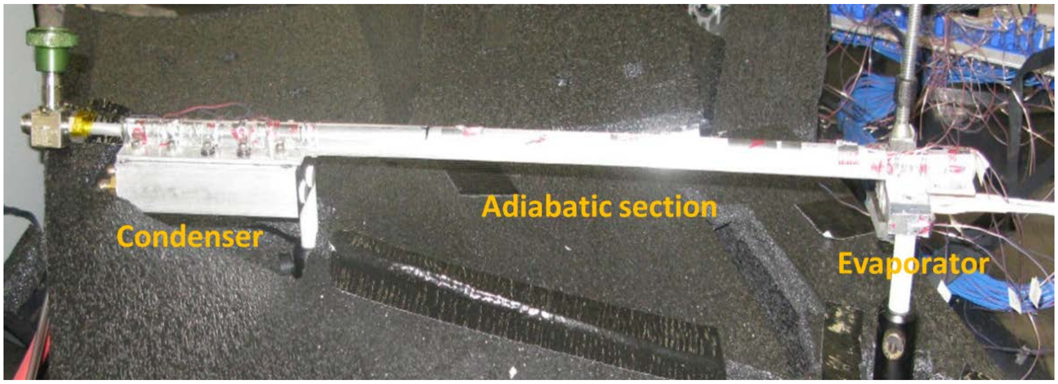


Figure 18. The overall test assembly for the aluminum/ammonia high heat flux CCHP testing set up. Insulation was removed to show the pipe features.

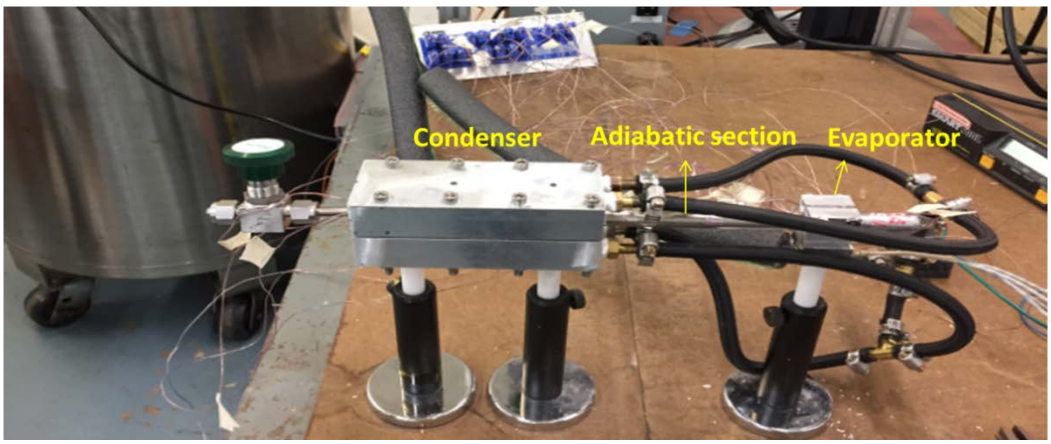
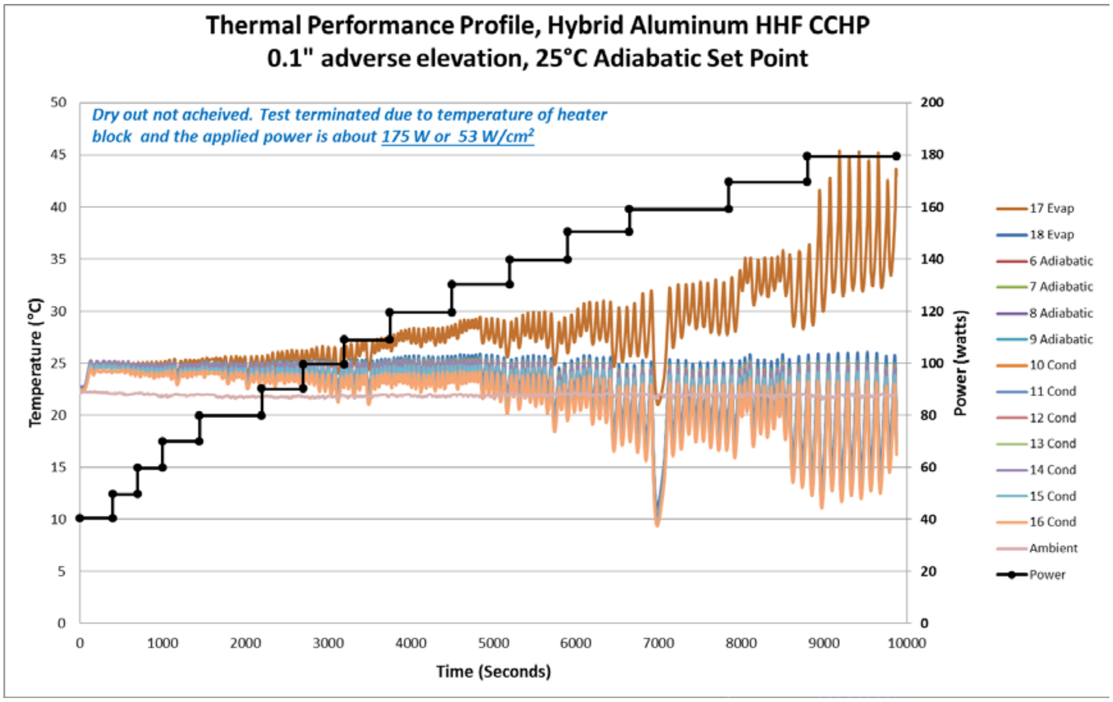


Figure 19. The overall test assembly for the stainless steel/ammonia high heat flux CCHP testing set up.

<u>Test Results</u>

The temperature and power profile as a function of time for both designs for the high heat flux hybrid wick CCHPs are shown in Figure 20. Initial tests performed on the hybrid wick CCHP indicated improved performance over the axial groove design. Basically, for both hybrid wick high heat flux CCHPs the temperature values are relatively higher at end of evaporator section near to the end cap due to the non-uniform heat distributed in the heater blocks. Testing of the heat pipe is performed at adverse elevation of 0.1 inch. Because at 0.0 inch a puddle flow, which would produce very optimistic results, prevents direct testing of the heat pipe at 0.0 inch elevation. For this reason, the heat pipe code includes a 0.1" adverse elevation term for the simulated space case. The hybrid wick high heat flux aluminum/ammonia and stainless steel/ammonia CCHPs carried up to approximately 175 watts and 165 watts respectively where the test was terminated due high heater block temperatures. The heat flux achieved at 175 watts was $53W/cm^2$ and at 165 watts was $51\ W/cm^2$. Notably, the power achieved before dryout for the standard axial grooved CCHP was approximately 58 watts, or $17.8W/cm^2$. This demonstrates an improvement in heat flux capability of 3 times over the standard axial groove CCHP design. At this temperature the performance predictions indicated that approximately 176.1 W should be achievable, versus the 175 W and 165 W experimentally demonstrated before the test terminated early due to heater block limitations. Also, the heat flux improvement was demonstrated, the theoretical model which is discussed in Section III showed excellent agreement with the experimental results as shown in Figure 21.



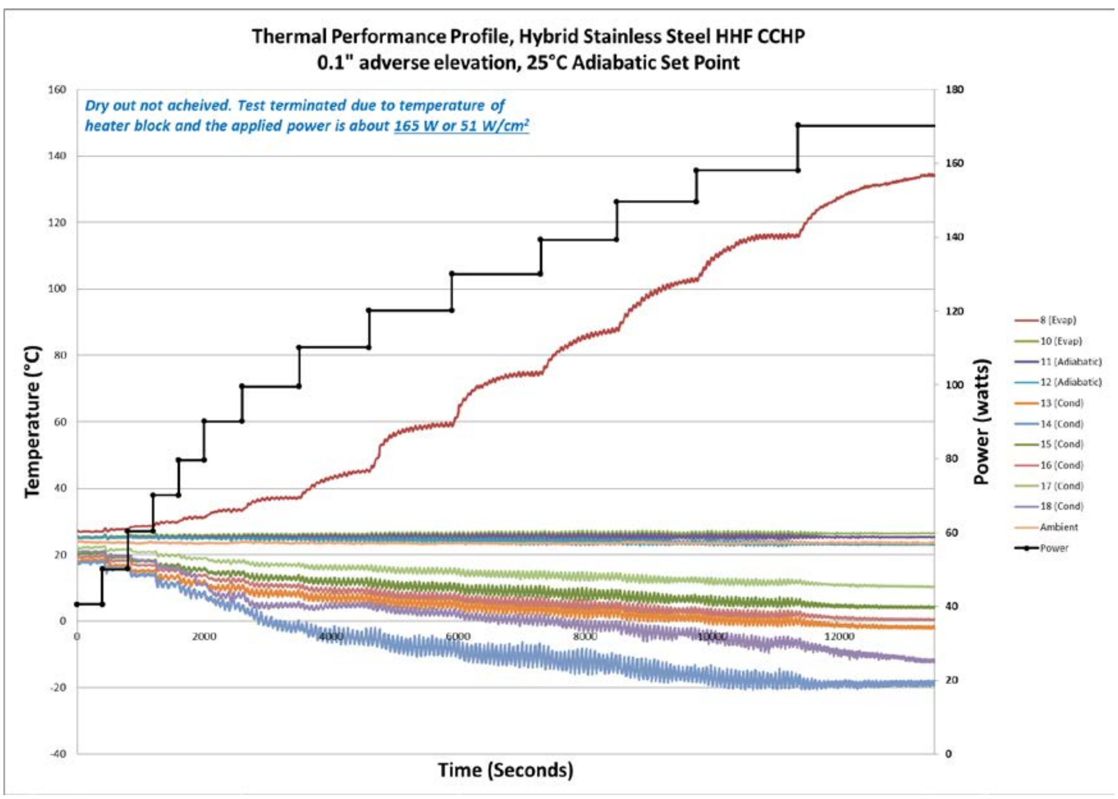


Figure 20. Thermal performance profile for the <u>aluminum/ammonia hybrid wick high heat flux</u> CCHP (Top) at 0.1 inch adverse elevation and a 25°C adiabatic set point temperature, and thermal performance profile for the <u>stainless steel/ammonia hybrid wick high heat flux</u> CCHP (Bottom) at 0.1 inch adverse elevation and a 25°C adiabatic set point temperature.

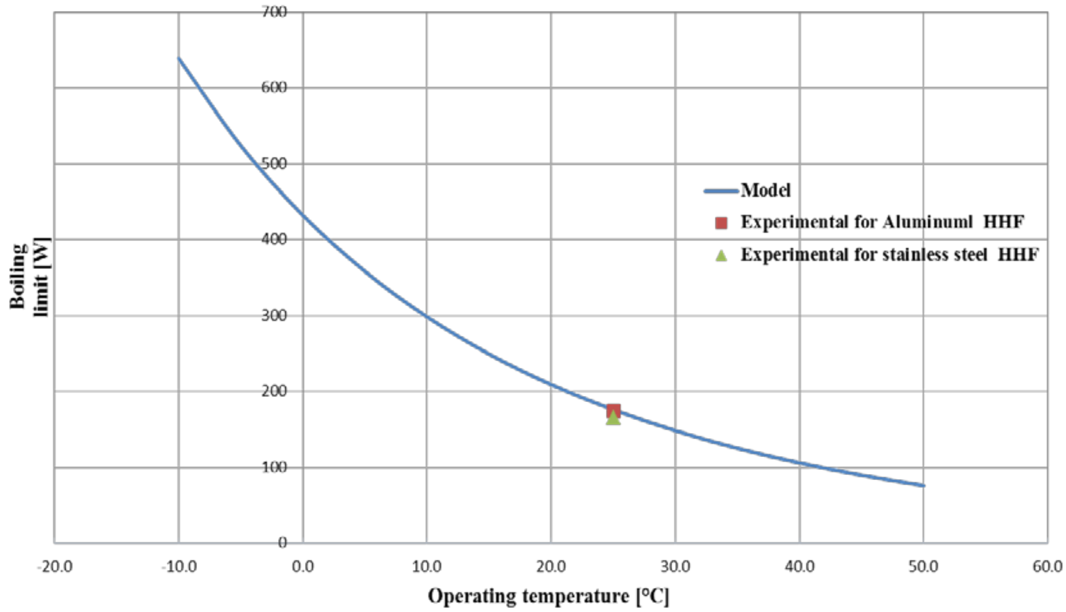


Figure 21. Comparison of experimental and theortical thermal performance for the hybrid wick high heat flux (HHF) CCHPs.

B. Planetary Hybrid Wick CCHPs Testing

The CCHP serving as the thermal link between the avionics and radiator were tested for thermal performance. Two types of tests were performed. The first was to determine performance under lunar conditions where the pipe could be oriented as much as 25° against gravity. The second test was to determine performance during transit to the lunar surface at zero-g conditions.

<u>**Planetary Hybrid Wick Aluminum/Ammonia CCHP Lunar Surface Testing**</u>

Testing was performed at a worst case simulated lunar gravity orientation as shown in Figure 22. The condenser will be nearly vertical, and adiabatic section will be gravity aided. The evaporator was at a slight gravity adverse inclination (4.2° on earth ≈ 25° on moon).

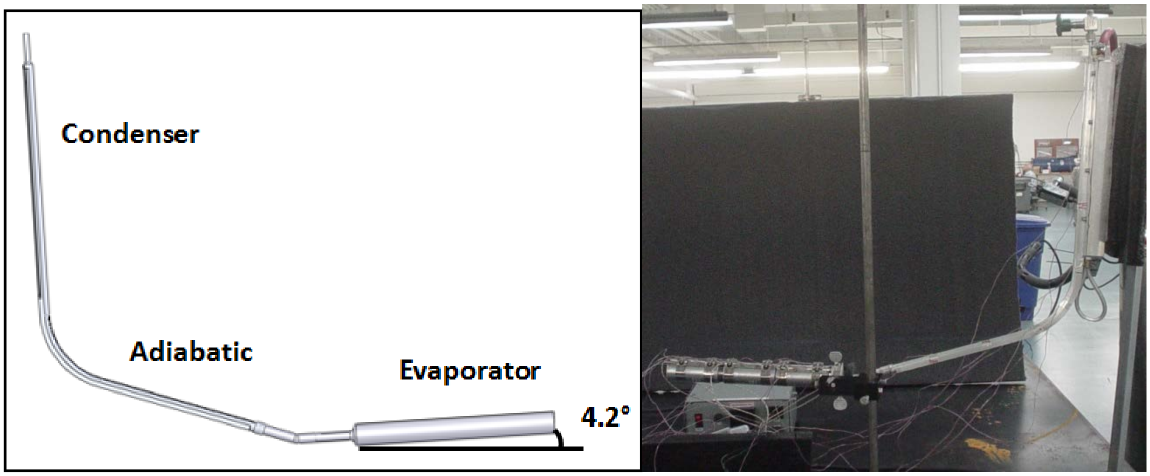


Figure 22. Thermal Link CCHP test orientation. The pipe is oriented to simulate the worst case lunar gravity conditions, where the evaporator is oriented at 4.2° against gravity to simulate 25° on the lunar surface.

Test Results

The test results for the Thermal Link planetary CCHP are shown in Figure 23 which plots the temperature and power profile as a function of time. The power achieved before dryout was approximately 202 W. The target power for the program is 150 W, so the pipe demonstrated 1.5 times the required power.

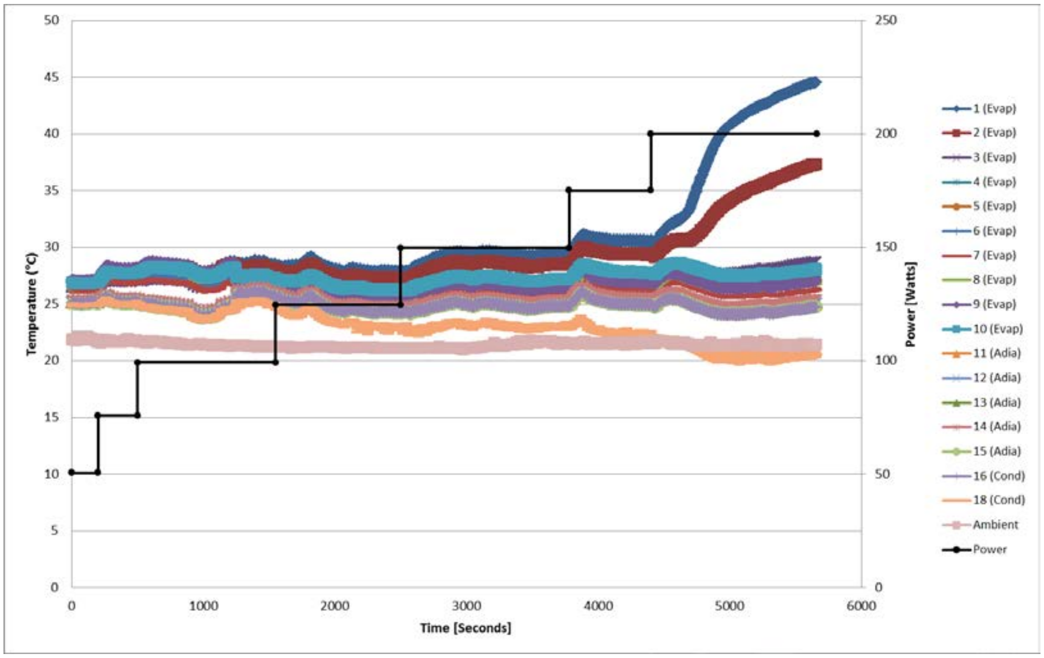


Figure 23. Thermal performance profile for the Thermal Link CCHP with 1.0 inch OD evaporator at 4.2° adverse elevation and a 25°C adiabatic set point temperature.

Thermal Link CCHP, Space Based Operation Testing

Testing was performed at several orientations to extrapolate zero-g performance to determine performance in space. The pipe was orientated at 0.1 inch, 0.2 inch and 0.3 inch adverse elevations and tested for performance at various power inputs. This data was used to extrapolate zero-g performance. Figure **24** shows the overall test assembly.

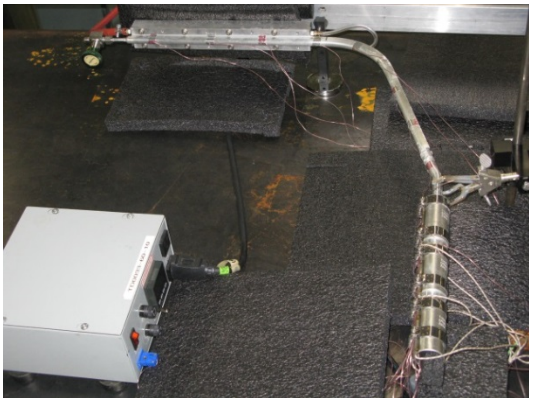


Figure 24. **Thermal Link CCHP testing set up for space based orientation. The evaporator is inclined 0.1 inch to 0.3 inch to extrapolate zero-g performance.**

Test Results

Testing was completed at 0.1 inch, 0.2 inch and 0.3 inch adverse elevations. The maximum power was established as the last (highest) power applied before dryout. For example, the maximum power for 0.1 inch, 0.2 inch and 0.3 inch elevations is 202W, 109W, and 27W, respectively. These values were plotted as a function of elevation as shown in Figure 25. The curve was linearly extrapolated to 0 inch inclination to establish the predicted maximum power the pipe will carry in zero-g. The predicted maximum power at zero-g is 288 watts.

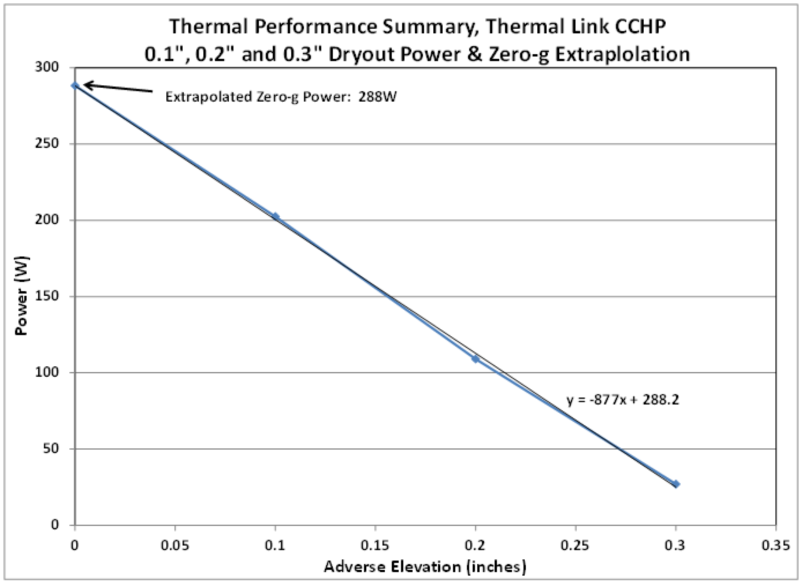


Figure 25. Thermal performance summary for the Thermal Link CCHP. The maximum powers measured at 0.1", 0.2" and 0.3" are used to extrapolate the zero-g performance for space based operation.

The Thermal Link planetary stainless steel/ammonia hybrid CCHP was designed and fabricated successfully. Testing for space and lunar gravity conditions is still ongoing.

VI. Conclusion

The innovation is to develop CCHPs with a hybrid sintered, metal foam, or screen mesh in the evaporator section and grooved wick in the adiabatic and condenser sections for planetary surface and high heat flux applications. A hybrid wick CCHP 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-sintered wick.

The modeling effort shows that the sintered nickel wick is the best candidate. As a consequence, during this work the sintered nickel powder (evaporator) wicks were thoroughly studied based on the pore radius, porosity, permeability and machinability. For the aluminum hybrid wick CCHPs, six sintered wick to axial groove interface designs were identified and tested successfully. Conversely, for the stainless steel hybrid CCHP, the internal sintering technique was performed successfully as well.

Aluminum and stainless steel/ammonia CCHP sets were fabricated and successfully tested to demonstrate the hybrid wick CCHPs concept - one set for high heat flux applications and other set for planetary applications. Notably, the aluminum envelope for the hybrid CCHP is required when the importance of heat leakage during shut off is moderate. While the stainless steel envelope for the hybrid CCHP is required when the heat leakage during shut off must be severely minimized. The following results were demonstrated during the successful program:

- The standard axial groove CCHP transported approximately 58 watts, or 17.8 W/cm^2 at 0.1 inch adverse elevation before dryout. The performance results were used to compare them with the new hybrid CCHPs.

- The hybrid wick high heat flux aluminum/ammonia CCHP transported a heat load of 175 watts with heat flux input of 53W/cm^2 at 0.1 inch adverse elevation. The test was terminated not because it reached the heat pipe limit but rather because it reached a safety limit on the heater block. This demonstrates an improvement in heat flux capability of **3 times** over the standard axial groove CCHP design.
- The hybrid wick high heat flux stainless steel/ammonia CCHP transported a heat load of 165 watts with heat flux input of 51 W/cm^2 at 0.1 inch adverse elevation. The test was terminated because it reached a safety limit on the heater block.
- The Thermal Link planetary aluminum/ammonia CCHP transported approximately 202 watts at a 4.2° adverse inclination before dryout, exceeding the 150W target.
- The planetary aluminum/ammonia CCHP was tested for maximum transport power at three different adverse elevations to extrapolate zero-g power. The maximum power at zero-g is 288 watts, exceeding the 150 watt target.
- The theoretical model showed agreement with the experimental results in estimating the boiling limit for the hybrid CCHPs.
- The X-ray micrographs for the interface between the sintered powder metal wick and the axial grooves in the stainless steel hybrid CCHPs shows much better contact in comparison to the aluminum CCHPs because of the successful internal sintering technique developed during this project.

Acknowledgments

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