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Copper-Water and Hybrid Aluminum-Ammonia Heat Pipes for Spacecraft Thermal Control Applications

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Abstract

Copper-water heat pipes are commonly used for thermal management of electronics systems on earth and aircraft, but have not been used in spacecraft thermal control applications to date, due to the satellite industry's requirement that any device or system be successfully tested in a microgravity environment prior to adoption. Recently, Advanced Cooling Technologies Inc., (ACT), NASA Marshall Space Flight Center, and the International Space Station office at NASA's Johnson Space Center demonstrated flight heritage in Low-Earth Orbit. The testing was conducted aboard the International Space Station (ISS) under the Advanced Passive Thermal eXperiment (APTx) project. The heat pipes were embedded in a high conductivity (HiK™) aluminum base plate and subject to a variety of thermal tests over a temperature range of -10 to 38 ºC for a ten-day period. Results showed excellent agreement with both predictions and ground tests. In addition, novel hybrid wick aluminum-ammonia heat pipes 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 50 W/cm^2 capability of the hybrid high heat flux heat pipes provides a realistic means of managing the high heat density anticipated for the next generation space designs.

Keywords: Copper-water heat pipes; Spacecraft thermal control; International Space Station (ISS); Advanced Passive Thermal experiment (APTx); Aluminum-ammonia heat pipes; Hybrid high heat flux heat pipes

1. INTRODUCTION

Copper-water heat pipes are valuable for electronic cooling industry since they offer low resistance thermal transport with operating temperatures in the 300 to 470 K range. As electronics continue to push the envelope on performance, thermal management systems are becoming increasingly more important. Electronics applications frequently require copper-water heat pipes to move heat from discrete components to air heat sinks. High heat fluxes are reduced and heat is moved to open volumes where heat sinks can be located. Heat pipes are excellent for reducing heat fluxes and transporting heat to heat sink hardware. HiK™ plates [1] and copper-water heat pipes are typically used on earth and aircraft applications, but have not been used in spacecraft thermal control applications, due to lack of testing in a micro-g environment.

HiK™ plates use copper heat pipes that are flattened and embedded in an aluminum plate to increase the effective thermal conductivity. The heat pipe layout is tailored to most efficiently conduct heat from the electronics to the area where the plate is cooled. Water is the most common working fluid, but methanol can be used when the heat pipe needs to operate at lower temperatures.

ACT, NASA Marshall Space Flight Center, and the International Space Station office at NASA's Johnson Space Center tested successfully copper-water heat pipes in Low-Earth Orbit, on board the ISS under the Advanced Passive Thermal eXperiment (APTx) project.

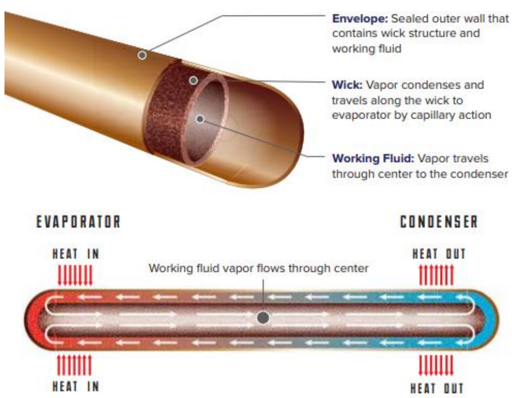


Fig. 1. Copper-water heat pipe.

Aluminum-ammonia Constant Conductance Heat Pipes (CCHPs) have been a proven technology for spacecraft thermal control for more than 40 years. A CCHP transports heat over long distances (up to 3 m or more) from a heat source to a heat sink with a very small temperature difference. However, the traditional CCHPs can handle relatively low heat flux (~10-15 W/cm^2).

Future spacecraft and instruments developed for space science 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. Hence, high flux heat acquisition and transport devices are required. Consequently, ACT demonstrated a more than 3x improvement in heat flux capability (more than 50 W/cm^2) with novel hybrid wick CCHPs.

2. AEROSPACE COPPER-WATER HEAT PIPES

The waste heat from electronics must be removed to keep them from over-heating. On Earth, the ultimate heat sink is typically either a liquid coolant, or the atmosphere. In space, the waste heat is typically transported by grooved-aluminum, CCHPs or Loop Heat Pipes (LHPs) to a radiator, and radiated into the environment. CCHPs represent an effective way to transport the heat over several meters, however they have two limitations:

- Maximum operating temperature, which is roughly 60°C for ammonia CCHPs and LHPs, before the power carrying capability drops off. It is desirable to operate at as high a temperature as possible, since the thermal radiation scales with T^4. Operating at a higher temperature allows a smaller and therefore lighter radiator.
- Ground Testability, grooved CCHPs have a very high permeability for flow, but a very low pumping capability. CCHPs are normally tested on Earth with an adverse elevation (evaporator above condenser) of 0.1in (2.5 mm). The power carrying capability drops to zero with an adverse elevation of about 0.4 in (1 cm). During ground testing of the spacecraft, the CCHP must be gravity aided or level. LHPs do not have this constraint, but are considerably more complex and expensive.

Copper-water heat pipes are commonly used in many military and consumer electronics, including almost all laptops, typically in heat pipe assemblies. The benefits of copper/water heat pipes include their ability to operate at temperatures up to about 150°C, operate against adverse elevations of up to 25cm, and tight bend radius. Their major limitation is that the heat pipes carry only low powers at temperatures below ~ 20°C, and only transfer heat by conduction when the water is frozen. However, by controlling the water inventory so that no free liquid is available, copper-water heat pipes have been shown to withstand thousands of freeze/thaw cycles during terrestrial testing. ACT has recently worked with NASA Johnson Space Center and NASA Marshall Space Flight Center to demonstrate flight heritage for two additional spacecraft thermal control devices: copper-water heat pipes and High Conductivity (HiK™) plates on the ISS under the APTx project.

The objectives for testing flight hardware on the ISS were to validate the operation and flight worthiness of the HiK™ plate and copper-water heat pipes. The TRL of the HiK™ plate was TRL 9 for terrestrial applications and TRL 6 for space applications. The micro-gravity tests on this plate raises the TRL level of the plates to TRL 8, since the plate tested is very similar to those used actual applications. The APTx consists of two separate payloads that will be tested sequentially:

- Payload 1 contains a variable conductance heat pipe (VCHP) with HiK™ plate assembly. (Payload 1 will be discussed in a separate paper)
- Payload 2 contains a HiK™ plate and the ElectroWetting Heat Pipe (EWHP) experiment, developed by the University of Texas at Austin.

2.1 Ground Testing for Payload 2

The first step in fabricating a HiK™ plate is to determine the location of the high power components on the aluminum board, as well as the location of the cooling areas. The second step is to design the heat pipe by selecting the working fluid and its amount and the wick structure. Water was selected as the working fluid and screen copper wick was selected as the heat pipe's wick structure. Two identical HiK™ plates were designed, fabricated, tested, and shipped to ISS. Each HiK™ plate had 9 copper-water heat pipes. Fig. 2 shows the expected performance for each heat pipe at 1 inch against gravity. Each heat pipe can carry up to 65 W at 70 °C before dryout due to the capillary limit [2].

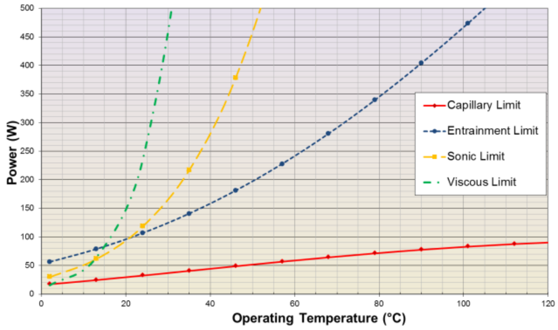
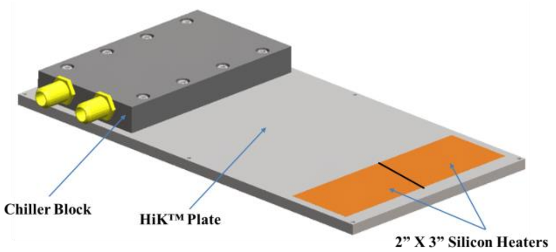
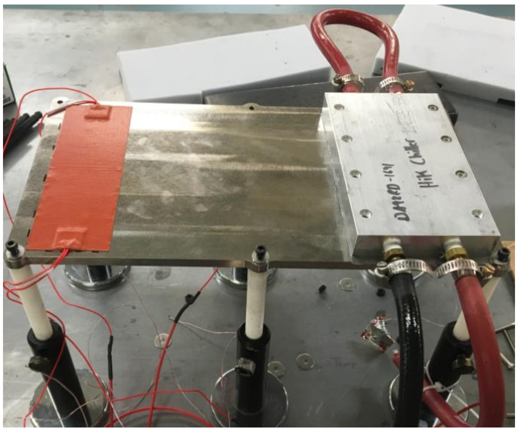


Fig. 2. Heat pipe limits chart for the embedded copper-water heat pipes into the HiK™ plates for ISS APTx.

Fig. 3 shows the design of the HiK™ plate for the ISS experiment in payload 2. Two 53W (2"x3") silicon heaters were used as a heat source on the top of the HiK™ plate; a chiller block was used to impose sink temperatures between -10 to 50°C, and about 30 TCs were used to monitor the temperatures. Freeze/thaw testing was performed successfully for the HiK™ plates on the ground as shown in Fig. 4. The freeze/thaw tests were conducted for both HiK™ plates from temperature ranging from -30 to +70°C for 15 cycles without any problems.



(a)



(b)

Fig. 3. The HiK™ plate for the ISS experiment in payload 2: (a) The CAD model, (b) The fabricated HiK™ plate under testing.

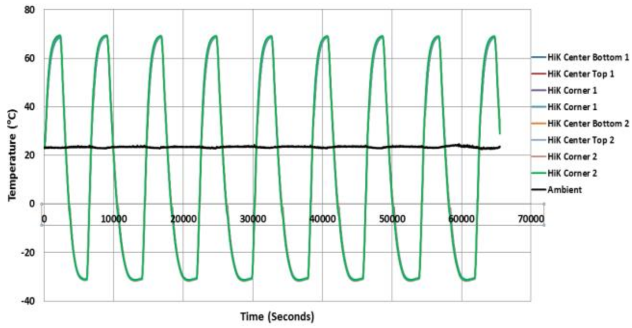


Fig. 4. The temperature profile of HiK™ plates exposed to thermal cycling.

2.2 In-Orbit Testing (IOT) for Payload 2

Freeze/thaw testing was carried out successfully for the HiK™ plate and the copper-water heat pipes on orbit as shown in Fig. 5. The freeze/thaw tests were conducted from temperature ranging from -10°C to ~ 40°C.

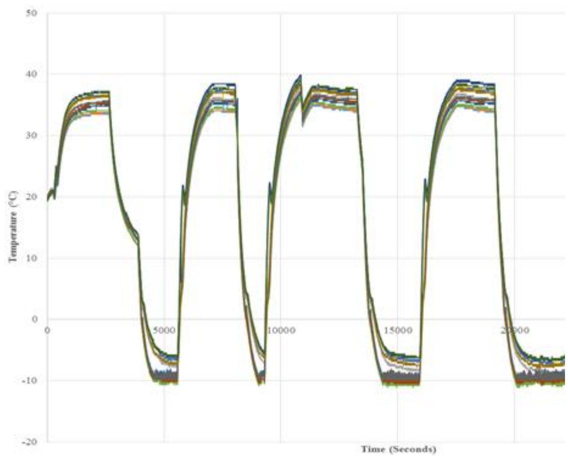


Fig. 5. Snapshot for the freeze/thaw cycles of the HiK™ plate on board ISS.

The following was demonstrated during 10 days of testing on the ISS:

1- Successful operation of the copper-water heat pipes and HiK™ plate.
2- Ability of the copper-water heat pipes and HiK™ plate to survive multiple freeze/thaw cycles.
3- Copper-water heat pipes can carry the required power.
4- Copper-water heat pipes and HiK™ plate can start up from a frozen state.

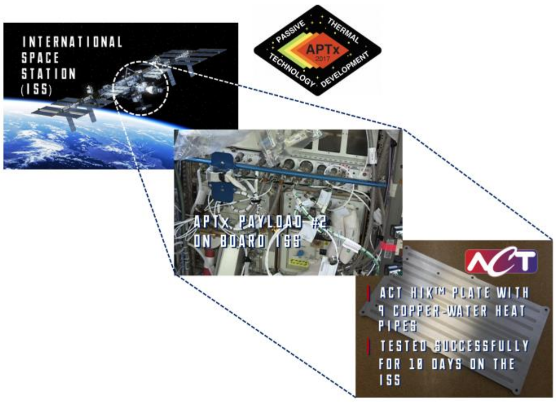


Fig. 6. The HiK™ plate with embedded copper-water heat pipes inside the International Space Station (ISS).

This flight test on-board ISS is an important step for qualifying copper-water heat pipes as a passive thermal management solution in support of future human and robotic space exploration missions.

3. HIGH-HEAT-FLUX ALUMINUM-AMMONIA HEAT PIPES

Aluminum-ammonia CCHPs with axial groove as a capillary wick structures are utilized because of the relative ease of manufacturing (aluminum extrusions) and their demonstrated heritage in spacecraft and instrument thermal control applications. CCHPs are typically used to transfer heat on-orbit, due to their high wick permeability and associated low liquid pressure drop, from specific thermal loads to a radiator panel or as part of an integrated heat pipe radiator panel. However, these CCHPs can handle relatively low heat flux (~10 - 15 W/cm^2).

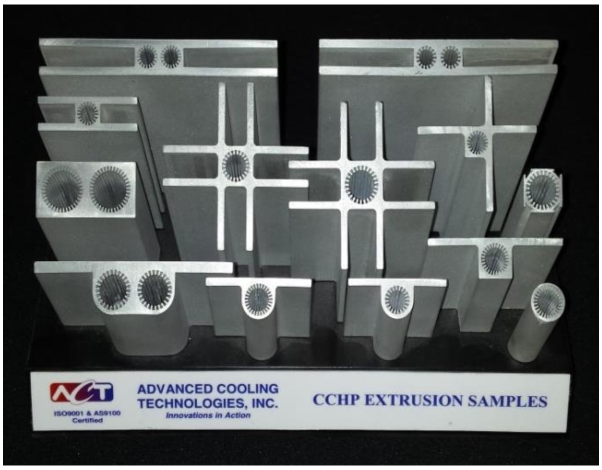


Fig. 7. Grooved aluminum extrusions for ammonia heat pipes. Grooves allow long heat pipes for spacecraft applications, but only work about 0.10 inch (0.00254m) against gravity for earth-based testing (ACT, Inc. [3]).

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. In order to increase the heat flux limit to more than 50 W/cm^2, ACT, Inc. developed a high heat flux heat pipes with a hybrid wick that contains screen mesh, metal foam, or sintered evaporator wicks, which can sustain high heat fluxes, for the evaporator region. The axial grooves in the adiabatic and condenser sections can transfer large amounts of power over long distances as shown in Fig. 8 [4].

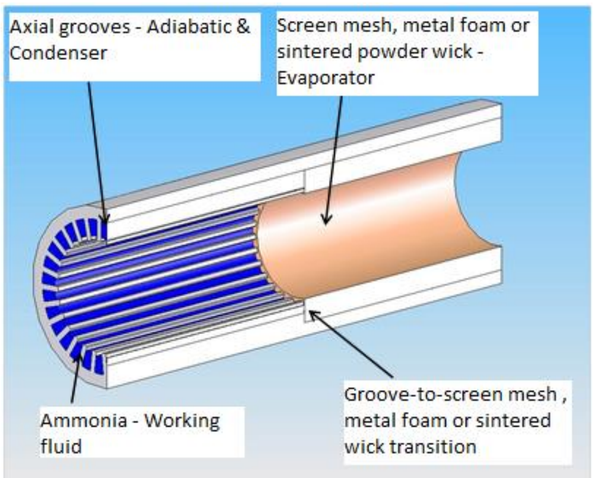


Fig. 8. The concept of the hybrid wick heat pipes for high heat flux applications.

3.1 High-Heat-Flux Heat Pipes Fabrication and Testing

Two aluminum/ammonia hybrid high-heat-flux (HHF) heat pipes were designed, fabricated, and tested:

- HHF1: Bended heat pipe.
- HHF2: Straight heat pipe.

These heat pipes, had ~ 12" long and charged with ~ 5 grams of ammonia

3.1.1 HHF1

The hybrid HHF1 CCHP which is shown in Fig. 9 was tested between 0° to 14.5° adverse elevation between the evaporator and the condenser.

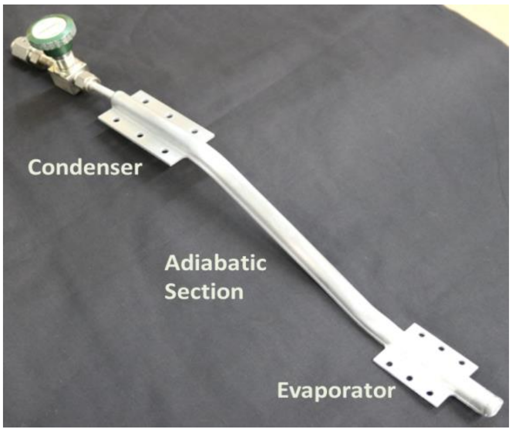


Fig. 9. ACT bended high-heat-flux (HHF1) heat pipe based on hybrid wick technology.

An aluminum heater block with two (200 watt) embedded cartridge heaters as the heat input source. The heat input area for is 6.45 cm^2. The condenser sink condition was established using an aluminum block connected with a Liquid Nitrogen (LN) source for the hybrid HHF CCHPs. The pipe was instrumented with type T thermocouples. Fig. 10 shows overall test assembly.

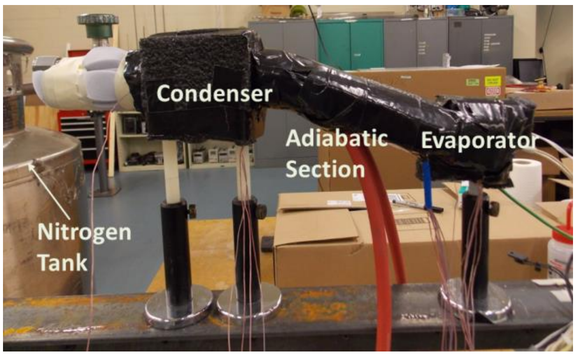


Fig. 10. The test setup for the bended HHF1 CCHP.

The HHF1 pipe transported a heat load of ~ 350 W up to 8° adverse elevation respectively before dry-out. The thermal resistance as a function of power for the bended hybrid HHF1 heat pipe in horizontal positions (between 0° to 14.5° adverse elevation) is shown in Fig. 11.

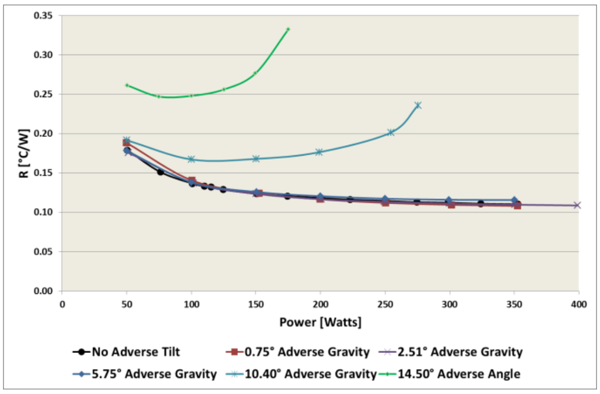


Fig. 11. Thermal resistance as a function of input power for the hybrid bended HHF1 heat pipe between 0° - 14.5° adverse elevation.

The bended HHF1 hybrid heat pipe was sent to Lockheed Martin Coherent Technologies, Inc. for validating the testing results that performed in-house. The testing results from Lockheed Martin are shown in Fig. 12.

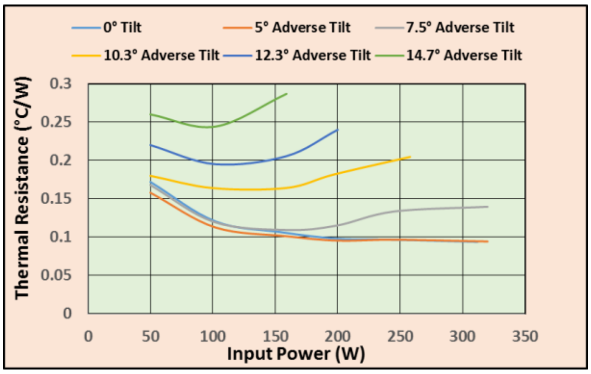


Fig. 12. Lockheed Martin assessment of thermal resistance as a function of power and adverse tilt for ACT's hybrid high-heat-flux heat pipe.

Fig. 13 shows the comparison of the thermal resistance as a function of input power for the high heat flux heat pipe at ~ 0º adverse tilt that performed at ACT and Lockheed Martin and a standard grooved CCHP. The HHF1 aluminum-ammonia CCHP transported a heat load of > 310 Watts with heat flux input of > 48 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 Fig. 13 are related to differences in testing methodologies between ACT and Lockheed Martin.

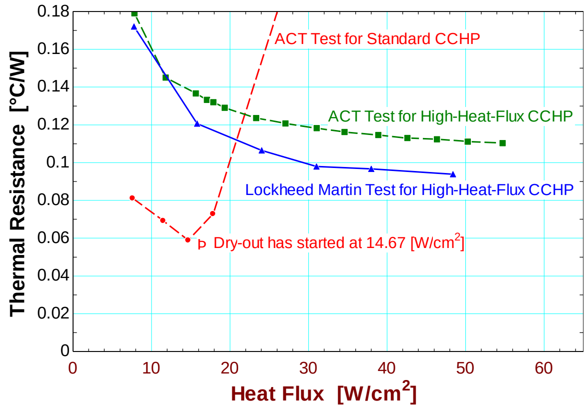


Fig. 13. Comparison of the thermal resistance as a function of heat flux for the bended HHF1 at 0º tilt that performed at ACT and Lockheed Martin and a standard grooved CCHP.

3.1.2 HHF2

The second straight high-heat-flux (HHF2) heat pipe which is shown in Fig. 14 was fabricated and tested. Fig. 15 shows the straight HHF2 under testing.

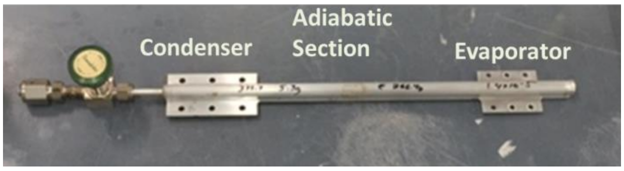


Fig. 14. ACT straight high-heat-flux (HHF2) heat pipe based on hybrid wick technology.

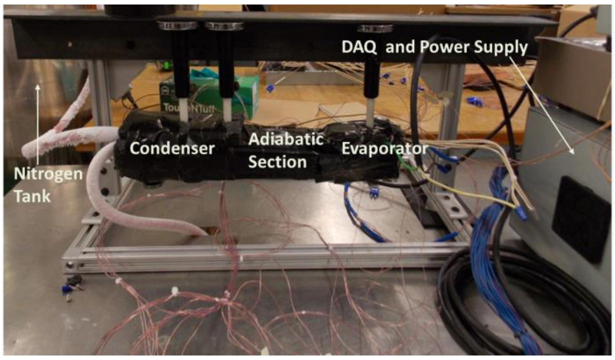
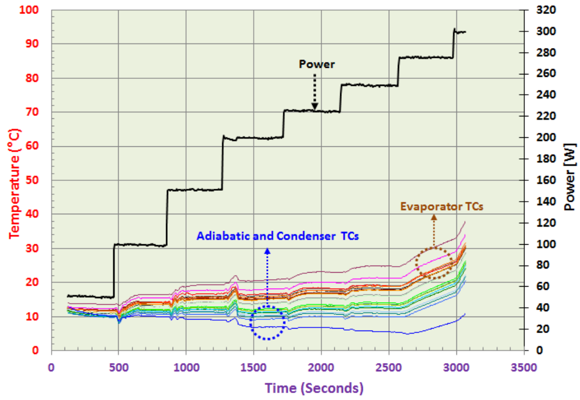
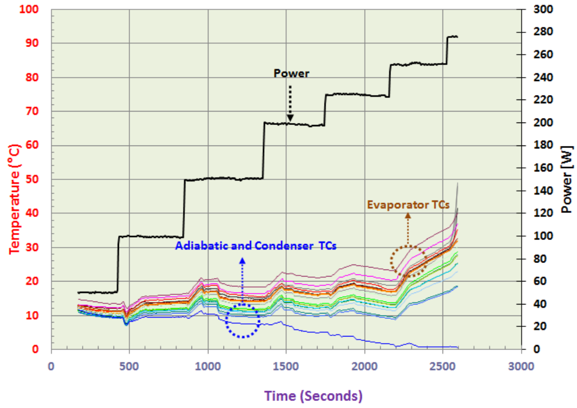


Fig. 15. The test setup for the straight HHF2 CCHP.

The hybrid HHF2 heat pipe was tested in horizontal positions (between 0.1" to 0.3" adverse elevation). Fig. 16 shows the thermal performance results for the pipe at 0.1" and 0.2" adverse elevation as a function of time respectively.



(a)



(b)

Fig. 16. Thermal performance for the straight hybrid HHF2 heat pipe with 10 °C condenser set point at: a) 0.1" and b) 0.2" adverse elevation.

As shown in Fig. 16, the hybrid wick HHF2 heat pipe 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. While, at 0.2 inch adverse elevation, HHF2 heat pipe transported a heat load of 250 Watts with heat flux input of 50 W/cm^2 and R=0.017 ºC/W. 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 input power for the HHF2 in horizontal positions (between 0.1" to 0.3" adverse elevation) is shown in Fig. 17.

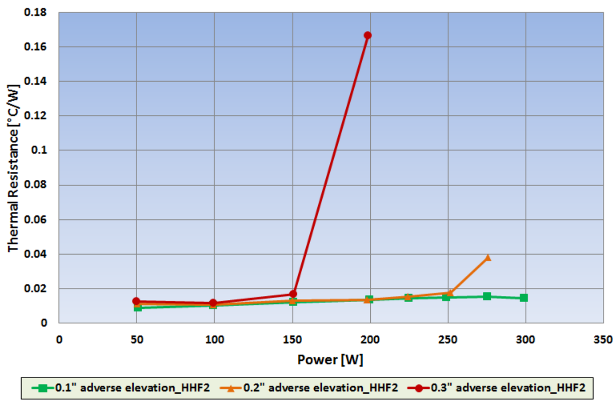


Fig. 17. Thermal resistance as a function of input power for HHF2 in horizontal positions (0.1, 0.2, and 0.3 inch adverse elevation).

4. CONCLUSIONS

This paper highlights the advancements in developing novel heat pipes for aerospace thermal control applications.

ACT, Inc. in collaboration with NASA Marshall space flight center and NASA Johnson Space Center worked together to test and validate HiK™ plates with embedded copper-water heat pipes in the ISS. The flight test verified the operation of the HiK™ plates and the copper-water heat pipes in micro-gravity environment. In the ISS test, the heat pipes were embedded in a HiK™ aluminum base plate and subject to a variety of thermal tests over a temperature range of -10 to 38 ºC for 10 days period. Results showed excellent agreement with both predictions and ground testing results. The HiK™ plate underwent 15 freeze-thaw cycles between -30 and 70 ºC during ground testing, and an additional 14 freeze-thaw cycles during the ISS test.

A new generation of high-heat-flux CCHPs based on hybrid wick technology was developed and validated. The 5-10 W/cm^2 heat density limitation of traditional grooved heat pipes has been a fundamental limitation in the current design for space applications. Two high-heat-flux hybrid CCHPs (HHF1 and HHF2) 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 confirmed by Lockheed Martin company. The second straight 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 exhibit an improvement in heat flux capability of more than 3X over the standard aluminum-ammonia CCHP design. The results show that the heat pipe performs efficiently, consistently and reliably and can adapt to several high-heat-flux applications.

These products offer full system thermal solutions; spot cooling of electronic devices with the space-qualified copper-water heat pipes, effective heat spreading of electronic boards and enclosures with the space qualified HiK™ plates, and efficient heat transport outside the electronics control box to dissipate the heat with CCHPs or hybrid CCHPs based on the required heat flux.

ACKNOWLEDGEMENT

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NOMENCLATURE

ACT	=	Advanced Cooling Technologies, Inc.
APTx	=	Advanced Passive Thermal experiment
CCHPs	=	Constant Conductance Heat Pipes
ISS	=	International Space Station
LHPs	=	Loop Heat Pipes
NASA	=	the National Aeronautics and Space Administration
VCHPs	=	Variable Conductance Heat Pipes

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