Development of High Heat Flux Titanium-Water CCHPs

Andrew Lutz[1], Calin Tarau[2], Bill Anderson[3]
Advanced Cooling Technologies, Inc., Lancaster, PA, 17601

CCHPs are the current method used for cooling almost all spacecraft, including NASA, DoD, and commercial satellites. The maximum heat flux for current aluminum-ammonia CCHPs is roughly 10-15 W/cm^2. This limit will affect more and more spacecraft electronics systems as electronics continue to increase in power and decrease in size. Traditionally, CCHPs have achieved limited heat flux due to dry-out at the critical heat flux in the evaporator. During previous development, Advanced Cooling Technologies, Inc. (ACT) identified a hybrid wick configuration that allows an increased critical heat flux, and therefore increased maximum heat flux of the aluminum-ammonia CCHP. Under a NASA Phase IIX SBIR program, ACT demonstrated a hybrid wick (with grooves), high heat flux, titanium-water heat pipe capable of maintaining less than 10 K temperature difference from condenser to evaporator at heat flux values up to 90 W/cm^2. Aluminum and ammonia were replaced by titanium and water because of a potential testing opportunity inside the ISS. The experiment was performed with the heat pipe evaporator elevated above the condenser to simulate reduced heat pipe performance relative to zero gravity performance. The experimental performance of the hybrid wick heat pipe was compared to the performance of an otherwise identical baseline titanium-water heat pipe without the hybrid wick to enable high heat flux. The baseline heat pipe exceeded 10 K temperature difference at a heat flux less than 40 W/cm^2.

Nomenclature

ACT	=	Advanced Cooling Technologies, Inc.
CCHPs	=	constant conductance heat pipes
ΔT	=	temperature difference between evaporator and condenser
EDM	=	electromagnetic discharge machining

[1] R&D Engineer, R&D, 1046 New Holland Ave.
[2] Principal Engineer, R&D, 1046 New Holland Ave.
[3] Chief Engineer, R&D, 1046 New Holland Ave.

I. Introduction

Constant conductance heat pipes (CCHPs) are used for heat transport on almost all spacecraft, including NASA, United States Department of Defense, and commercial satellites. The maximum heat flux for current aluminum-ammonia CCHPs is about 10-15 W/cm^2 [1]. When heat flux greater than 10-15 W/cm^2 is applied to a conventional CCHP evaporator dry-out occurs because the critical heat flux is surpassed. In these conventional CCHPs a grooved wick is used to provide liquid flow from the condenser to the evaporator, but previous grooved wick designs are incapable of supplying enough liquid flow to the evaporator to avoid dry-out at heat flux values greater than 15 W/cm^2. Future spacecraft and instruments developed for space missions will involve highly integrated electronics with increasing power density and heat dissipation requirements. For example, the current incident heat flux for laser diode applications is 5-10 W/cm^2, but this value is expected to increase to 50 W/cm^2. Advanced Cooling Technologies, Inc. (ACT), has been developing hybrid wick CCHPs that incorporate novel combinations of grooved wick and porous wick to achieve heat flux up to 90 W/cm^2. In previous work, ACT fabricated and tested aluminum-ammonia CCHPs capable of heat flux up to 50 W/cm^2 [2].

CCHPs are two-phase heat transfer devices which utilize vaporization and condensation of a working fluid to transport heat. 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 transfers heat to the walls. 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. Grooved wicks are typically used in spacecraft CCHPs and VCHPs. 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 due to low capillary pressure.

This paper will discuss ACT's current work involving the development of hybrid wick titanium-water CCHPs which are capable of at least 90 W/cm^2 heat flux into a flanged evaporator. In a flanged heat pipe, heat is applied to a flat surface of the flange and conducts through the flange and heat pipe material into the heat pipe working fluid. Since the flange width is greater than the heat pipe width, as shown in Figure 1, the heat flux into the heat pipe can be high when greater magnitudes of heat need to be transported by the heat pipe. When the heat flux into the liquid working fluid, which fills the heat pipe grooves, increases beyond the critical heat flux for a grooved configuration, the vapor generated by boiling fluid prevents effective liquid return to the evaporator and the thermal resistance of the heat pipe increases dramatically. By integrating a porous wick in the evaporator of a CCHP, ACT has developed hybrid wick high-heat-flux CCHPs which increase the critical heat flux of the CCHP by enhancing liquid return to the heated area. In the worked described here, one hybrid wick high-heat-flux titanium-water CCHP was fabricated and tested, and one conventional titanium-water CCHP was fabricated and tested to serve as a control sample for performance comparisons.

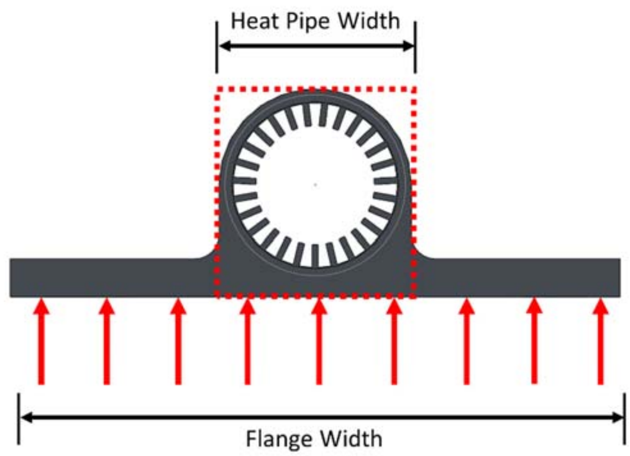

Figure 1. Diagram of Flanged Heat Pipe

II. Description of the Prototypes

In this work, ACT fabricated one hybrid wick high-heat-flux titanium-water heat pipe and one conventional heat pipe to serve as a control sample. The two heat pipes were identical except for the hybrid wick architecture in the high-heat-flux CCHP. Figure 2 shows a rendering of the groove geometry and grooved section of the titanium-water CCHP prototypes fabricated for this experiment. The grooved section was produced by electromagnetic discharge machining (EDM) the grooves in a 0.625-inch outer diameter titanium rod. The two heat pipes are composed of a grooved section for the condenser and adiabatic section. In the conventional CCHP prototype the grooved wick continues through the length of the evaporator. In the hybrid wick CCHP the evaporator section includes a hybrid wick combination of grooves and porous material.

Figure 2. Rendering of the Groove Geometry and Grooved Section of the CCHP Prototypes

The heat flux limit in axial grooved heat pipe evaporators is typically 10-15 W/cm^2. In order to increase the heat flux limit, the concept as shown in Figure 3 is to develop heat pipes with a hybrid wick that contains screen mesh or sintered powder evaporator wicks in 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. Standard flanged CCHPs are manufactured from aluminum extrusions where the entire length of extrusion is flanged, but the flange is cut away in all locations where heat will not be applied so that weight is reduced. As with any conventional flanged CCHP, this hybrid wick technology can be implemented at the locations of evaporator flanges.

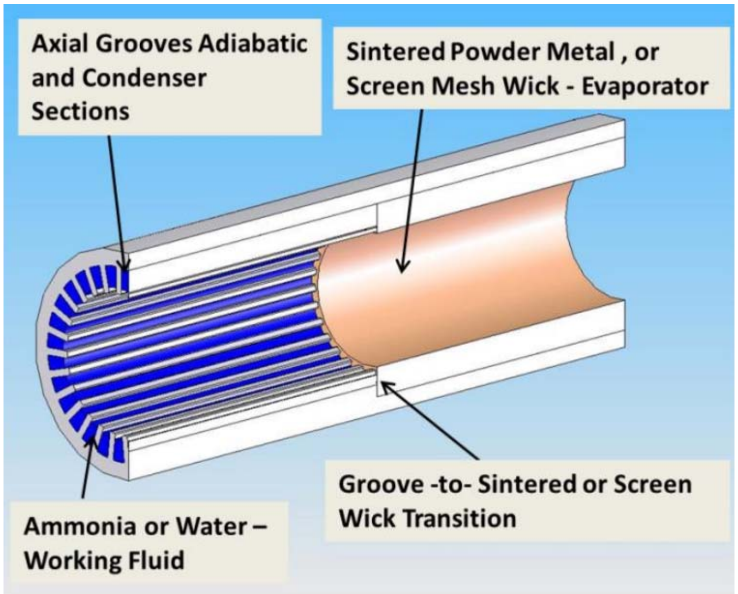

Figure 3. Hybrid Wick CCHPs: Axial Grooved Adiabatic and Condenser Sections with Screen Mesh or Sintered Powder in the Evaporator Section

The two CCHPs were fabricated with a copper flange where heat was supplied to the flat surface of the flange. The copper flange is bonded to the titanium heat pipe by a mechanically activated solder. Figure 4 shows a picture of the high-heat-flux CCHP. The overall length of the heat pipe was 12 inches, and the flange was offset from the end of the heat pipe. The ends of the CCHPs were welded using standard CCHP manufacturing practices and a fill tube and valve were left on the heat pipes to adjust charge if needed.

Figure 4. Picture of the High-Heat-Flux Titanium-Water CCHP

III. Description of the Experiment

The high-heat-flux CCHP and conventional CCHP control sample were tested under identical conditions to develop a comparison of the heat transfer capability of the two heat pipes relative to each other. Heat was applied to the flat surface of the evaporator flange via an aluminum heater block, with cartridge heaters installed, which was bolted to the flange. The footprint area on the flange where heat was applied was 6.45 cm^2. A liquid-nitrogen-cooled aluminum block was clamped onto the condenser section of each CCHP to provide the heat sink. All experiments were conducted while holding the CCHP temperature at 80 °C as measured by a thermocouple on the wall of the adiabatic section. Liquid nitrogen flow rate was controlled to maintain a constant CCHP temperature. Figure 5 shows a diagram of the experimental setup with temperature control of the adiabatic section to hold a surface mounted thermocouple temperature at 80 °C by adjusting liquid nitrogen flow rate through the condenser block. The testing was conducted with the heat pipes in two oreientations: one oreientation where heat was applied to the downward facing flange (bottom heating), and the other where heat was applied to the flange while facing upward (top heating). The entire test apparatus was insulated to minimize heat leak between the apparatus and the ambient environment. A ceramic fiber insulation was wrapped around the entire heat pipe, heater block, and condenser block. For each test case, heat was applied to the evaporator flange and the system was allowed to equilibrate to steady state before changing the heater power to collect data for a subsequent test case.

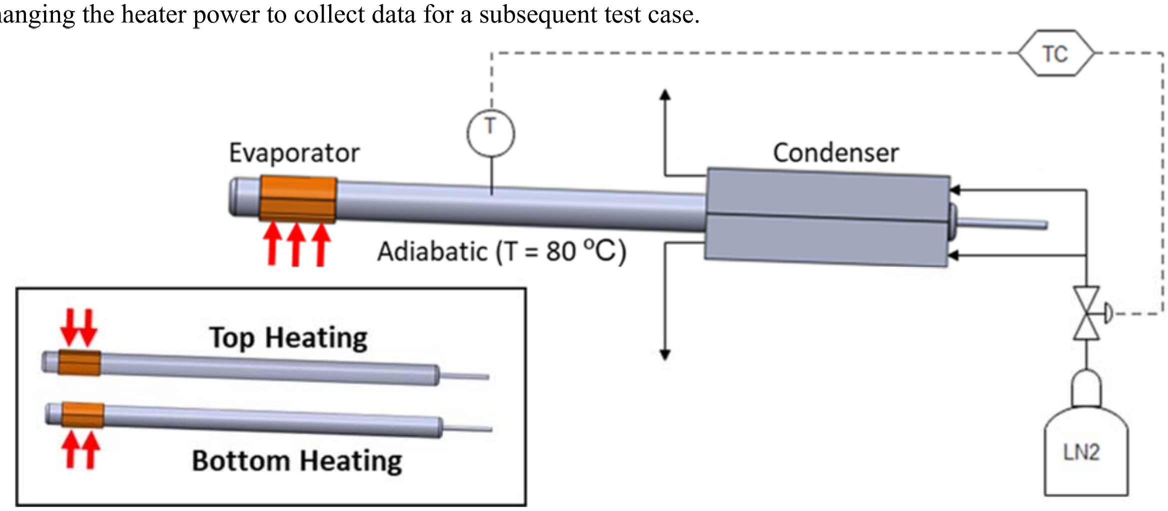

Figure 5. Diagram of Experimental Setup Showing the Two Orientations of Heat Application Tested

Before thorough testing of the hybrid wick high-heat-flux CCHP, the conventional CCHP was tested and characterized at varying elevations against gravity and varying working fluid charge amounts. This characterization was conducted by applying heat to the evaporator flange while the conventional CCHP was at a fixed elevation. After reaching a steady state condition at each power level the heater power was increased in a stepwise manner until dry-out was observed, as indicated by drastically increased temperature difference between the evaporator and condenser. Figure 6 shows the heater power during the testing of the conventional CCHP at 0.25 inches against gravity with 6.0 mL water charge.

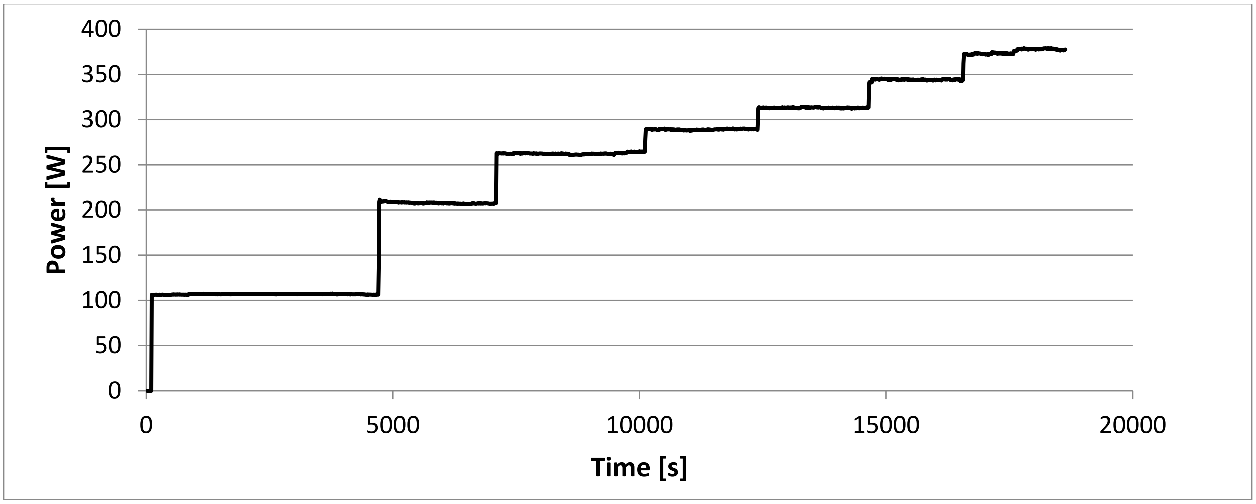

Figure 6. Heater Power during Conventional Heat Pipe Characterization at 0.25 inches Against Gravity with 6.0 mL Charge

Figure 7 shows an example of the raw data collected during the baseline testing of the conventional CCHP at 0.25 inches against gravity with 6.0 mL charge. The temperature difference between the evaporator and condenser (ΔT) is a measurement of the heat pipe temperature difference on the walls of the evaporator and condenser. For the conventional heat pipe, the ΔT surpassed 5 K at a heat flux greater than 32.5 W/cm^2 (~200 W). Thermocouples were used to measure heat pipe wall temperatures along the length of the heat pipes, heater temperature, heater block temperature, flange temperature, and a reference to the ambient room temperature. As the heat applied to the CCHP increases, the ΔT increases, and the temporal variability of the ΔT increases, indicating partial or total dry-out.

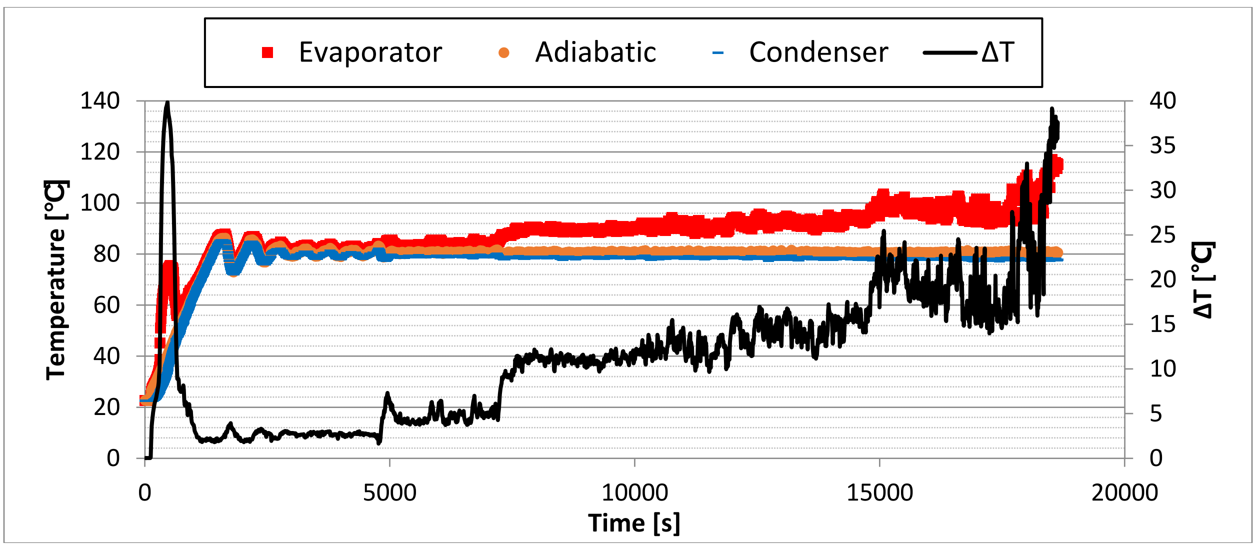

Figure 7. Raw Data Collected during Conventional Heat Pipe Testing at 0.25 inches Against Gravity with 6.0 mL Charge

For each heater power level tested and allowed to reach steady state, an average value of each temperature measurement was determined for the final 5-10 min. time period of the steady state condition. Figure 8 shows data characterizing the performance of the conventional heat pipe with various working fluid charge amounts and various adverse elevations. The standard deviation of temperature measurements during the steady state time period used to determine average temperature values was calculated and is reported in the form of error bars. At an overcharged condition (7.8 mL) the heat pipe performance is unrealistic because a puddle is formed which reduces the required capillary rise height between the puddle liquid-vapor interface and the evaporator. At a reduced charge value (6.0 mL) where each groove would be mostly filled with liquid but no excess liquid could form a puddle, the heat pipe performance is limited at higher heater power levels. The conventional heat pipe performance was measured at varying elevations against gravity to verify that the capillary limit of the heat pipe would not be exceeded during testing of either heat pipe. Once the baseline heat pipe was characterized at 0.25 in. against gravity and shown to dry-out due to critical heat flux in the evaporator, this condition was chosen as the testing condition for the hybrid wick high-heat-flux CCHP.

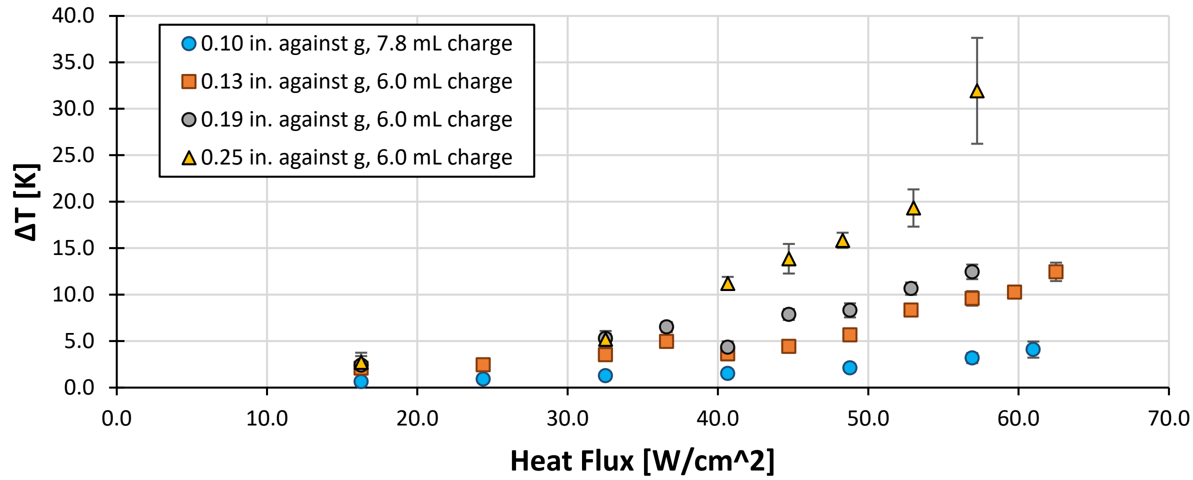

Figure 8. Data Characterizing the Performance of the Conventional CCHP

IV. Experimental Results

The hybrid wick high-heat-flux titanium-water CCHP was tested at 0.25 inches against gravity in an identical manner to the testing of the conventional grooved titanium-water CCHP. Figure 9 shows the heater power during the hybrid wick CCHP testing. The improved performance of the hybrid wick heat pipe relative to the conventional heat pipe allows much greater heat loads without increasing the temperature of the heated components. During these experiments heat loads up to 575 W were applied to the 6.45 cm^2 heated footprint on the evaporator flange without the ΔT exceeding 10 K.

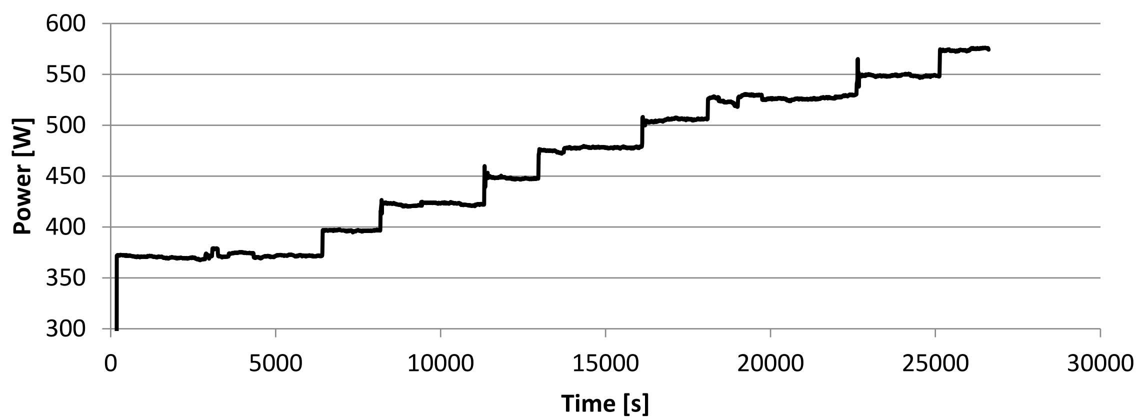

Figure 9. Heater Power during Hybrid Wick High-Heat-Flux CCHP Testing at 0.25 Inches Against Gravity

Figure 10 shows raw data measuring temperatures during the testing of the hybrid wick high-heat-flux heat pipe with heater power corresponding to Figure 9**Error! Reference source not found.**. The ΔT does not surpass 10 K up to the available power limit of the test apparatus (575 W, 89.4 W/cm^2). Additionally, the temporal variability of temperature values is greatly reduced relative to the conventional CCHP.

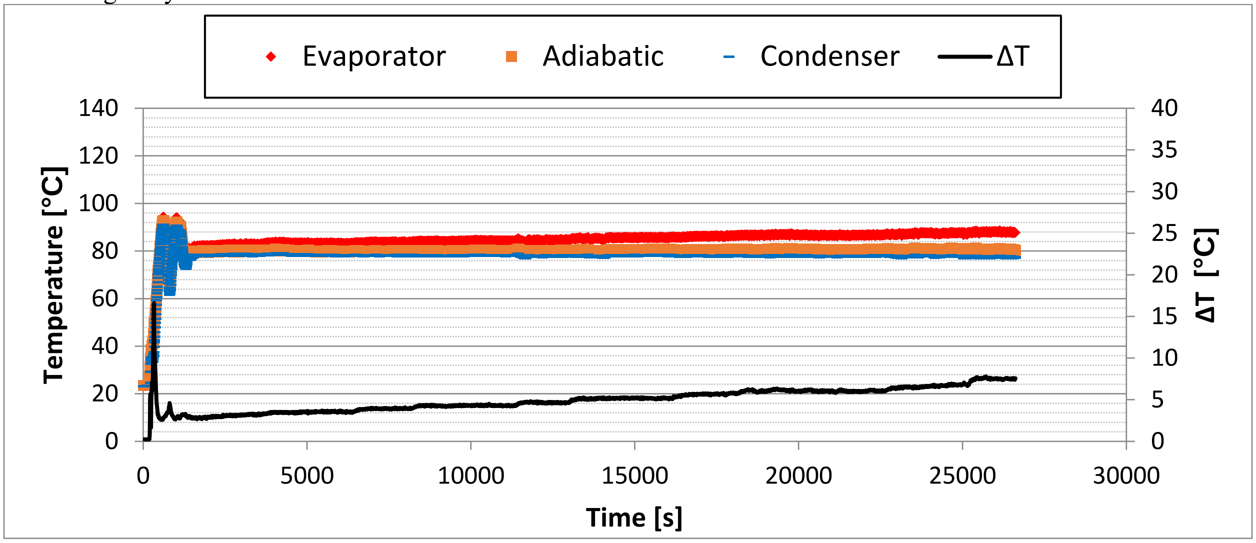

Figure 10. Raw Data Collected during Hybrid Wick High-Heat-Flux Heat Pipe Testing at 0.25 inches Against Gravity

During the first set of tests conducted with both CCHPs, heat was applied to the flange in an orientation where the flange was facing downward, so heat was applied to the bottom of the heat pipe. A second set of tests was conducted where the heat pipes were rotated about their axes 180° such that heat was applied to the top of the heat pipes. This set of tests yielded similar results to the first set of tests, so there is no indication that the performance of either heat pipe is affected by this change.

Figure 11 shows the performance of the hybrid wick high-heat-flux titanium-water CCHP and the conventional titanium-water CCHP. The hybrid heat pipe can maintain a ΔT less than 10 K between the evaporator and condenser up to 89.4 W/cm^2 whereas the ΔT of the baseline heat pipe would exceed 10 K at less than 40 W/cm^2. The testing was performed by applying heat to the flange on the heat pipe evaporator in two orientations: top heating and bottom heating. This testing was performed in order to verify that the hybrid wick allowed liquid to bridge across the heat pipe height at a worst-case and best-case scenario with respect to gravity. For both orientations, the hybrid wick allowed the heat pipes to maintain a low ΔT at high heat flux.

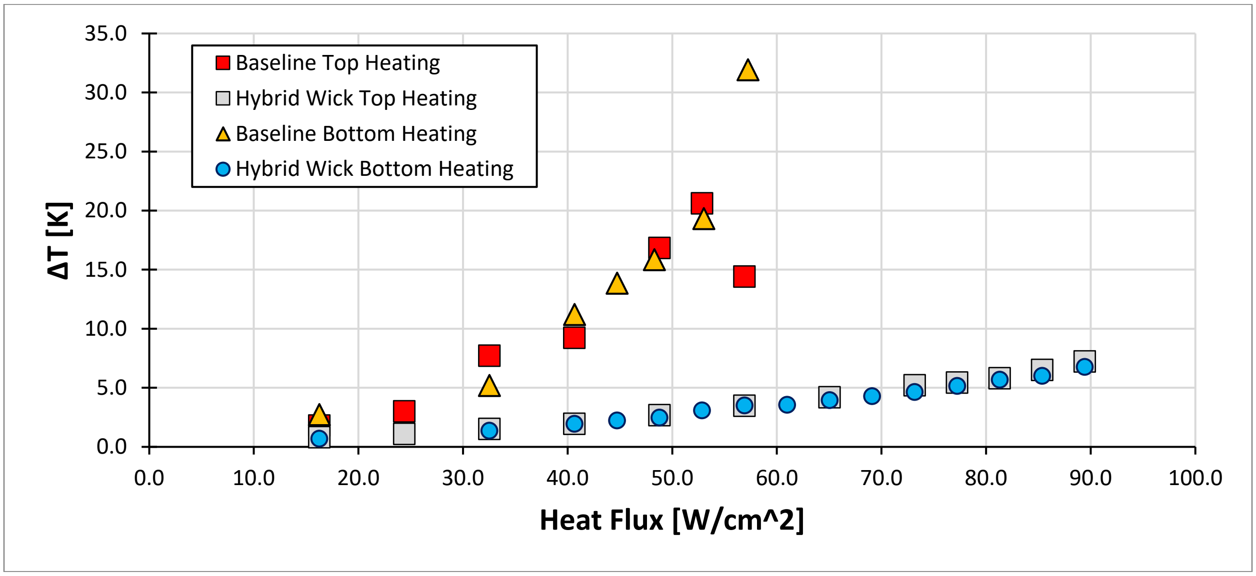

Figure 11. Hybrid Wick High-Heat-Flux CCHP and Conventional CCHP Performance

V. Conclusion

CCHPs, which are a standard thermal management tool for spacecraft heat transport applications have traditionally been limited to heat flux values in the 10-15 W/cm^2 range. This limitation is caused by the groove geometry that allows high permeability heat pipe wicks for spacecraft, but ACT has developed hybrid wick CCHPs that extend the critical heat flux limit in the evaporator by integrating porous wick architectures with the grooves in the evaporator. ACT fabricated one hybrid wick high-heat-flux titanium-water CCHP and one conventional titanium-water CCHP. The two heat pipes were tested under identical conditions and compared based on performance. The conventional CCHP ΔT exceeded 5 K at a heat flux less than 30 W/cm^2 and exceeded 10 K at a heat flux of about 40 W/cm^2. The hybrid wick high-heat-flux CCHP was able to achieve a heat flux greater than 70 W/cm^2 before exceeding 5 K and was demonstrated to achieve 89 W/cm^2 without exceeding a 10 K ΔT.

Acknowledgments

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References

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