Non-Integrated Hot-Reservoir Variable Conductance Heat Pipes

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In this paper, Advanced Cooling Technologies, Inc. (ACT) will discuss the design and testing of two unique non-integrated hot-reservoir VCHPs. The first VCHP is flight hardware designed to fly onboard Astrobotic Technology's lunar lander Peregrine I as a technology demonstration unit. The Astrobotic VCHP is designed to operate during transit and on the lunar surface and utilizes a hybrid wick design. The evaporator wick was 3D printed while the adiabatic and condenser sections utilized grooved wicks with high permeability, ideal for operation in a microgravity environment. The second VCHP was designed for NASA's lunar rover VIPER. A unique feature of the VIPER VCHP was the flexible adiabatic section. In order to accommodate relative motion between the heat spreader panel and the radiator panel, due to launch induced vibrations, nested flexible lines for the VCHP envelope and internal non-condensable gas tube were used in the adiabatic section. Both VCHPs utilized a non-integrated hot reservoir of non-condensable gas. The non-integrated reservoirs provided high thermal turn-down ratios and the ability to independently heat the reservoir in order to purge working fluid to increase the reliability of the device.

Nomenclature

ACT	=	Advanced Cooling Technologies
NCG	=	Non-Condensable Gas
TC	=	Thermocouple
TDU	=	Technology Demonstration Unit
VCHP	=	Variable Conductance Heat Pipe

I. Introduction

AS NASA prepares to further expand human and robotic presence in space, it is well known that spacecraft architectures will be impacted by unprecedented power requirements and extreme thermal environments. Thermal management systems need to reject large heat loads into hot environments and have high heat rejection turn-down ratios in order to minimize vehicle power needs during periods of darkness, such as the 14-day lunar night. Variable conductance heat pipes (VCHP) are capable of passively transporting large quantities of heat and provide high thermal turn-down ratios ideal for surviving extreme cold environments.

This paper discusses the design and testing of two non-integrated hot-reservoir VCHPs with hybrid wicks recently developed by ACT for Lunar surface applications. The first VCHP was designed and fabricated as a Technology Demonstration Unit (TDU) for NASA's VIPER thermal management system. The second VCHP is a TDU that will fly onboard Peregrine I, a lunar lander developed by Astrobotic Technology set to launch in 2022.

The non-integrated hot-reservoir and the hybrid wick designs are ideal for lunar and planetary surface applications and provide the following advantages:

- The hot-reservoir provides superior passive thermal control compared to a cold-reservoir VCHP.[1]
- The non-integrated reservoir improves control over the distribution of working fluid and non-condensable gas (NCG) during periods of non-operation.

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- The hybrid wick allows the VCHP to operate effectively in both microgravity (transit) and on the surface in a gravity aided orientation.[2]

This paper begins with a background discussion of hot-reservoir VCHPs and hybrid wicks. Then the design and experimental testing of the two VCHPs is discussed.

II. Background

A. Variable Conductance Heat Pipes

A VCHP is similar to a conventional heat pipe but has a reservoir containing a controlled amount of non-condensable gas (NCG). The VCHP works by passively varying the amount of condenser available to the working fluid, see Figure 1, in response to changes in vapor pressure which is a function of vapor temperature. A decrease in either sink temperature or power input will cause the vapor temperature and pressure to decrease. This allows the NCG to expand and block a portion of the condenser. The passive increase in thermal resistance limits the decrease in vapor and heat source temperature.

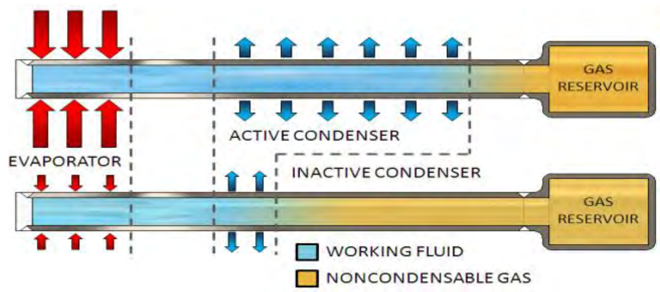

Figure 1. Operation of a cold-reservoir VCHP.

Figure 1 illustrates a cold-reservoir VCHP where the temperature of the NCG reservoir follows the sink temperature. As the sink temperature decreases, the NCG temperature within the reservoir will also decrease, limiting the ability of the NCG to expand and block the condenser. During applications in extreme cold environments, such as the long lunar night (100K), the NCG must expand to fully block the condenser and adiabatic section in order to minimize heat leaks from the evaporator to the condenser. For a cold-reservoir VCHP, this typically requires electrically heating the reservoir with 1-2W for the entire 14-day long lunar night.[3]

A hot-reservoir VCHP, illustrated in Figure 2, utilizes an NCG reservoir close to the evaporator which follows the heat source temperature. An internal tube passes through the heat pipe envelope to connect the NCG reservoir to the condenser. The hot-reservoir VCHP operates in the same manner as the cold-reservoir VCHP; a decrease in vapor temperature allows NCG to expand and block the condenser, but the elevated temperature of the reservoir results in superior passive temperature control and eliminates the need for electrical reservoir heating during survival mode.[1,4,5] The performance of both a cold and hot-reservoir VCHP can be analytically modeled using the flat-front theory described by Marcus.[4] This model assumes a flat, infinitely thin boundary separating working fluid vapor and NCG.

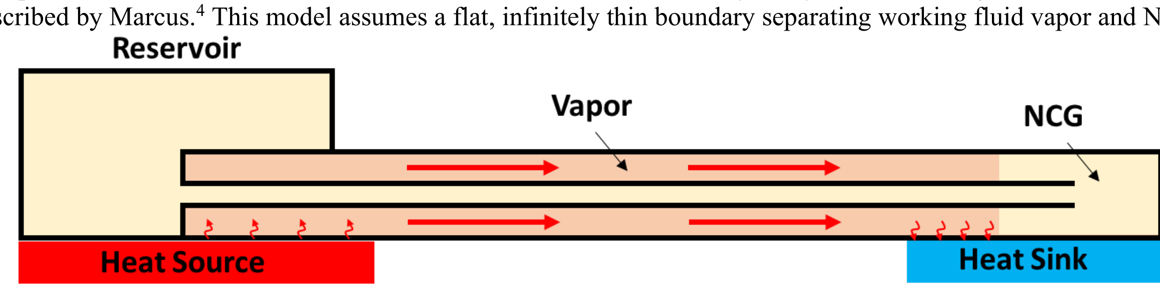

Figure 2. Hot-reservoir VCHP. NCG reservoir is closely integrated with the evaporator and follows the heat source temperature.

While hot-reservoir VCHPs offer superior passive thermal control compared to cold-reservoir VCHPs, over time their performance can be degraded due to the migration of working fluid into the reservoir.[6] The partial pressure of superheated vapor into the hot reservoir displaces NCG from the reservoir resulting in a higher nominal operating temperature for the heat pipe. This challenge was experimentally observed by ACT during microgravity testing of a hot-reservoir VCHP onboard the International Space Station, indicating the need for advanced fluid control.[6] In the illustration of Figure 2, representative of the VCHP tested onboard the International Space Station, the NCG reservoir was closely integrated with the evaporator. If the reservoir is not integrated with the evaporator (separated from the evaporator), then during periods of non-operation an independent heater can be applied to the reservoir in order to purge the working fluid from the reservoir and restore normal operation. This is critical to ensure long-term reliability of the hot-reservoir VCHP. The reservoir purge process is experimentally demonstrated in Section IV.

B. Hybrid Wicks

Grooved wicks are commonly used in spacecraft heat pipes due to their very high permeability which allows heat transfer over long distances in microgravity. On the lunar or planetary surface, it is generally desirable for the heat pipe to operate in a gravity aided orientation to maximize its power carrying capability. In a gravity aided orientation, grooved wicks have a tendency to exhibit large temperature spikes during startup due to the working fluid pooling at the bottom of the evaporator.[2]

The hybrid wick concept, illustrated in Figure 3, utilizes a hybrid wick that contains screen mesh, metal foam or sintered powder wicks for the evaporator and axial grooves in the adiabatic and condenser sections. The porous wick in the evaporator eliminates the temperature spikes observed in grooved wicks during startup in a gravity aided mode by distributing the working fluid throughout the evaporator via capillary action.[2] In addition, the hybrid evaporator wick is capable of sustaining much higher heat fluxes than the grooved wick.[7] The grooved wick in the adiabatic and condenser sections allow for large heat transfer over long distances due to the high wick permeability and associated low liquid pressure drop.

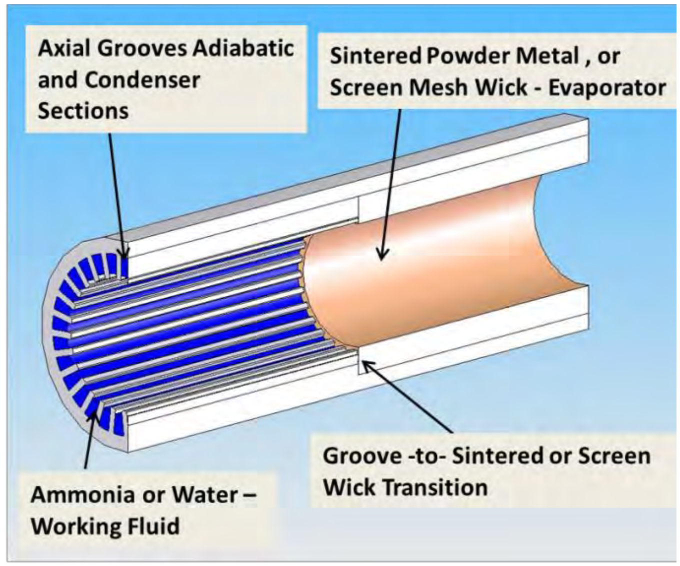

Figure 3. Hybrid wick for planetary surface and high heat flux applications.[2]

III. NASA VIPER VCHP

C. VIPER VCHP Design

NASA's rover, VIPER is designed to investigate and map volatiles in the lunar south pole region. During its 100-day mission, VIPER must operate and survive in the extreme thermal environment of the lunar surface with temperatures ranging from 400K during lunar day to 100K during the lunar night. The general thermal management system of VIPER consists of a warm electronics box made up of heat pipe heat spreaders. The heat spreaders collect heat from the electronics and direct it towards a thermal transport system which then carries the heat to the radiator panels on top of the rover. As part of a Phase II-X SBIR program, ACT worked closely with NASA Johnson Space Center to design and fabricate a TDU for VIPER's thermal management system. One potential option for the heat transport system carrying the thermal energy to the radiator was a non-integrated hot-reservoir VCHP with hybrid wick operating in thermosyphon (gravity-aided) mode.

Figure 4 shows the CAD model of the VIPER hot-reservoir VCHP. Numbered boxes refer to locations of thermocouples (TC) used during experimentation. The VCHP was required to carry 147W in thermosyphon mode with the evaporator below the condenser using ammonia as the working fluid. The VCHP was not intended for operation in a microgravity environment and therefore only contained wick in the evaporator. The purpose of this wick was to distribute working fluid throughout the evaporator during startup in order to avoid temperature spikes that may result from the working fluid pooling at the bottom of the evaporator when the pipe is not operating.[2] The lengths of the evaporator, adiabatic and condenser sections were 25.4 cm, 81.3 cm and 33.0 cm, respectively. The evaporator, condenser and reservoir were fabricated from aluminum. Argon was used for the NCG. The reservoir size and NCG amount were selected based on VCHP modeling using the flat-front theory described by Marcus.[4]

A unique feature of this VCHP was the flexible adiabatic section. In anticipation of significant vibrations between the heat spreaders and radiator panels during launch it was required that the adiabatic section of the VCHP be flexible in order to accommodate a maximum deflection of 25mm in any direction. This was accomplished with the use of nested flexible lines throughout the adiabatic section for both the outer envelope and the inner NCG tube. This is shown in Figure 4. The flexible lines in the adiabatic section were made from stainless steel. The stainless-steel section was joined to the aluminum evaporator and condenser via bimetallic junctions. The use of a stainless-steel adiabatic section improves the thermal turndown ratio of the VCHP. During the cold lunar night, the vapor temperature of the VCHP decreases allowing the NCG to expand and block the condenser and adiabatic section, shutting down two-phase heat transfer. Heat leaks can still occur from the warm-electronics box to the radiator via conduction through the VCHP envelope. The thermal resistance of the VCHP in survival mode is increased with the use of a stainless-steel adiabatic section.

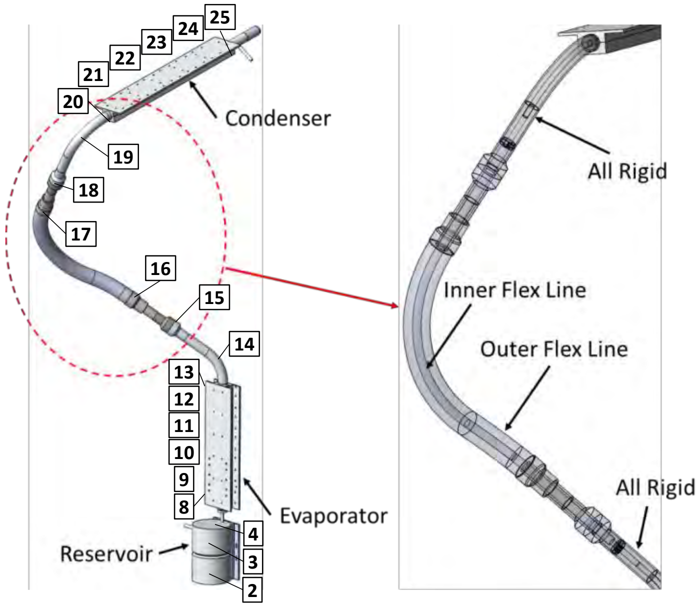

Figure 4. Model of the VCHP designed and fabricated as part of NASA's VIPER Thermal Management System Engineering Demonstration Unit. Locations of numbered TCs are indicated.

A non-integrated hot-reservoir for NCG was located below the evaporator. By using a non-integrated reservoir that was separate from the evaporator it was possible for the reservoir to operate at a higher temperature than the evaporator. The reservoir and evaporator were heated by the same heat source. By strategically placing the reservoir relative to the heat source and evaporator, the reservoir can operate at an elevated temperate. This prevents working fluid from condensing in the reservoir. Any working fluid that migrates into the reservoir will be superheated vapor. In addition, an independent heater can be applied to the reservoir in order to purge working fluid that may migrate to the reservoir. It should be noted that the heater on the reservoir is only required for short periods of time when the VCHP is otherwise not operating. During long periods of non-operation, working fluid may migrate into the reservoir. Prior to startup, the reservoir heater can be used for a short time to purge the working fluid from the reservoir. Reservoir heating is not required while the VCHP is operating.

D. VIPER VCHP Experimental Testing

An image of the VIPER VCHP experimental test setup at ACT is shown in Figure 5. The VCHP was mounted to a garolite plate to thermally isolate it from the support structure. The reservoir and evaporator were mounted to a common aluminum plate equipped with a heater pad. The heater was placed such that the reservoir would operate at a slightly higher temperature than the evaporator.

Figure 6 shows the startup behavior of the VIPER VCHP. The plot shows temperature along the pipe vs. time during startup. Note that groups of lines representing the reservoir, evaporator, adiabatic and condenser are indicated as well as the TC numbers, refer to Figure 4. A clearer understanding of the instantaneous temperature distribution along the pipe will be provided below in Figure 8.

The startup test shown in Figure 6 began at room temperature with 147W applied to the evaporator. The chiller block setpoint was set to 15°C. The startup process showed no sign of temperature spikes typically observed in vertically oriented grooved heat pipes indicating that the hybrid screen wick in the evaporator was successful in mitigating this effect. It took approximately 2000 seconds for the evaporator to reach a near steady state temperature of 30°C. The reservoir took considerably longer, reaching a steady state temperature after about 4000 seconds.

Figure 7 shows the results of a thermal control test for the VIPER VCHP. Sections of the pipe and TC numbers are indicated. A clearer picture of the temperature distribution is provided in Figure 8, discussed below. The thermal control test, Figure 7, began at the steady state nominal condition of max power 147W and chiller block setpoint of 15°C. At this operating condition the vapor temperature was 30°C. Over approximately the next 5000 seconds the setpoint of the chiller block was reduced in increments of 20°C approximately every 20 minutes until reaching -65°C. At chiller block setpoint of -65°C the evaporator temperature was 2.8°C. After letting the VCHP approach a steady state at a setpoint of -65°C, the power applied to the VCHP was decreased. As can be seen in Figure 7 the power was reduced in several increments while maintaining the chiller block set point of -65°C. At an applied power of 1W, the evaporator temperature was steady at -9.8°C. Based on the results in Figure 7 it was possible to estimate the turndown ratio of the VCHP. The overall conductance of the VCHP was estimated using the applied power and the temperature difference between the evaporator flange and chiller block.

At the design operating condition (t=0s in Figure 7) the conductance was estimated to be 9.8 W/°C. At the low temperature/low power survival condition (t=21,000s in Figure 7) the conductance was estimated to be 0.018 W/°C. The turndown ratio was defined as the ratio of these two conductance values. Based on these results the estimated turndown ratio of the VCHP was 544:1.

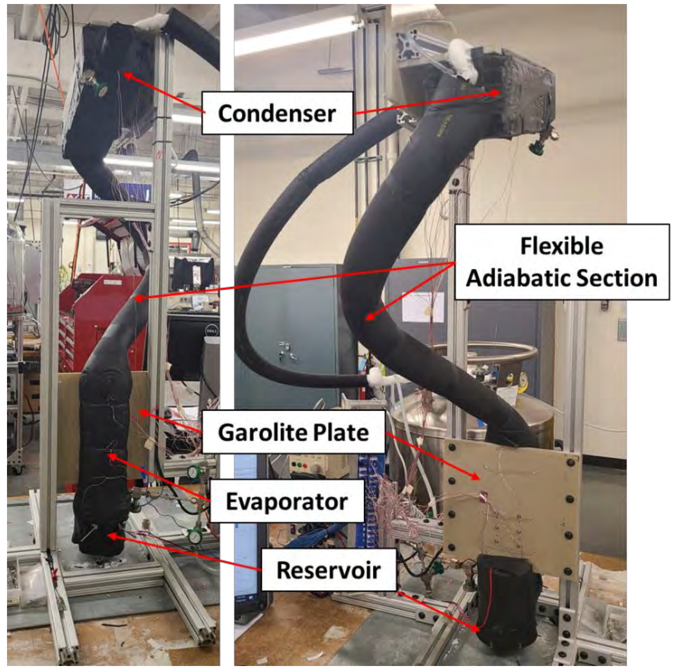

Figure 5. Image of the VIPER VCHP tested at ACT.

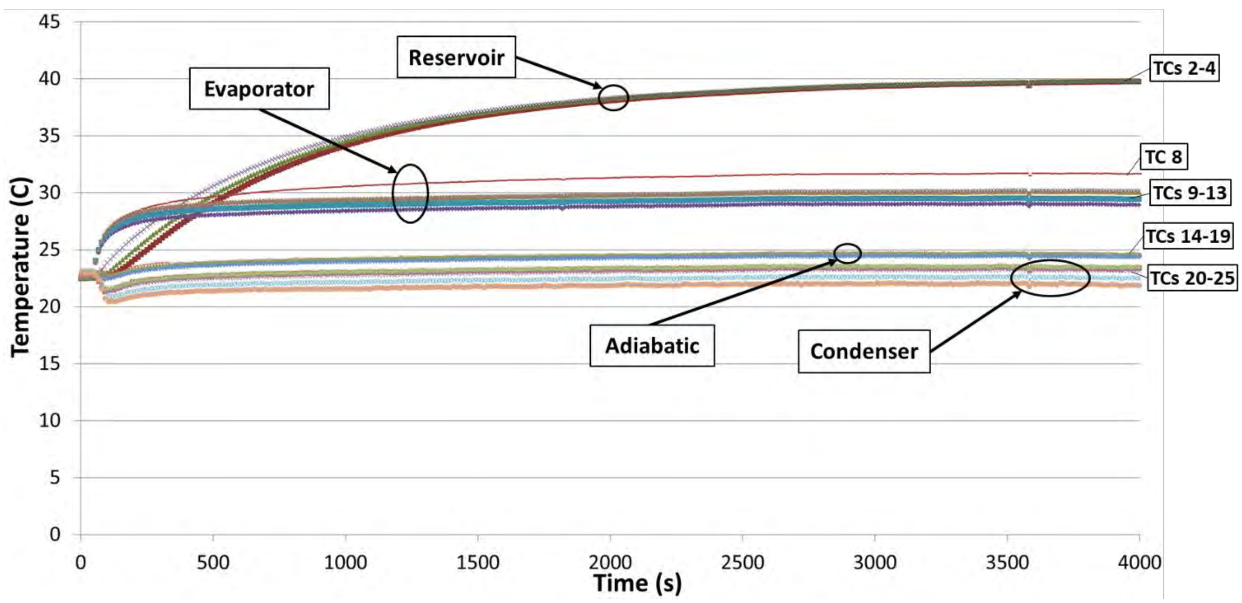

Figure 6. Temperature observed during different stages of the VIPER VCHP startup in a vertical orientation. Startup conditions included Power of 147W. Chiller Block Setpoint at 15°C. Refer to Figure 4 for TC numbers.

Figure 8 compares the instantaneous temperature distributions along the VIPER VCHP at the design operating condition (147W and 15°C) and the low temperature/low power condition (1W and -65°C sink). At the design condition (Figure 8a) it can be seen that the reservoir operated approximately 5°C hotter than the evaporator. The elevated reservoir temperature was due to its placement relative to the heat source. A slight temperature gradient within the condenser was observed beginning approximately around TC22. This gradient was due to NCG within the condenser. At the low temperature/low power condition (Figure 8b) the temperature of the condenser was relatively uniform and a significant temperature gradient was observed between TC17 and TC20. This indicates the NCG front had expanded beyond the condenser into the adiabatic section of the VCHP blocking two-phase heat transfer to the condenser.

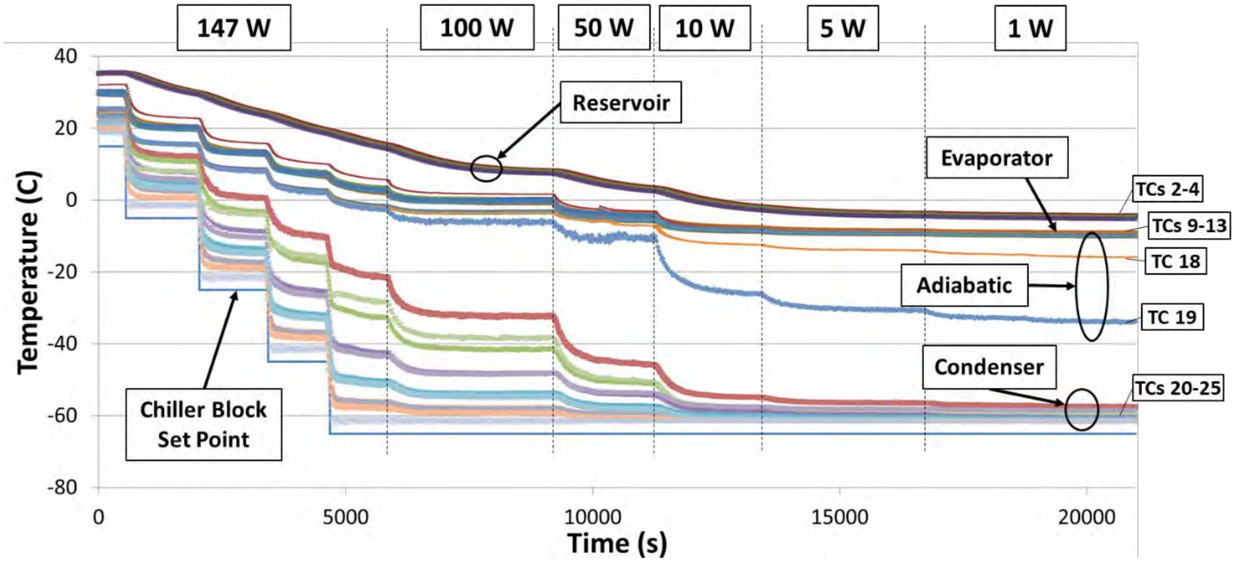

Figure 7. Thermal control test of VIPER VCHP. Minimum chiller block setpoint was -65°C to avoid freezing of the working fluid. The initial phase of the test demonstrates reducing sink temperature at constant power. This was followed by reducing the power with constant sink temperature. Refer to Figure 4 for TC numbers.

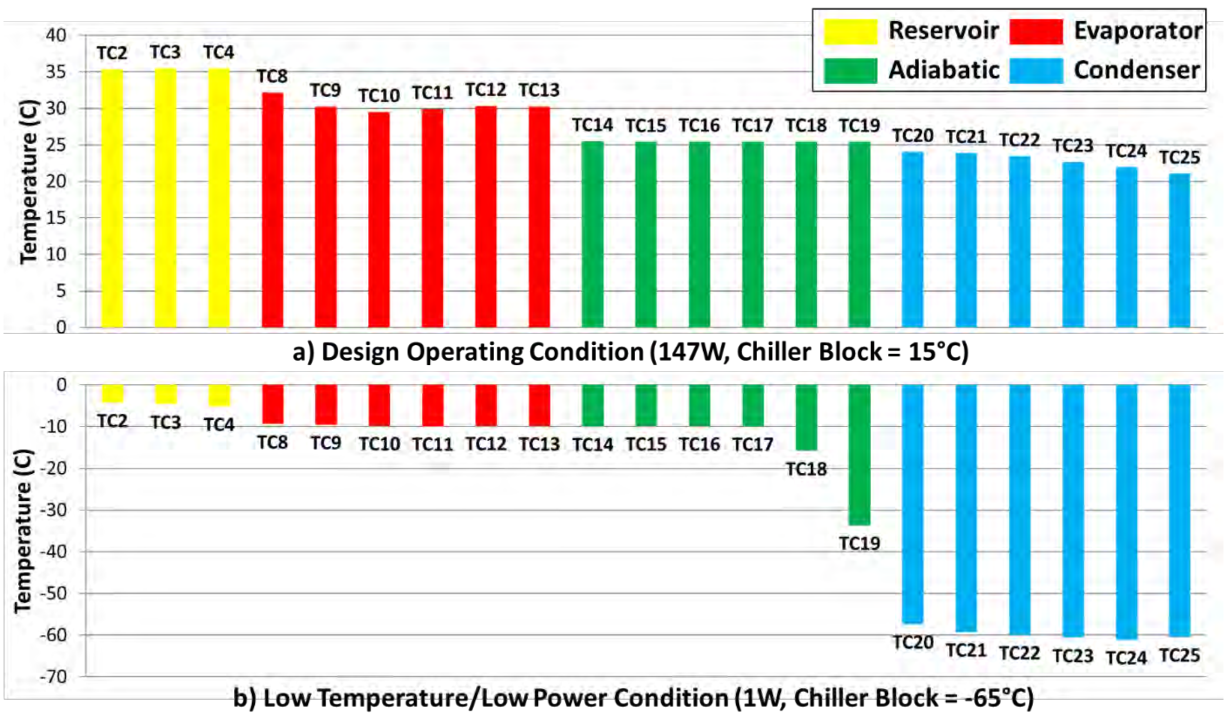

Figure 8. Comparison of instantaneous temperature distribution along the VIPER VCHP during a) the design operating condition and b) the low temperature/low power condition. Refer to Figure 4 for TC numbers.

IV. Astrobotic VCHP

A. Astrobotic VCHP Design

Under a Phase III SBIR program ACT designed, fabricated and tested an aluminum-ammonia non-integrated hot-reservoir VCHP with a hybrid wick as flight hardware for Peregrine I, a lunar lander developed by Astrobotic Technology. The VCHP will operate as a stand-alone technology demonstration unit onboard the lander in microgravity and on the lunar surface in a gravity-aided orientation. The VCHP will be mounted to the enclosure panel alongside electronic components but the heat transported by the VCHP will be supplied by dedicated heaters. The purpose of this TDU is to demonstrate the operation of a non-integrated hot-reservoir VCHP in microgravity and on the lunar surface.

Early in the design process, Astrobotic provided the limitation that the VCHP heaters could require a maximum of 40W. The hybrid wick VCHP was originally intended to utilize a grooved wick in the condenser and adiabatic section and a sintered powder wick in the evaporator. Due to scheduling constraints and the time required to manufacture sinter powdered wicks, ACT elected to design a 3D-printed evaporator that contained a 3D-printed porous wick. Figure 9 shows an image of the aluminum 3D-printed evaporator. The evaporator was printed by Castheon Inc.

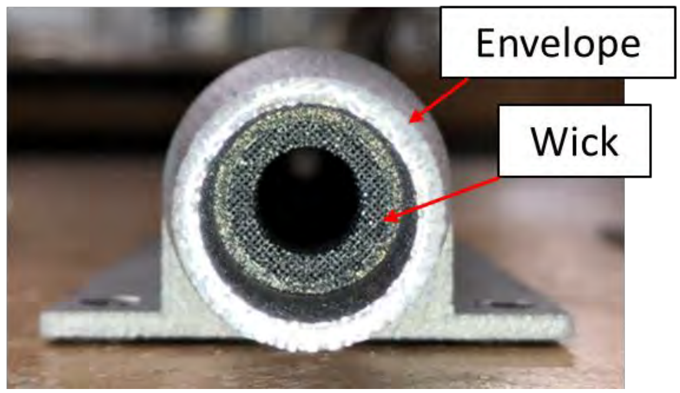

Figure 9. Images of the 3D-printed aluminum evaporator for the Astrobotic VCHP. The porous wick and solid wall were simultaneously printed as one continuous part.

The adiabatic and condenser sections of the Astrobotic VCHP were fabricated from one of ACT's standard aluminum grooved extrusions. Figure 10 shows that the 3D-printed evaporator was designed so that the 3D-printed wick would interface directly with the grooved wick of the adiabatic/condenser section. This hybrid wick design allowed the VCHP to operate effectively in microgravity due to the high permeability of the adiabatic and condenser section. The porous wick in the evaporator effectively distributes the liquid ammonia within the evaporator when the VCHP starts up in a vertical orientation. Without the porous wick, the liquid would pool in the evaporator when the VCHP is not

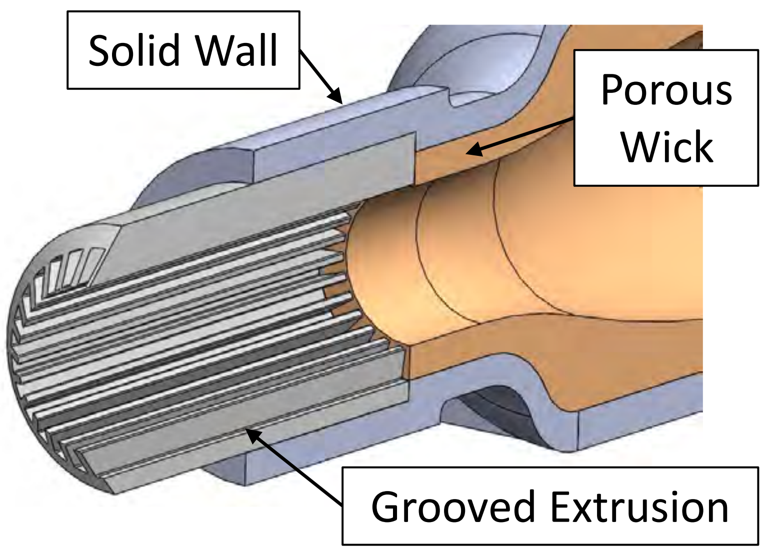

Figure 10. CAD model of aluminum grooved extrusion interfacing with 3D-printed porous wick of the evaporator for the Astrobotic

functioning on the lunar surface. The liquid pool leads to temperature spikes during startup that are alleviated by the porous wick.[2]

Figure 11 shows an image of the completed aluminum-ammonia non-integrated hot-reservoir VCHP with hybrid wick for Astrobotic's Lunar Lander Peregrine I on a test stand at ACT. As mentioned above, the VCHP will fly as a technology demonstration unit onboard the lander and will have a dedicated heater for experimental purposes only. The VCHP will be mounted to the same enclosure panel as the electronic components. As shown in Figure 11, the evaporator and reservoir were mounted to the same aluminum plate that will be offset from the enclosure panel of the lander by legs manufactured from Ultem-1000, a low thermal conductivity material. After the evaporator, the grooved extrusion was bent so that the condenser could be mounted directly to the enclosure panel. The lengths of the evaporator, adiabatic and condenser sections were 10.2 cm, 10.2 cm and 17.8 cm, respectively. The NCG reservoir was sized using the flat front theory described by Marcus.[4] Argon was used as the NCG. The total mass of the VCHP, including the aluminum plate and low thermal conductivity legs was 0.347 kg. The numbered boxes in Figure 11 indicate the locations of TCs for experiments at ACT.

A strip heater was placed on the backside of the aluminum plate shared by the reservoir and evaporator as indicated in Figure 11. Similar to the VIPER VCHP, the heater was placed so that the reservoir operated at a higher temperature than the evaporator. Figure 11 also shows that a separate heater was placed on the reservoir. The purpose of this heater was to demonstrate the ability of the non-integrated hot-reservoir VCHP to purge working fluid from the reservoir via heating. The reservoir heater was only used during the reservoir purging process discussed below. During normal operation, the dedicated reservoir heater was off.

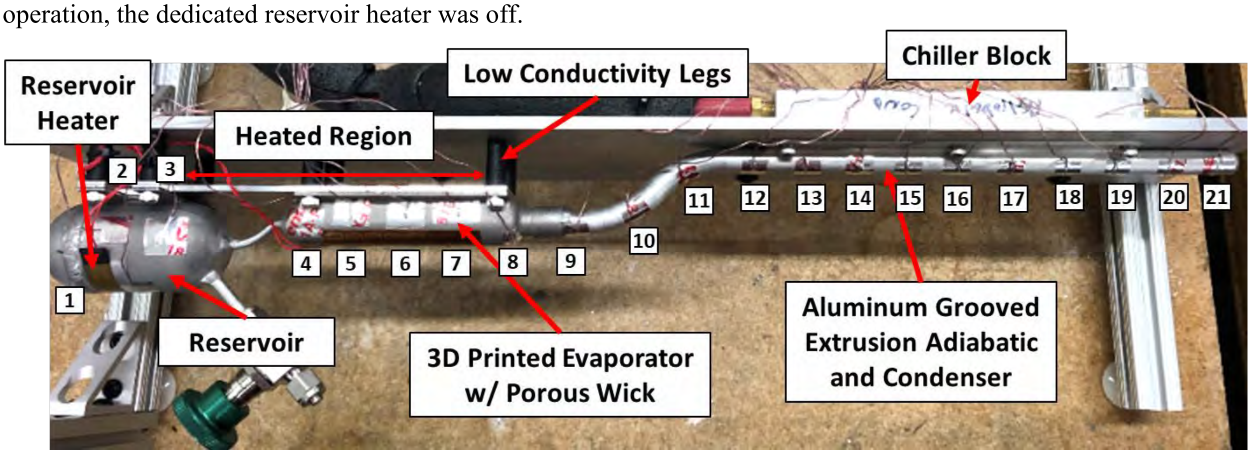

Figure 11. Image of the completed aluminum-ammonia non-integrated hot-reservoir hybrid wick VCHP for Astrobotic's Lunar Lander Peregrine I. Locations of numbered TCs are indicated.

B. Astrobotic VCHP Experimental Testing

Figure 12 shows experimental data of the startup process of the Astrobotic hot-reservoir VCHP in the vertical orientation with 40W applied to the evaporator and a chiller block setpoint of 40°C. A smooth startup was observed indicating that the hybrid wick successfully prevented temperature spikes associated with the working fluid pooling in the evaporator. The steady-state temperatures of the evaporator and reservoir were 53.6°C and 61.8°C, respectively. The hot-reservoir VCHP was intentionally designed to be warmer than the to prevent working fluid from condensing in the reservoir.

Note that the Astrobotic VCHP is intended to operate in both microgravity and on the lunar surface. While the experimental results presented here were acquired in the vertical orientation, the VCHP was also tested with a slight adverse elevation (evaporator above the condenser by 2.54mm). Testing at a slight adverse elevation is standard practice to ensure the heat pipe can operate in microgravity. The intended operating condition of 40W is significantly lower than the predicted maximum power of the heat pipe (~200W based on the capillary limit). As a result, the orientation of the VCHP had negligible effect on performance at the design condition.

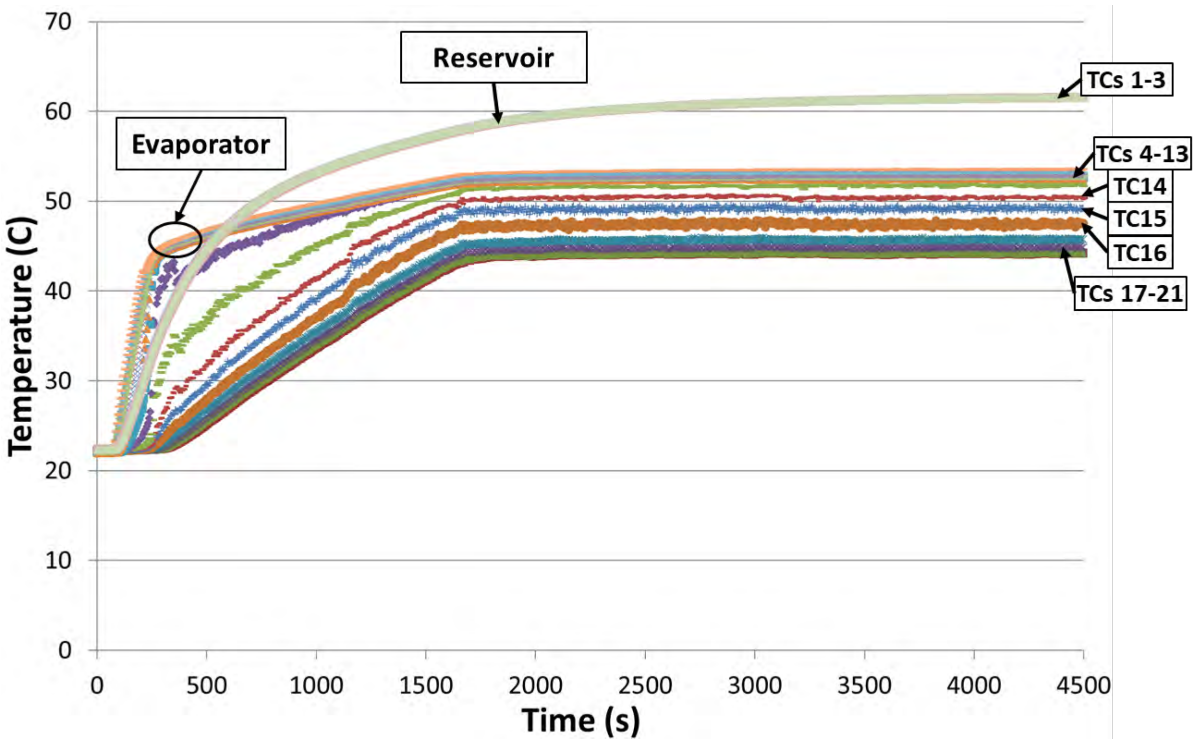

Figure 12. Startup of Astrobotic hot-reservoir hybrid-wick VCHP in the vertical orientation. Power = 40W. Chiller Block Setpoint temperature = 40°C. Refer to Figure 11 for TC numbers.

Figure 13 shows a thermal control test of the Astrobotic hot-reservoir VCHP. The plot begins shortly after a startup period. The power was 40W and the chiller block setpoint was 40°C. The steady-state evaporator (TC 4) temperature was 53.6°C. After achieving the initial steady state, the chiller block setpoint temperature was decreased in 20°C increments. The pipe remained at each new setpoint for short period of time, approximately 15-20 minutes in order to allow the pipe to approach a new steady state condition and then the setpoint of the chiller block was further reduced. This process was carried out until the chiller block setpoint temperature was -100°C. While applying 40W to the VCHP, reducing the setpoint temperature from 40°C to -100°C the evaporator temperature decreased from 53.6°C to 37.3°C, a reduction of only 16.3°C. Between approximately 8,000 and 10,000 seconds the power to the evaporator was reduced to 10W and then after 10,000 seconds the power was further reduced to only 1W. The pipe remained at 1W and a setpoint of -100C until a new steady state was reached resulting in an evaporator temperature of -37.0°C. Many electronics have a survival temperature of approximately -40°C. In the current setup the VCHP requires 1W of survival power with a sink temperature of -100°C.

The overall conductance of the VCHP was estimated using the applied power and the temperature difference between the evaporator flange and chiller block. At the design operating condition (t=0s in Figure 13) the conductance was estimated to be 2.93 W/°C. At the low temperature/low power survival condition (t=14,500s in Figure 13) the conductance was estimated to be 0.0158 W/°C. The turndown ratio was defined as the ratio of these two conductance values. Based on these results the estimated turndown ratio of the VCHP was 185:1.

Figure 14 shows the variation in the Astrobotic VCHP estimated conductance as a function of the chiller block temperature at a constant applied power of 40W. The conductance at the minimum sink and only 1W of applied power is also indicated. As the sink temperature was reduced, the decreasing vapor pressure allowed the NCG front to advance further into the condenser resulting in increased thermal resistance. It should be noted that due to time constraints it was not possible to test the VCHP at high powers so the true maximum conductance of the pipe and therefore the true turndown ratio are not known.

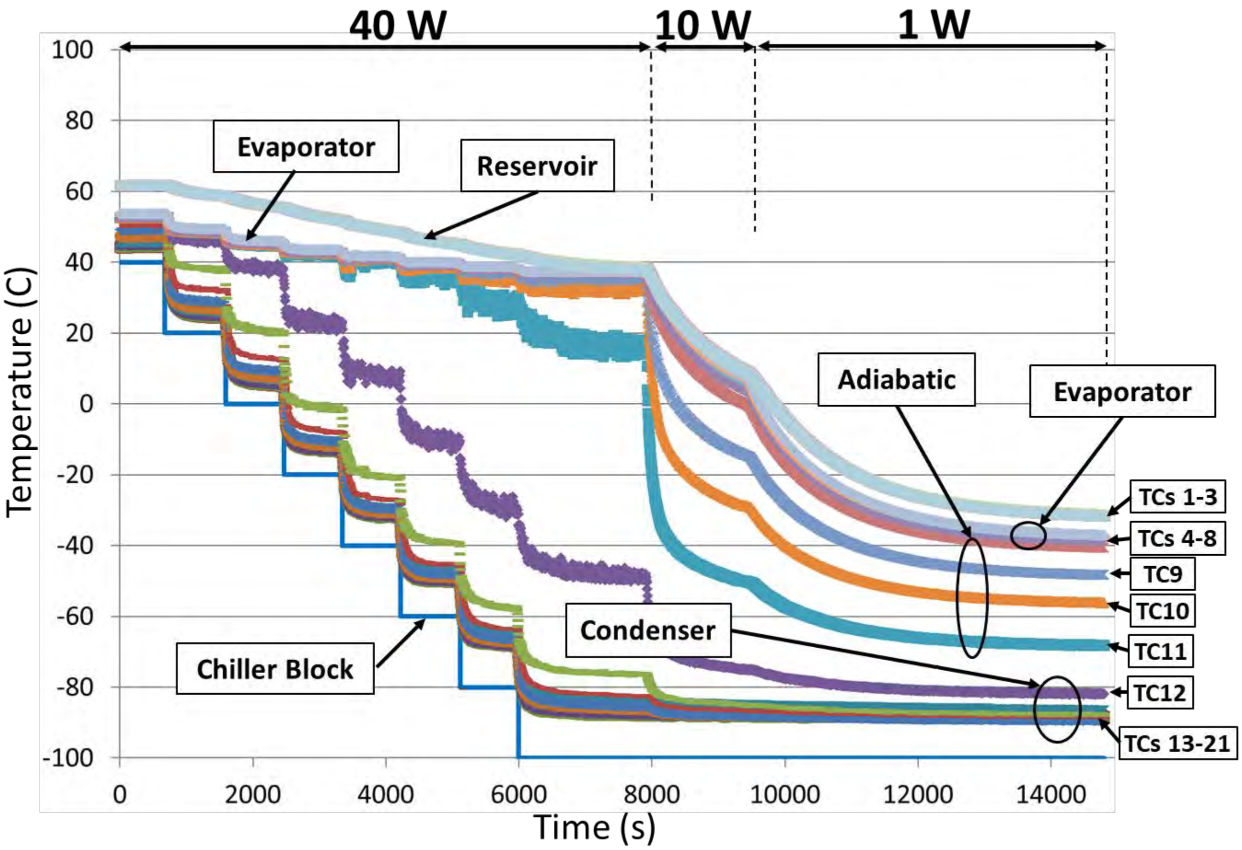

Figure 13. Thermal control test of the Astrobotic hot-reservoir hybrid-wick VCHP. Initial conditions: Power = 40W, Chiller Block Setpoint = 40°C, Evaporator Operating Temperature = 53.6°C. Refer to Figure 11 for TC numbers.

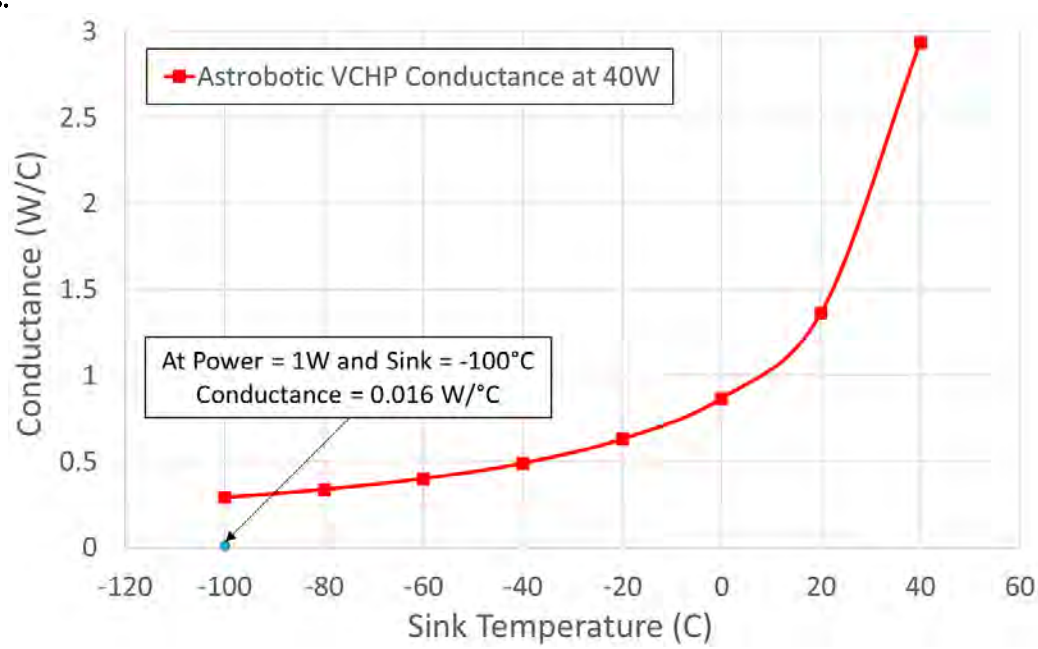

Figure 14. Variation in conductance of the Astrobotic VCHP with sink temperature at a fixed power of 40W. The conductance at the minimum sink temperature and 1W applied power is also indicated.

Figure 15 compares the instantaneous temperature distributions along the Astrobotic VCHP at the design operating condition (40W and 40°C sink) and the survival operating condition (1W and -100°C sink). At the design condition (Figure 15a) it can be seen that the reservoir operated approximately 8°C hotter than the evaporator. The elevated reservoir temperature was due to its placement relative to the heat source. The VCHP was isothermal from TC4 in the evaporator to TC13 located within the condenser (see Figure 11 for TC locations). The temperature began decreasing after TC13 due to the presence of NCG. Note that based on this plot the VCHP was overcharged with NCG for the operating condition of 40W and sink temperature of 40°C, the condenser was not being fully utilized at this condition. Unfortunately, there was insufficient time to fine tune the NCG charge. At the low power/low temperature condition (Figure 15b) the condenser was at a relatively uniform temperature of approximately -90°C while the evaporator was at approximately -38°C. A significant temperature gradient was observed throughout the adiabatic section indicating that the NCG front had exited the condenser and was approaching the evaporator. While the VCHP was modeled using the flat-front theory, in reality the boundary of vapor and NCG was diffuse and was further obscured by heat conduction through the aluminum envelope of the heat pipe.

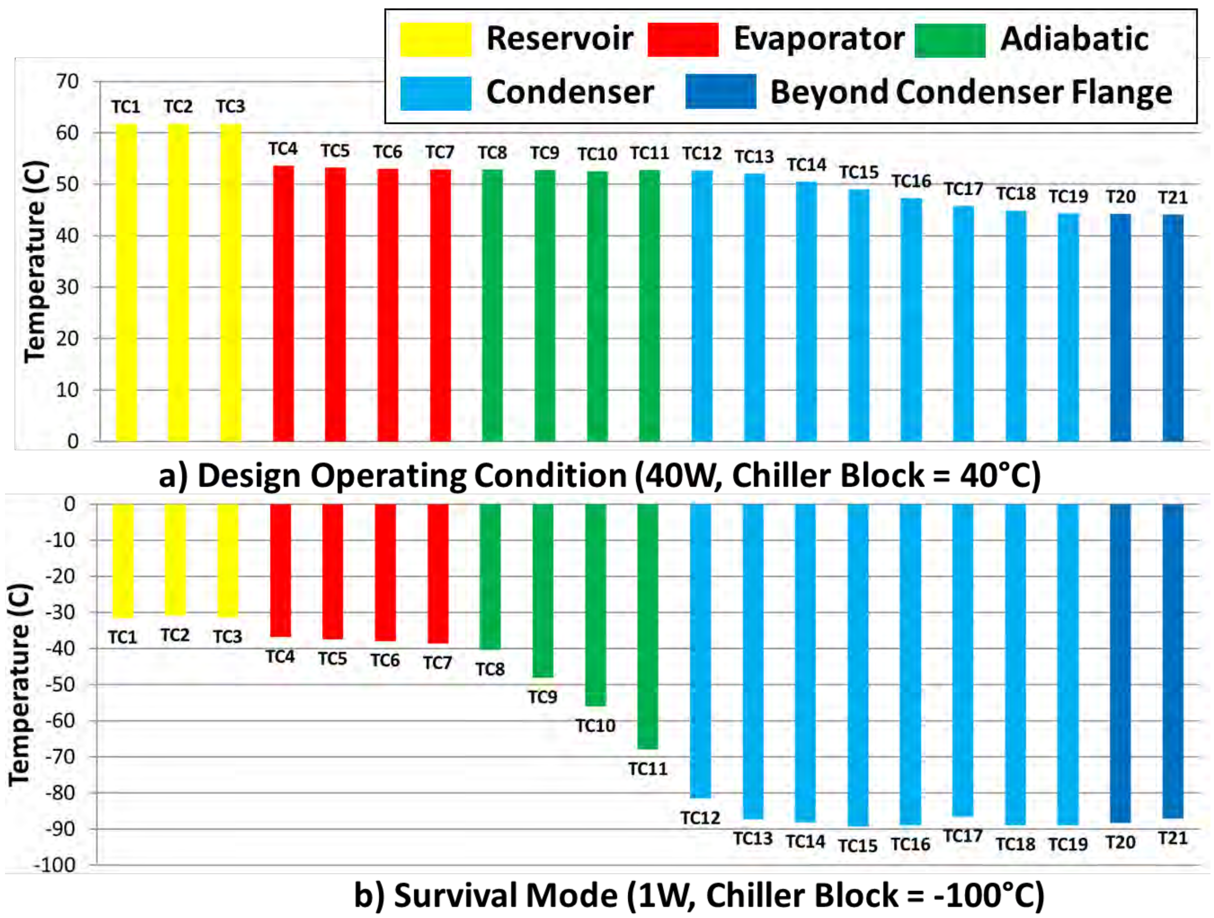

Figure 15. Comparison of instantaneous temperature distribution along the Astrobotic VCHP during a) the design operating condition and b) the low temperature/low power survival condition. Refer to Figure 11 for TC numbers.

During long periods of non-operation, working fluid migrates into the NCG reservoir. This primarily occurs via diffusion however jostling of the VCHP, for example during setup or shipping, can cause larger amounts of working fluid to end up in the reservoir. During operation, the partial pressure of the working fluid vapor within the reservoir will displace additional NCG into the condenser increasing the thermal resistance of the VCHP and increasing the operating temperature. With a non-integrated reservoir it is possible to independently heat the reservoir during periods of non-operation in order to purge working fluid from the reservoir.

Figure 16 shows example purge tests of the Astrobotic hot-reservoir VCHP. Prior to this test the VCHP had been dormant for several days allowing the working fluid to diffuse into the NCG reservoir. The initial steady state condition, indicated at approximately 4,000 seconds, had a vapor temperature of 58.9°C for the nominal power of 40W and chiller block setpoint of 40°C. Note this vapor temperature is 4-5°C higher than the results shown in Figure 12 and Figure 13 despite identical power and sink conditions. At approximately 5,000 seconds the first purge test was initiated. During the purge test, power to the evaporator was shutoff, the chiller block setpoint was reduced to 0°C and 12W of heater power was applied to the heater mounted directly on the NCG reservoir, shown in Figure 11. This resulted in a significant increase in reservoir temperature.

The reservoir heater was shutoff and the evaporator heater was reapplied allowing the system to return to the nominal operating condition. After this initial purge the steady-state evaporator temperature was approximately 56.5°C, a reduction of 3.4°C indicating that some working fluid had left the reservoir. At approximately 13,000 seconds a second purge test was initiated. After the second purging, the steady-state evaporator temperature was 55.0°C a nearly 4°C decrease from prior to purging. These results indicate that reservoir heating is an acceptable method of removing working fluid from the reservoir and returning the VCHP to its nominal operating state.

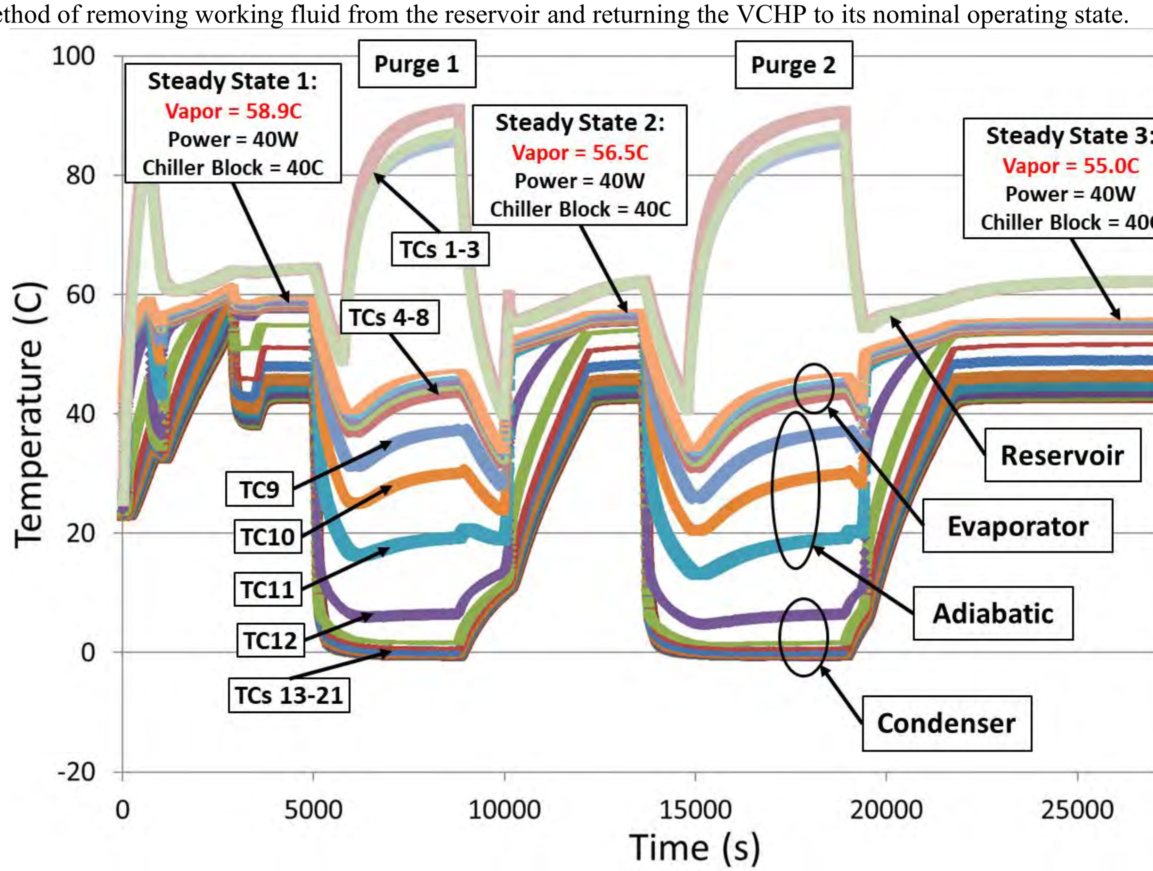

Figure 16. Example of two subsequent purge tests of the Astrobotic non-integrated hot-reservoir VCHP. Test was initiated after several days of non-operation allowing working fluid to diffuse into the NCG reservoir resulting in a higher steady-state operating temperature. During the Purge tests, power to the evaporator was turned off and 12W of heater power was applied directly to the NCG reservoir using a dedicated heater. Refer to Figure 11 for TC numbers.

V. Conclusion

This paper detailed the design, fabrication and testing of two non-integrated hot-reservoir hybrid wick VCHPs developed by Advanced Cooling Technologies, Inc. The first VCHP discussed was fabricated as part of a TDU for the thermal management of NASA's lunar rover VIPER. This hot-reservoir VCHP utilized nested flexible lines throughout the adiabatic section for both the outer envelope and the inner NCG tube to accommodate launch induced vibrations. The second VCHP will fly onboard Astrobotic's Lunar Lander Peregrine I as a TDU. The Peregrine I is set to launch in 2022. The Astrobotic VCHP was fabricated with a 3D printed evaporator that included a 3D printed porous wick. The 3D printed wick interfaced to the grooved wick of the adiabatic and condenser section of the heat pipe. Thermal testing of both VCHPs demonstrated several key features of non-integrated hot-reservoir hybrid wick VCHP:

- The hybrid wick (screen or 3D printed porous structure in the evaporator and grooves or no wick in the adiabatic/condenser) prevented temperature spikes during startup in a gravity-aided orientation. The porous wick distributes working fluid throughout the evaporator even when the pipe is not operating.
- The hot-reservoir VCHP, which maintains the NCG reservoir at a warmer temperature than the evaporator, exhibits excellent passive temperature control. Turndown ratios of 544:1 and 185:1 were estimated for the VIPER and Astrobotic VCHP, respectively.
- The non-integrated NCG reservoir allows for independent heating of the reservoir which can be effectively used to purge working fluid from the reservoir. As a result, it is possible to return the VCHP to nominal operating conditions even after long periods of non-operation during which working fluid migrates into the reservoir.

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