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Integrated Hot Reservoir Variable Conductance Heat Pipes with Improved Reliability

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A hot reservoir variable conductance heat pipe (VCHP) that can offer tight and passive thermal control is an ideal thermal link for future planetary landers and rovers. This is especially useful for the moon operation as surviving during the lunar night is energetically challenging. Under a Small Business Technology Transfer (STTR) program, Advanced Cooling Technologies (ACT) and Case Western Reserve University (CWRU) developed an advanced integrated hot reservoir VCHP with improved reliability. This novel design enables a momentum-induced flow to circulate through a non-condensable gas (NCG) loop, which can continuously and effectively remove the excessive working fluid vapor from the reservoir (i.e. purging) without using an electric heater. Based on the purging test results, the bulk induced flow velocity is in a cm per second range. Without the flow, purging is dominated by diffusion and it will take hours to complete. With momentum-induced flow, the purging rate is much faster and the heat pipe can get back to normal operation within 20 minutes. This paper summarizes prototype development and experimental study of hot reservoir VCHP loop, including a detailed analysis of the VCHP purging process, purging, and startup testing of VCHP loop. A compact hot reservoir VCHP loop prototype with both reservoir and NCG tube integrated was developed and tested.

Nomenclature

ACT	=	Advanced Cooling Technologies, Inc.
CWRU	=	Case Western Reserve University
NCG	=	Non-Condensable Gas
VCHP	=	Variable Conductance Heat Pipe
STTR	=	Small Business Technology Transfer

I. Introduction

NASA's vision to deploy more landers and rovers on the moon surface poses a significant thermal design challenge. There is a need to extend the duration of the missions in both cold and hot environments, including cis-lunar and planetary surface excursions. The heat rejection turn–down ratio of the increased thermal loads in the above-mentioned conditions is crucial for minimizing vehicle resources (e.g. power). Therefore, future exploration activities will need advanced thermal management systems that can provide higher reliability and turn-down ratio , and, at the same time, with reduced power and mass. To meet these requirements a passive thermal link that offers a large turn-down ratio is highly encouraged, which can be a Hot Reservoir Variable Conductance Heat Pipe (VCHP).

Advanced Cooling Technologies, Inc. (ACT) has developed multiple versions of hot reservoir VCHP and successfully demonstrated their thermal control capability through a series of ground testing (ref. 1, 2 and 3). A

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reliable operation of hot reservoir VCHP requires a good working fluid management strategy, which includes the feature to avoid working fluid entering the warm reservoir and to efficiently remove moisture from the reservoir (i.e. purging) using minimal energy resources.

To address the fluid management challenge of hot reservoir VCHP, ACT in collaboration with Case Western Reserve University (CWRU) performed a fundamental study to investigate a hydrodynamic characteristic within a hot reservoir VCHP. A new VCHP loop configuration as Figure 1 illustrated was developed. This new configuration consists of a warm reservoir (can either be integrated or non-integrated with the evaporator), a heat pipe section, and two NCG tubes. One is internal, coming out from the reservoir and going through the heat pipe section from the evaporator side. The second NCG tube is external, coming out from the reservoir and connecting to the end of the condenser. Because of the loop configuration, a circulating flow induced by the momentum of the primary vapor flow through the annular region of the heat pipe can be generated. This flow will provide continuous purging and reduce the moisture level of the reservoir. This purging process and mechanism are fully passive, meaning that no additional electric heating to the reservoir is required. The previous numerical and experimental studies successfully demonstrated the existence of momentum induce flow (ref. 4 and 5). This paper will focus on reliability improvement of a VCHP loop, including prototype development, purging performance testing, parametric study, induced flow velocity estimation, and development of a final VCHP loop prototype with both reservoir and external NCG tube integrated.

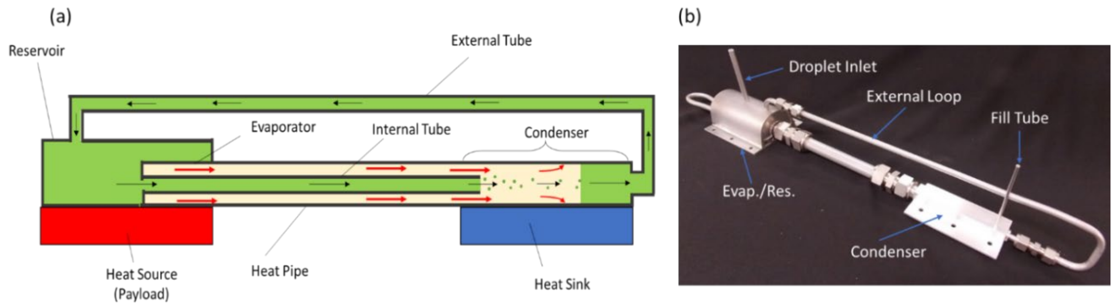

Figure 1. Advanced hot reservoir VCHP with (a) conceptual design of VCHP (b) proof-of-concept prototype developed in Phase I.

II. VCHP Loop Prototype Development

A VCHP loop prototype made of aluminum was developed for purging process study. Figure 2(a) shows all the components before assembling, including a reservoir integrating with a heat pipe evaporator, an internal NCG tube, condenser, external NCG tube, and two fill tubes. The integrated reservoir/evaporator with end cap (Figure 2(b)) is made with additive manufacturing as a single component. There are two fill tubes in this prototype: One fill tube at the end of the condenser is the major fill tube for working fluid and NCG charging. Another fill tube attached to the top of the reservoir is for purge testing. Droplets of the working fluid will be directly injected into the reservoir via this fill tube while the heat pipe is operating. Key dimensions of this prototype are summarized in Table 1.

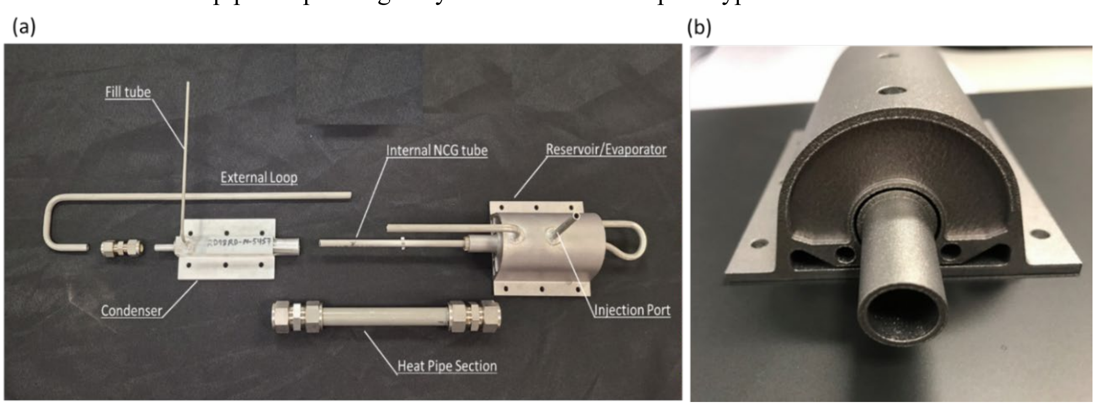

Figure 2. Aluminum VCHP loop prototype with an integrated reservoir (a) all components (b) additive manufactured evaporator/reservoir.

Table 1. Specifications of hot reservoir VCHP loop prototype.

Heat pipe evaporator length	10.16 cm (4 inches)
Adiabatic length	15.24 cm (6 inches)
Condenser length	15.24 cm (6 inches)
Heat pipe section diameter	1.6 cm (0.63") OD / 1.27 cm (0.5") ID
Internal NCG tube diameter	0.64 cm (0.25") OD/ 0.48 cm (0.19") ID
External NCG tube diameter	Same as the internal NCG tube

A. Internal NCG tube design

Based on previous numerical analysis (ref. 5), The internal NCG tube design is a key for flow generation., to induce a flow in a VCHP loop, the internal NCG tube outlet must be located before the vapor/NCG front in the condenser. As Figure 3 shows, the internal NCG tube outlet is 8.3 cm (3.25 inches) away from the condenser. The NCG tube has a Venturi-style outlet: The NCG tube has radial outlets and the axial end is closed. When the vapor flows through the annular space between the heat pipe and the internal NCG tube, it will create a low hydrostatic pressure region around the outlet of the internal NCG tube, which will pull NCG from the inner tube to the heat pipe. Three different NCG tube outlets were tested, including (1) 1.6mm (1/16 inch) radial holes (2) 1.3 cm (½ inch) long slit and (3) completely closed tube. The completely closed tube design is the baseline to mimic a conventional hot reservoir VCHP design without a loop.

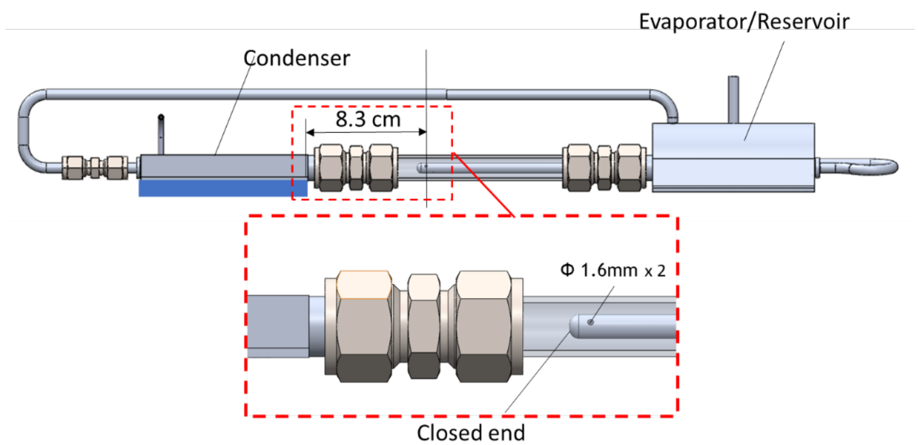

Figure 3. CAD of VCHP loop and detailed drawing of internal NCG tube design (two-hole Venturi style).

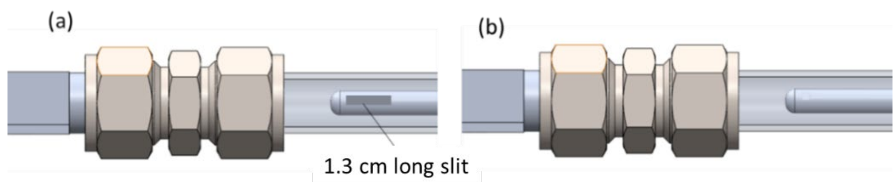

Figure 4. (a) Slit NCG tube (b) fully-closed NCG tube.

III. VCHP Purging Test and Discussion

B. VCHP Purging Test

The objective of the purging test is to study how fast a VCHP can remove excessive working fluid from a reservoir and recondition the distribution of NCG and vapor in the pipe so that the VCHP can get back to normal operation mode. A picture of the experimental setup is shown in Figure 5. The pipe is situated in a slight gravity-aided orientation. In addition to temperature measurement at various spots, the internal pressure of the VCHP is monitored by a pressure transducer attached to the reservoir. The test procedure is as follows:

a. Charge calculated amount of working fluid (acetone) and NCG (helium) into the heat pipe via fill port A.
b. Apply heating and cooling to the evaporator and condenser and wait for steady-state.
c. Adjust test conditions to make sure that the vapor/NCG is in the middle of the condenser.
d. Add a certain amount of working fluid liquid into the reservoir via fill port B.
e. Observe the variation of temperature and pressure.

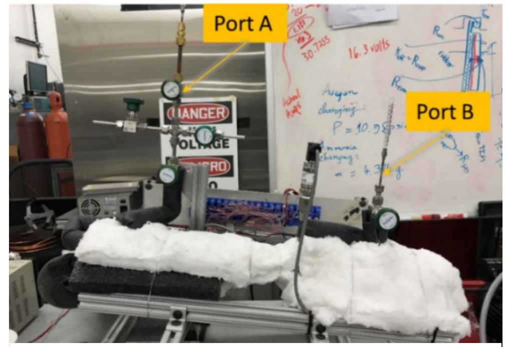

Figure 5. Experimental system for VCHP purging test.

C. Purging Test Results and Discussion

1. Fully-closed NCG tube

The internal NCG tube with no hole (as Figure 3 shows) was first tested. This configuration can be considered as a regular hot reservoir VCHP without a loop. Figure 6 below shows the variation of temperature (upper) and pressure (lower) of VCHP after 0.4 ml of the working fluid is added directly to the reservoir at t=3600 seconds. As soon as the working fluid liquid enters the hot reservoir, it immediately flashes and the vapor occupies the entire reservoir volume. NCG originally in the reservoir is pushed to the condenser. As more condenser area is blocked by NCG, adiabatic and reservoir temperatures (the green line and red lines) increase. Then heat pipe start purging (i.e. re-organizing fluid distribution). In this configuration, purging can be achieved only by diffusion. Since the diffusion rate depends on the concentration gradient between the reservoir and condenser, the purging rate will decay as time goes. As shown by the pressure data (lower figure), the slope of pressure decay become smaller and smaller. After 3 hours of purging, the pressure value of VCHP is still approximately 10% higher than the initial value.

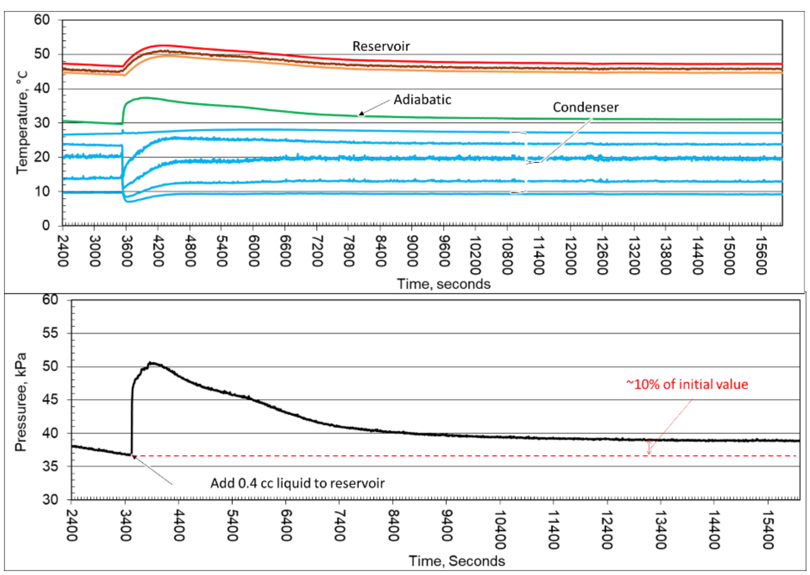

Figure 6. Purging test results of VCHP without a loop. The top figure shows the temperature variation and the bottom figure shows the pressure variation.

2. NCG tube with radial holes

Figure 7 shows the pressure and temperature variation of the VCHP with an open internal NCG tube. At t=5660 seconds, 0.4 ml is added to the reservoir. Pressure and temperature spike up similarly with the case without a loop. After reaching the peak value, pressure and temperature drop at a much faster rate compared to the case without a loop. This indicates that this heat pipe is purging with a different mechanism. The pressure value drops back to the original state after 840 seconds (~14 mins) after adding liquid to the reservoir. This is at least 13 times faster than a diffusion-based purging, which is not completed after 3 hours.

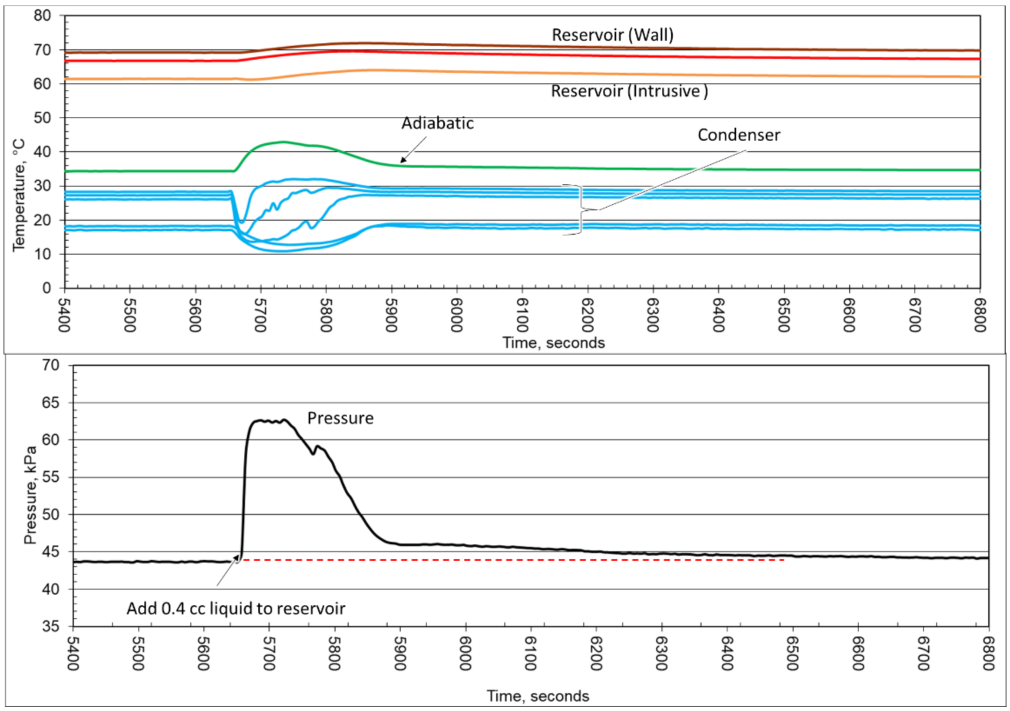

Figure 7. Purging test results of VCHP loop. Top: Temperature variation; Bottom: Pressure variation.

3. Repeatability testing

ACT also performed a repeatability test to demonstrate this mechanism is reproducible. One set of test data (with different sink temperature and NCG inventory) is shown in Figure 8. In this test, different amounts of working fluid liquid are consecutively added to the reservoir. It can be seen that the pipe can successfully recover from an abnormal state quickly.

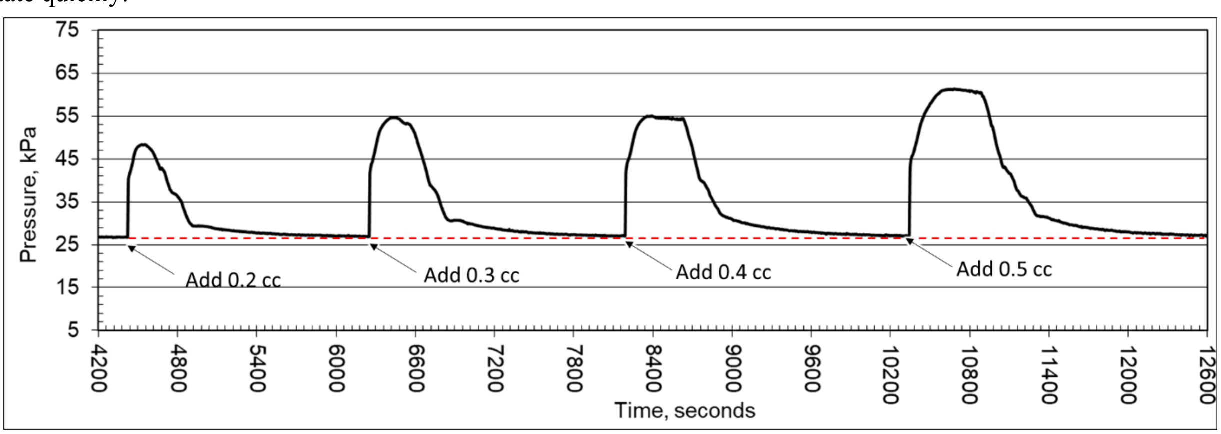

Figure 8. Repeatability test of VCHP loop purging (2-hole outlet).

Figure 9 shows purging rates comparison amount three internal NCG tube designs shown in Figure 3 and Figure 4. The y-axis is the normalized pressure, defined as:

$$\hat{P}(t) = \frac{P\ (t)}{P_{peak} - P_{initial}}$$

For both slit and 2-hole designs, the purging rates are significantly higher than the baseline (i.e. no hole). The normalized pressure drops below 10% within 1000 seconds. The purge rate of the slit design is slightly faster. For the no-hole design, the pressure is always above the 10% line during the test.

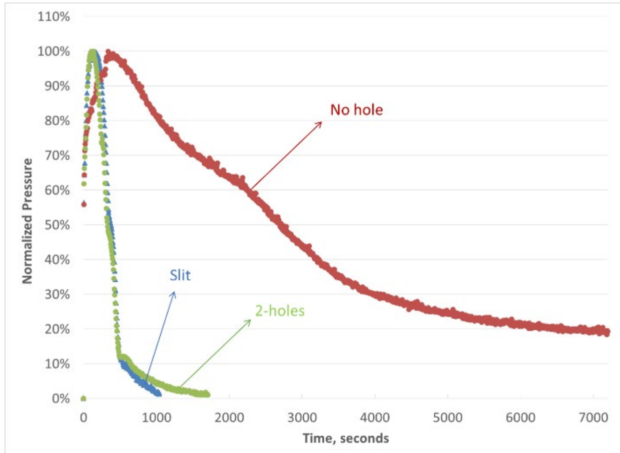

Figure 9. Purging rate with different NCG tube designs.

D.VCHP Purging Process

A purging curve is presented in Figure 10 to study vapor/NCG front migration during a purging process. In this test, 100W of heat is applied to the evaporator, and the sink temperature is at 0°C. The internal NCG tube has 2 radial holes. Figure 11 shows the temperature distribution along the heat pipe at various instants. At 4895 seconds, 0.2 ml of acetone liquid was injected into the reservoir.

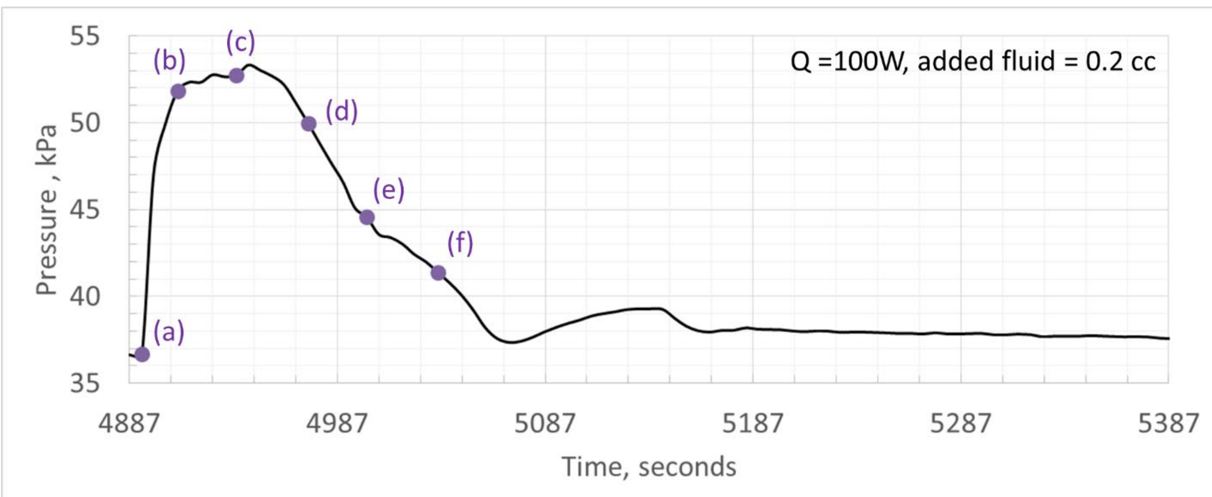

Figure 10. Pressure variation during purging. Heat input of 100W; 2-hole NCG tube design; added acetone liquid = 0.2 cc to the reservoir.

Before injection (t = 4893 s), the vapor/NCG front is in ~¾ length or condenser. Immediately after liquid injection, pressure increases significantly. At t = 4910 seconds, the system pressure reaches 7.5 psi and the corresponding saturation vapor temperature is 37.6°C. This is the highest temperature measured in the adiabatic section (see Figure 11(b)). The vapor/NCG front is in the adiabatic section and the condenser is fully closed. The heat cannot be removed by the condenser. Vapor temperature and pressure keep increasing until they reach a peak value at t=4939 seconds. It can be seen from the temperature profile that the vapor/NCG front at this moment is about to go back to the condenser (Figure 11(c)). The purging starts. The dryer gas from the condenser flows back to the reservoir via the external NCG tube and the gas vapor mixture from the reservoir flows into the heat pipe section via the internal NCG tube. It can be seen from Figure 11(d) – (f) that the vapor/NCG front moves toward the condenser. As more condenser areas are open, vapor temperature and pressure in the heat pipe decrease. The system pressure drops quickly from the peak value to the original value. The entire process takes less than 300 seconds.

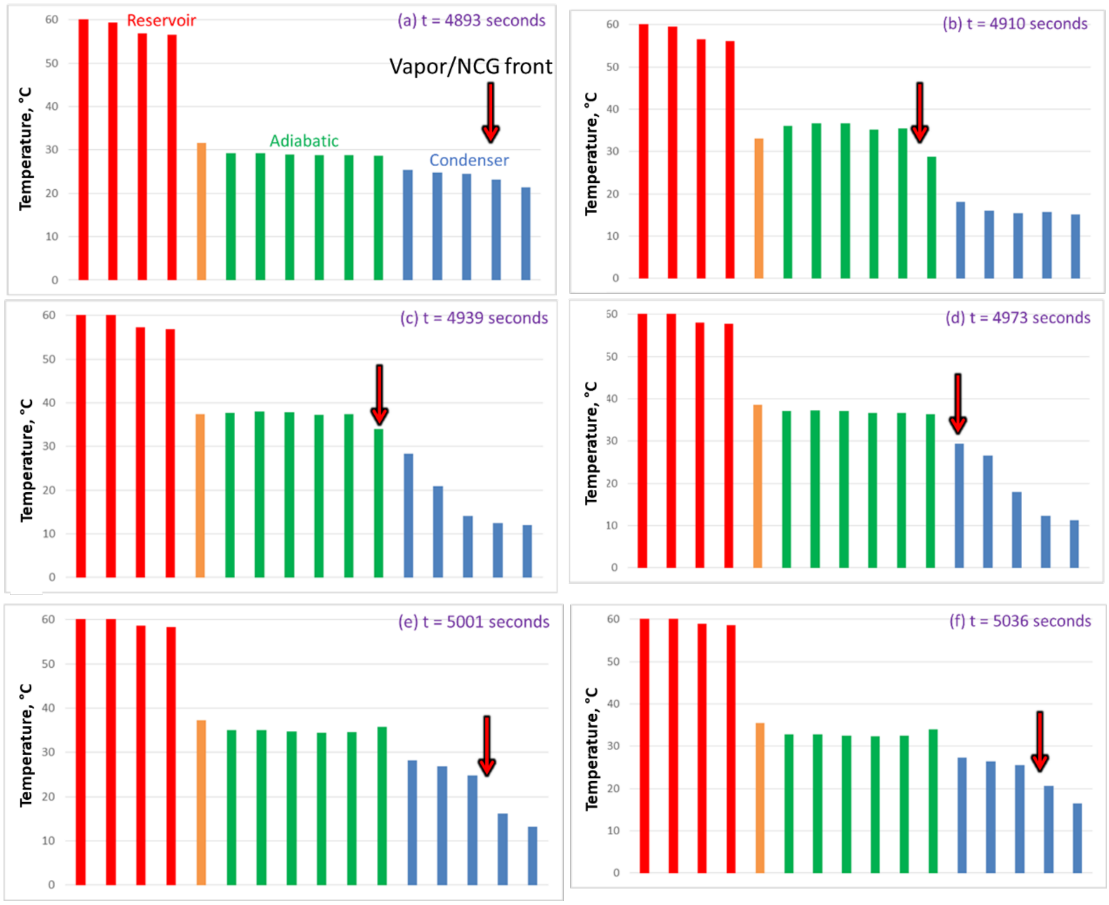

Figure 11. Instantaneous temperature profiles at different time stamps during purging (red arrow indicates the vapor/NCG front location).

IV. Parametric Study of VCHP Purging

A. Purging Profiles with different added fluid volumes

Figure 12 plots pressure variation with different added fluid volumes. It can be observed that adding more liquid into the reservoir would increase the peak value. This is because more superheated vapor will be generated within the reservoir after injection and it would need more time to remove moisture from the reservoir. It can also be seen that the slopes of pressure decay are similar for all cases, meaning that the purge flow velocity is independent of added fluid volume.

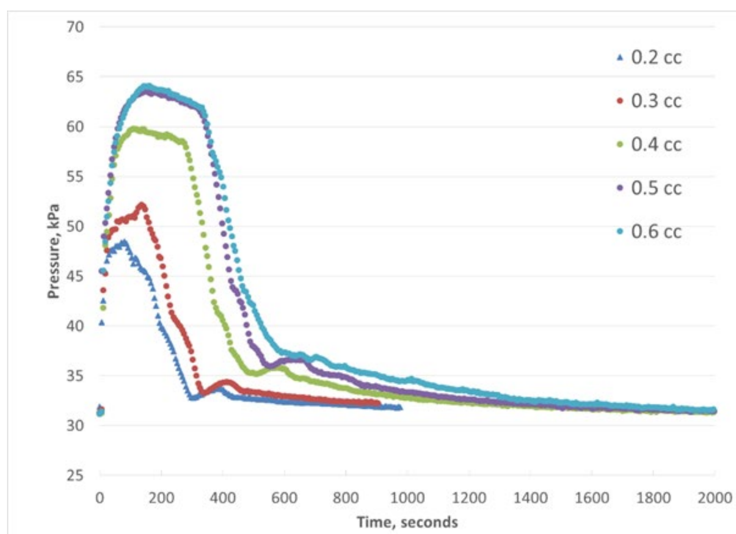

Figure 12. Purging rate with different added fluid volume into a warm reservoir.

B. Influence of heat inputs and NCG charge

Figure 13 (a) shows the purging time with different added acetone volumes, different heat inputs, and different initial NCG charge pressure. Higher heat inputs result in a higher purge rate (i.e. shorter purge time). This makes sense since the vapor flow in the heat pipe section will carry more momentum with higher heat inputs. It can also be seen from this figure that having more NCG in the heat pipe section would result in a slower purging. This can be explained as follows,

1. With more NCG charge, the equilibrium vapor/NCG front under the same heating condition will be closer to the internal NCG tube exit. In other words, the distance between the vapor/NCG front and the NCG tube outlet is shorter. This is unfavorable for flow generation based on CFD analysis results (ref. 5).
2. The total pressure in the heat pipe would be higher with more NCG charges. This means that the density of vapor would be higher. Under the same heat load, the velocity of vapor flow would be lower.
3. The density of NCG is higher so it would need higher momentum to drive the flow.

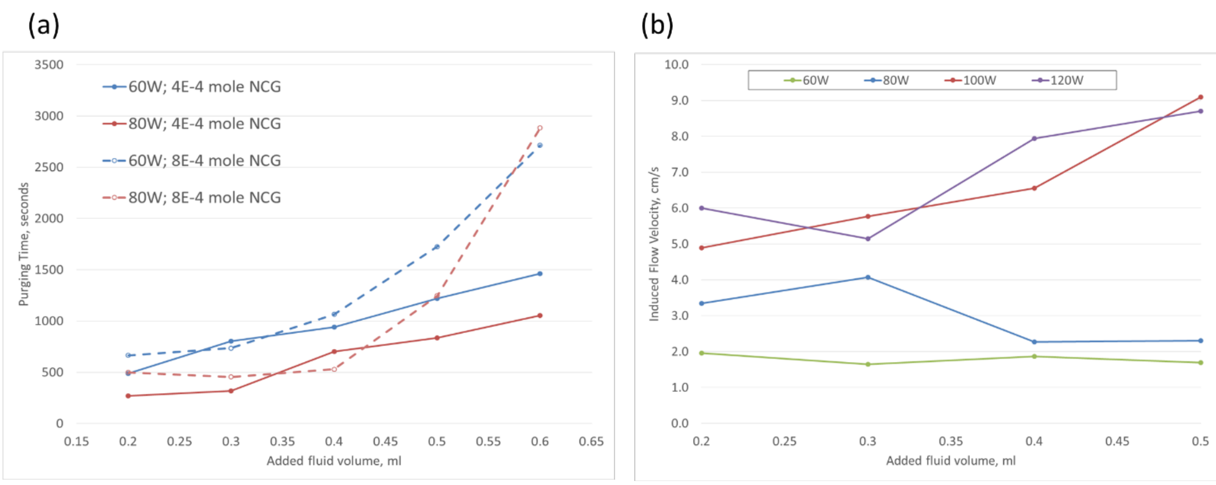

Figure 13. (a) Measured purging time with different heating powers and NCG amount (b) estimated bulk momentum-induced flow velocity under different heating powers with NCG of 4x10^{-4} moles.

C. Induced flow velocity estimation

Based on the measured purging time and a known amount of injected fluid, the bulk purging flow velocity can be estimated with the following two assumptions:

1. The calculated velocity is based only on the vapor flow (i.e. 100% humidity) and therefore it is conservative.
2. The liquid added into the reservoir vaporizes immediately (no liquid state).

The calculation procedure is as follows:

First calculate the added fluid mass at room temperature. For example, 0.4 ml acetone liquid at room temperature is 0.314 grams. Then calculate the average mass removal rate based on the measured purging time. For example, if the measured purging time is 840 seconds, the corresponding fluid removal rate from the reservoir is 3.74E-4 grams per second. Afterward, calculate the corresponding volumetric vapor flow rate assuming all liquid turns into saturation vapor. For example, the average vapor pressure during the purging process is 41,370 pa (6 psi). The corresponding saturation vapor density is 0.975 kg/m3. The volumetric flow rate is 0.38 cm^3/s. The bulk flow velocity can be estimated based on the given NCG tube inner diameter. Figure 13(b) summarizes the estimated induced flow velocity at different heat inputs and added liquid volume.

D. Purge rate with different working fluid – Toluene

A similar test was performed using Toluene as the working fluid. The test result is shown in Figure 14. In this test, the initial helium charge is 2E-4 moles and the sink temperature is 40°C. Heat input is 60W.

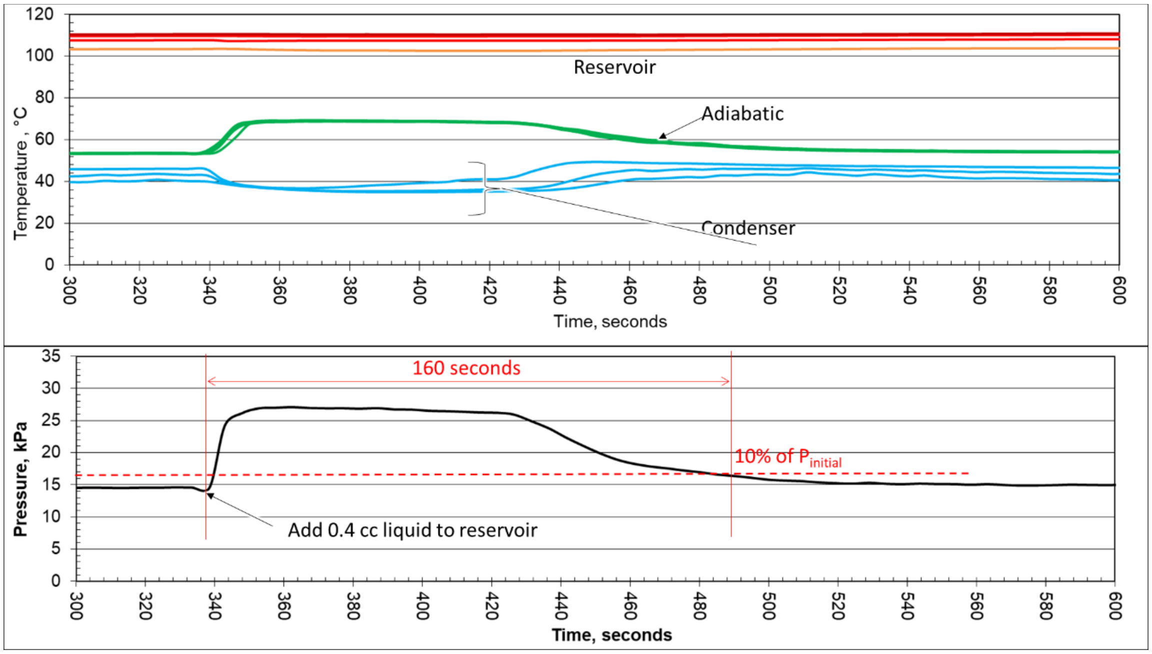

Figure 14. Purging test results with toluene as working fluid and helium as NCG.

It can be seen that purging is completed within 160 seconds. The estimated momentum-induced flow velocity is 18.87 cm/s. The higher purging velocity for Toluene can be explained by the fluid properties. As summarized in Table 2 Toluene has a vapor density and lower latent heat of vaporization. This means that (1) under same heating condition, toluene would have a stronger vapor flow velocity in the adiabatic section and (2) as liquid being added into the reservoir, toluene will vaporize faster than acetone and can be quickly taken away by the flow because of lower density.

Table 2. Comparison between acetone and toluene purging test results.

	Acetone Test	Toluene Test
Heat input	60W	60W
Added fluid volume	0.4 ml	0.4 ml
Sink Temp	0°C	40°C
Average Purging Pressure	41,370 pa (6 psi)	20,685 pa (3 psi)
Inclination	7.5 degrees	7.5 degrees
hjuVapor density	0.975 kg/m^3	0.625 kg/m^3
Latent heat	527 kJ/kg	392 kJ/kg
Estimated Purge Velocity	2.1 cm/s	18.87 cm/s

V. Start-up behavior of VCHP loop

A startup test was also performed to study how fast the VCHP can start up with the presence of working fluid liquid in the reservoir. Figure 15 shows one of the test results, using the following testing procedure:

1. Charge 1 psi of helium and 4 cc of acetone into the VCHP loop
2. Without applying heat, cool down the condenser to 0°C
3. Inject 0.4 cc of acetone liquid into the reservoir (t = 4800 seconds in Figure 15)
4. Immediately after liquid injection, apply 100W of heat to the evaporator/reservoir
5. Record the startup process of VCHP

As the pressure graph (bottom figure in Figure 15) shows, the pressure first reaches a peak value of 10 psi and then quickly drops to 6 psi. Next, the pressure increases and drops again, forming the 2nd peak. The system reaches equilibrium within 1400 seconds (23 mins). This startup condition is considered to be the most challenging situation (i.e. 100% humidified reservoir). At t =7800 seconds, the heater was turned off to let the heat pipe cool down again. The test was repeated at t = 13600 seconds. The same startup behavior was observed, showing the repeatability of the system.

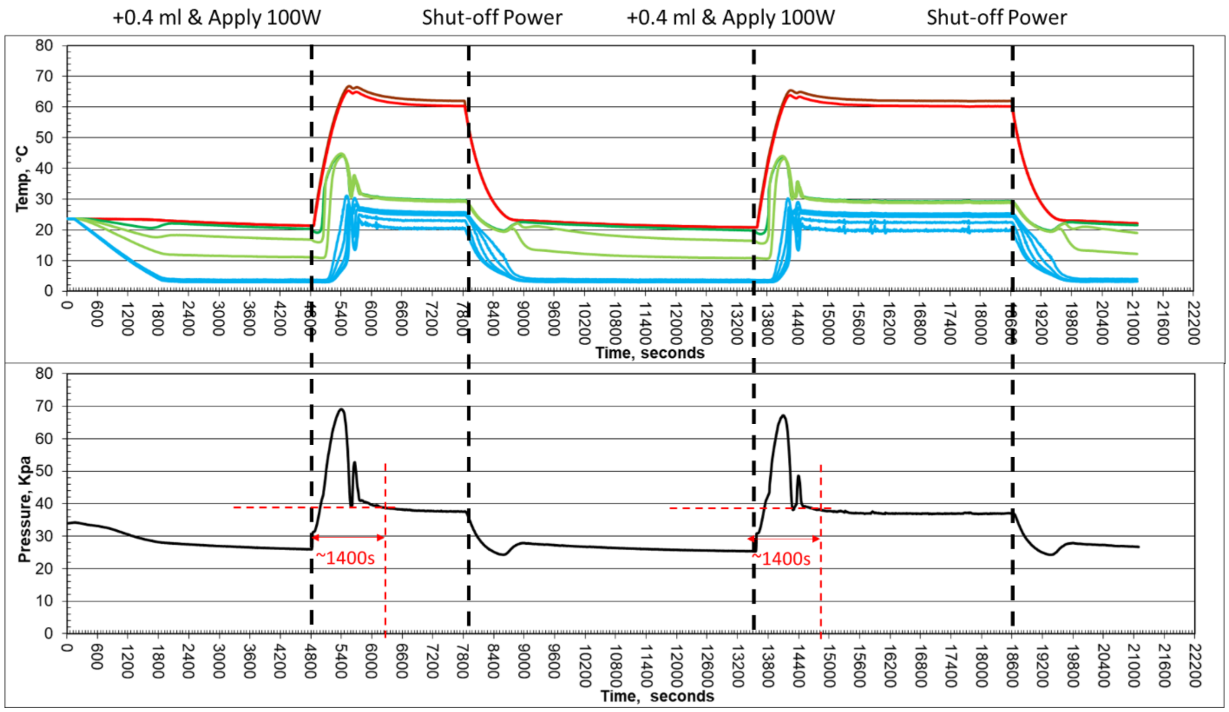

Figure 15. Startup of VCHP Loop from 100% humidity reservoir (conservative scenario).

After this test, the pipe was left in ambient for three days. Because of diffusion, vapor and NCG will homogenously distribute within the heat pipe and reservoir. Another startup test was performed after three days of idling. The test result is shown in Figure 16. The test procedure is similar to the 1st test. The only difference is at t = 4800 seconds, no extra liquid is added into the reservoir. As the figure shows, the heat pipe can start up quickly. The test was repeated at t =13000 seconds. Since this time the reservoir is already dry, the heat pipe startup smoothly without showing any pressure spike. The 2nd start test condition is more common in real space applications.

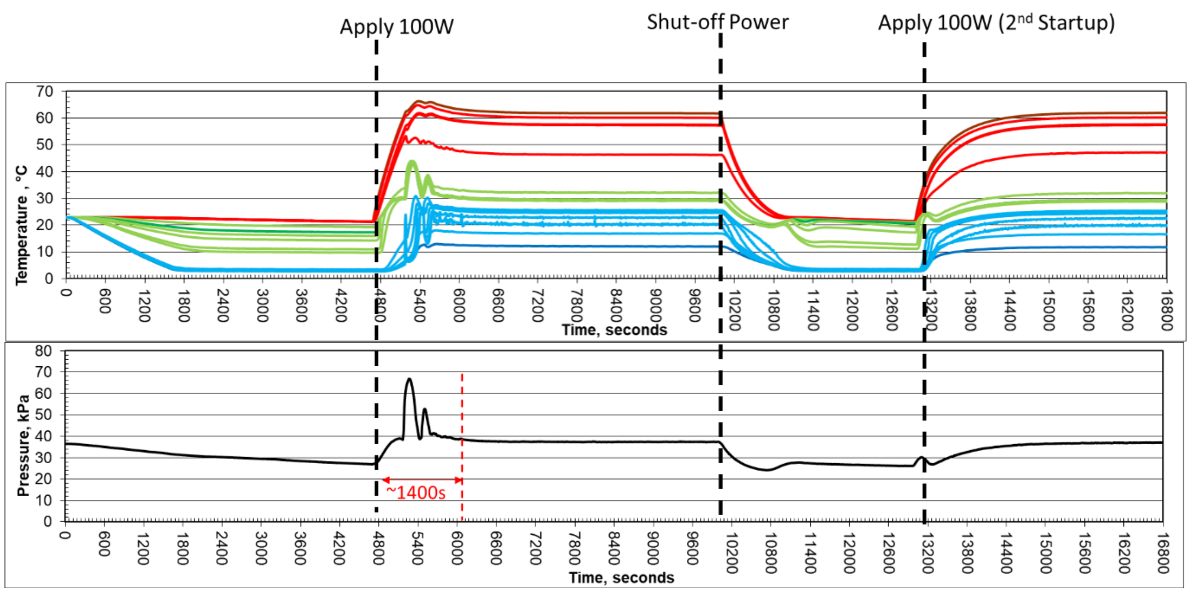

Figure 16. Startup of VCHP Loop from homogenous vapor/NCG distribution condition (a realistic scenario).

VI. Final Prototype – Advanced Integrated Hot Reservoir VCHP

A proto-flight VCHP loop with improved reliability was developed for an envisioned lander survival application. Figure 17 is the photograph of the final prototype. The evaporator integrated reservoir is 10.2 cm (4 inches) long. The length of the condenser is 15.2 cm (6 inches) and the adiabatic section is 14.6 cm (5.75 inches). This heat pipe uses axial grooves as the wick structure. The design is compact as both reservoir and external NCG tubes are integrating with the heat pipe main body. One advantage of having an integrated external loop is that the external NCG tube has a thermal connection with the heat pipe. This will avoid working fluid being frozen in the line during normal operation. The internal NCG (not shown in the figure) stops in the adiabatic section and the Venturi-style outlet design is used. ACT plans to perform three sets of experiments: (1) thermal control testing (2) purging test and (3) startup test to verify that this advanced VCHP can reliably operate in space. The thermal control test result is shown in Figure 18 below, using toluene as working fluid and helium as NCG.

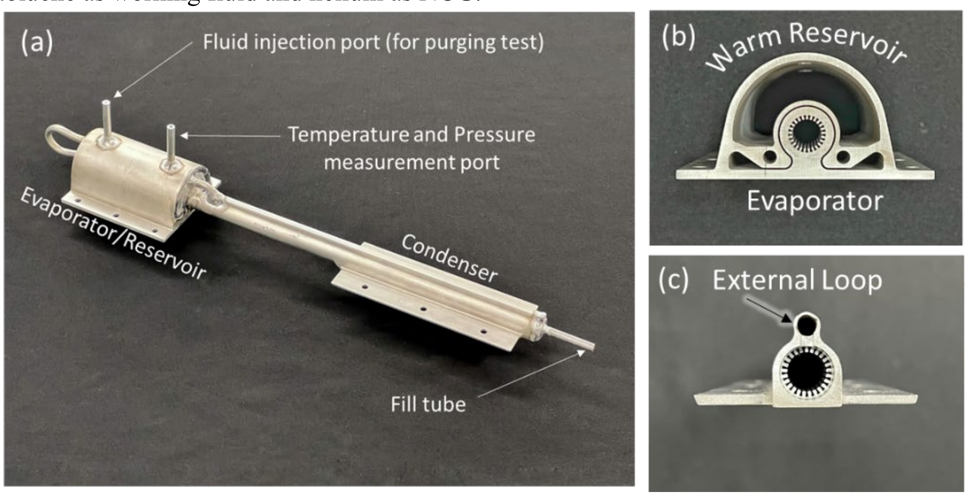

Figure 17. A compact VCHP loop with both reservoir and external loop integrated (a) isometric view (b) reservoir integrating with the evaporator (c) external NCG tube integrated with the heat pipe section.

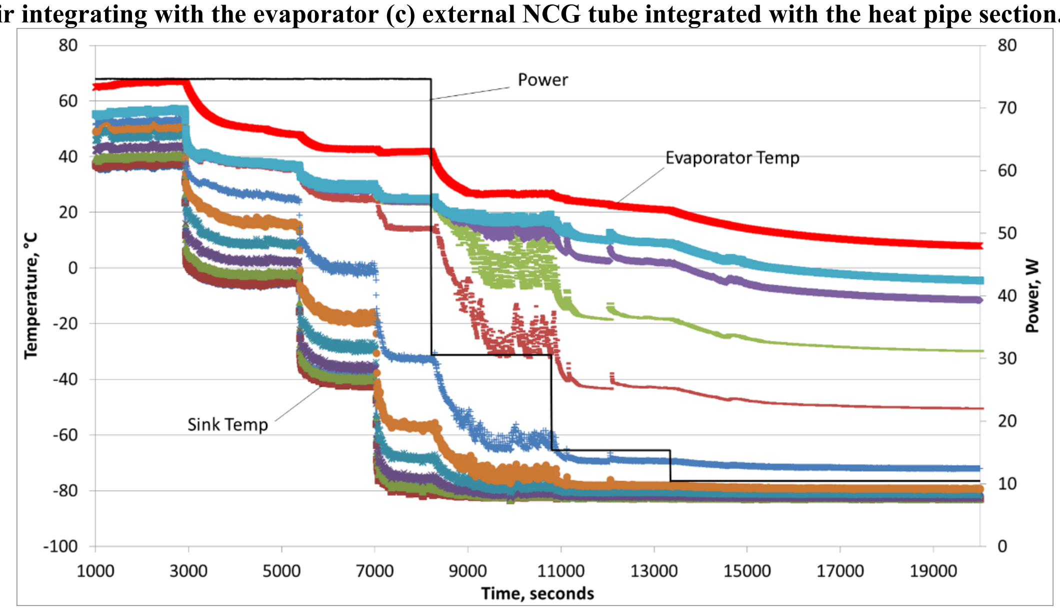

Figure 18. Thermal control performance of the VCHP loop.

The heat pipe initially operates at a nominal condition with a heat input of 75W. ΔT between the evaporator flange and the sink is 25°C and the thermal resistance is 0.33 K/W. At t = 2500, the sink temperature is decreased from a hot condition (40°C) to a cold condition (-80°C). It can be seen that the evaporator (i.e. flange temperature) is maintained above 40°C in the cold condition. The heat input is then scaled down from 75W to 10W. The evaporator temperature reaches a steady state at about 8°C. The thermal resistance increases to 8.8 K/W. The turn-down ratio is around 26.7. Note that by further scaling down the survival power, the evaporator temperature can be even lower until reaching -40°C, which will result in a higher turn-down ratio. Also, note that the parasitic heat leak from ambient was not considered so the result is not conservative. Through this test, it is assured that adding a loop will not degrade the temperature control capability of hot reservoir VCHPs.The reliability (purging and startup behavior) of this VCHP loop is being characterized and will be presented at the conference.

VII. Conclusions

ACT in collaboration with CWRU is developing an advanced hot reservoir VCHP with loop configuration (VCHP loop). The special loop feature will allow a purge flow to generate and circulate within the VCHP, which can continuously remove excessive moisture from the reservoir without using any additional electric heating. This will improve fluid management and result in a more reliable hot reservoir VCHP for future space thermal control applications. This paper presents the recent development activities of an integrated hot reservoir VCHP loop, including a purging test to characterize the effectiveness of the concept, a parametric study of VCHP purging, startup process at two different conditions, and a proto-flight VCHP loop with both reservoir and loop integrated. Based on the purging test results, the following conclusions can be made:

- Compared to a diffusion-based purging which is driven by the concentration gradient, the convective-based purging process is significantly faster.
- With a flow generation within a VCHP loop, purging can be completed within 20 mins
- Higher heat input will result in a higher flow velocity and increase the purge rate
- High pressure will result in a lower purge rate as more gas particles need to be driven by the momentum induced flow
- Using acetone as the working fluid, the estimated bulk purging velocity is in the range of 2 cm/s – 8 cm/s
- Toluene purge flow velocity would be faster than acetone. This is mainly due to lower latent heat of vaporization and lower saturation vapor density of toluene.
- With loop configuration, the VCHP can startup from highly humidified reservoir conditions relatively quickly (less than 30 mins).

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