Development of Flight Demonstration Hot Reservoir Variable Conductance Heat Pipes for Microgravity Testing and Future Lunar Landers and Surface Systems

Kuan-Lin Lee[1], Calin Tarau[2], Ramy Abdelmaksoud[3], William Anderson[4]
Advanced Cooling Technologies, Inc, Lancaster, PA, 17601

Chirag Kharangate[5] and Yasuhiro Kamotani[6]
Case Western Reserve University, Cleveland, OH, 44106

The lunar landers and rovers require a reliable tight passive thermal control technology due to their exposure to the ambient's harsh temperature conditions such as the lunar night where the temperature drops to about -280˚F (-173.3˚C) and lasts for a continuous 14-day period. Advanced Cooling Technologies Inc. (ACT) has devised and demonstrated a hot reservoir variable conductance heat pipe (HR-VCHP) to be an ideal passive variable thermal link between the payloads and the radiator for such lunar landers since HR-VCHP can offer much tighter thermal control capability when compared to a regular cold-biased reservoir VCHP. Under NASA Small Business Technology Transfer (STTR) program, ACT and Case Western Reserve University (CWRU) further matured this technology by introducing a novel fluid management feature that enables a non-condensable gas (NCG) flow to generate inside the device. This flow can maintain the moisture level of the reservoir and lead to more reliable VCHP operation in space. Two flight demonstration units (FDU) of HR-VCHPs with NCG flow are under development: one for microgravity testing on International Space Station (ISS) and another one for lunar lander thermal control applications. The FDU for microgravity testing is made from copper where the working fluid is water while the HR-VCHP for the future lunar landers is made from aluminum where the working fluid is ammonia or propylene. This paper will present a compact HR-VCHP prototype description, reliability testing results, and the development status of two FDUs.

Nomenclature

A	=	Cross-Sectional Area of the Heat Pipe, (m^2)
ACT	=	Advanced Cooling Technologies, Inc.
CWRU	=	Case Western Reserve University
FDU	=	Flight Demonstration Unit
h_{fg}	=	Latent Heat of Vaporization, (J/kg)
HR-VCHP	=	Hot Reservoir Variable Conductance Heat Pipe
K.E.	=	Kinetic Energy per Unit Volume, (Pa)
NCG	=	Non-Condensable Gas
P	=	Pressure, (Pa)
psia	=	Absolute pound force per square inch
Q	=	Power (or heat rate input), (W)
STTR	=	Small Business Technology Transfer
T	=	Temperature, (˚C)
t	=	Time, (s)
ρ_v	=	Vapor Density, (kg/m^3)

[1] Lead Engineer, Advanced Cooling Technologies, Inc., 1046 New Holland Ave., Lancaster, PA 17601
[2] Principal Engineer, Advanced Cooling Technologies, Inc., 1046 New Holland Ave., Lancaster, PA 17601
[3] Engineer II, Advanced Cooling Technologies, Inc., 1046 New Holland Ave., Lancaster, PA 17601
[4] Chief Engineer, Advanced Cooling Technologies, Inc., 1046 New Holland Ave., Lancaster, PA 17601
[5] Assistant Professor, Case Western Reserve University, 10900 Euclid Ave., Cleveland, OH 44106
[6] Professor, Case Western Reserve University. 10900 Euclid Ave., Cleveland, OH 44106

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I. Introduction

NASA's moon landing program includes significant scientific leaps in different technologies such as the development of advanced lunar landers. The development of advanced lunar landers and surface systems is challenging since 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 resource needs (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 (HR-VCHP).

Advanced Cooling Technologies, Inc. (ACT) has developed multiple versions of hot reservoir VCHPs (HR-VCHP) and successfully demonstrated their thermal control capability through a series of ground testing.[1, 2, 3] A reliable operation of hot reservoir VCHP requires a good fluid management strategy, which includes the feature to avoid working fluid entering the warm reservoir and to efficiently and passively remove moisture from the reservoir (i.e., purging). To address the fluid management challenge of hot reservoir VCHP, ACT in collaboration with Case Western Reserve University (CWRU) performed a fundamental study, during NASA STTR Phase I and II programs, to investigate and optimize the thermos-hydrodynamic flow behavior within the HR-VCHP. The schematic of the HR-VCHP configuration is illustrated in Figure 1. This configuration consists of an integrated hot reservoir, 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 end of the condenser into the reservoir. 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-induced flow.[4, 5, 6] During the Phase II program, the design of the HR-VCHP prototype was matured from an initial design, shown in Figure 2(a), to the final prototype shown in Figure 2(b).

Under this NASA STTR Phase III program, ACT will continue to mature the technology by testing HR-VCHP purging with different working fluids, NCG and at different orientations (horizontal and gravity-aided). The objective is to develop two FDUs with integrated hot reservoir and NCG tube: FDU I is for near-future lunar lander thermal management and FDU II is for microgravity testing on the International Space Station (ISS).

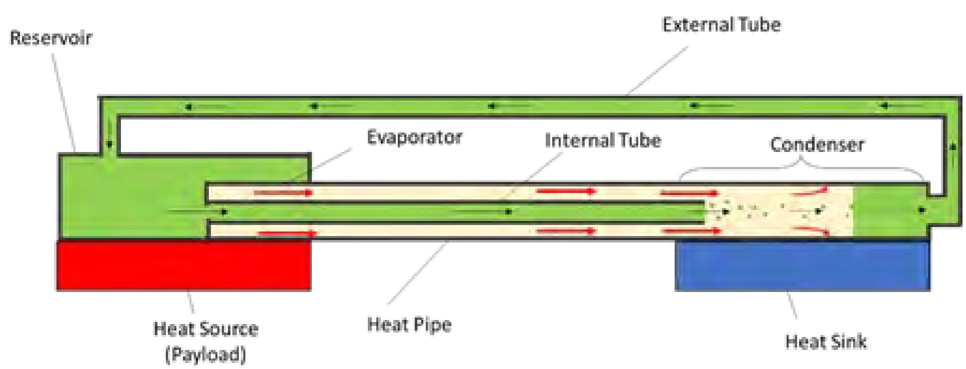

Figure 1. A schematic of the HR-VCHP configuration.[5]

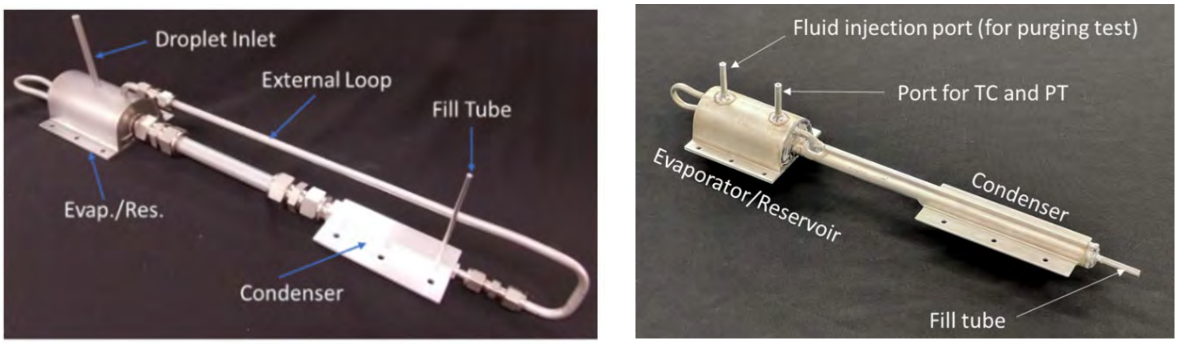

Figure 2. (a) Initial prototype developed in Phase I and (b) VCHP prototype developed in Phase II.[5]

This paper will present a compact HR-VCHP prototype description, reliability testing results, and the development status of two FDUs. In addition, the challenges associated with using high saturation pressure working fluids (e.g., propylene or ammonia) in the HR-VCHP are discussed.

II. Design of HR-VCHP FDUs

A. FDU I (Lunar Landers and Surface Systems)

FDU I is designed to be used as a passive thermal control device for future lunar landers and surface systems. The design will be similar to the Phase II prototype shown in Figure 2(b). The reservoir and the external NCG tube will be integrated with the heat pipe main body as shown in the CAD model below. The wick structure in the whole heat pipe consists of axial grooves fabricated by Electrical Discharge Machining (EDM). The VCHP envelope will be made out of aluminium. The working fluid can be ammonia or propylene. NCG can be helium or argon. The design requirements and specifications of FDU I are summarized in Tables 1-2.

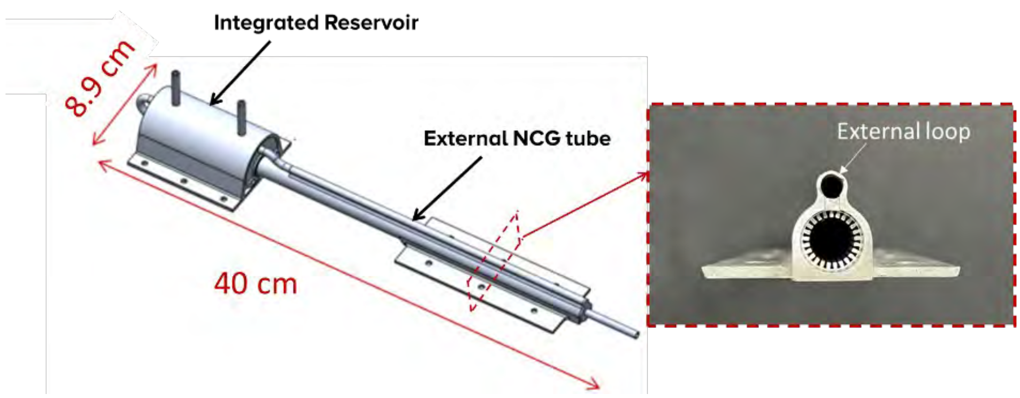

Figure 3. FDU I CAD model and sectional view.

Table 1. Design requirements of FDU I.

Nominal Power (W)	50
Nominal Operating Temperature (˚C)	50
Maximum Sink Temperature (˚C)	30
Minimum Sink Temperature (˚C)	-130
Payload Survival Temperature (˚C)	-40

Table 2. Specifications of FDU I.

Heat pipe evaporator length	10.16 cm (4 inches)
Adiabatic length	14.6 cm (5.75 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

Preliminary analysis shows that for minimum and maximum operating temperatures of -10˚C and 50˚C, the HR-VCHP will be able to efficiently transport the required nominal power whether propylene or ammonia is used as the working fluid (see Figure 4). Two orientation scenarios (i.e., 0˚ inclination and 10˚ against gravity) are considered in the heat transfer limit calculation in Figure 4. As expected ammonia provides significantly better thermal performance when compared to propylene in both horizontal and against gravity inclinations.

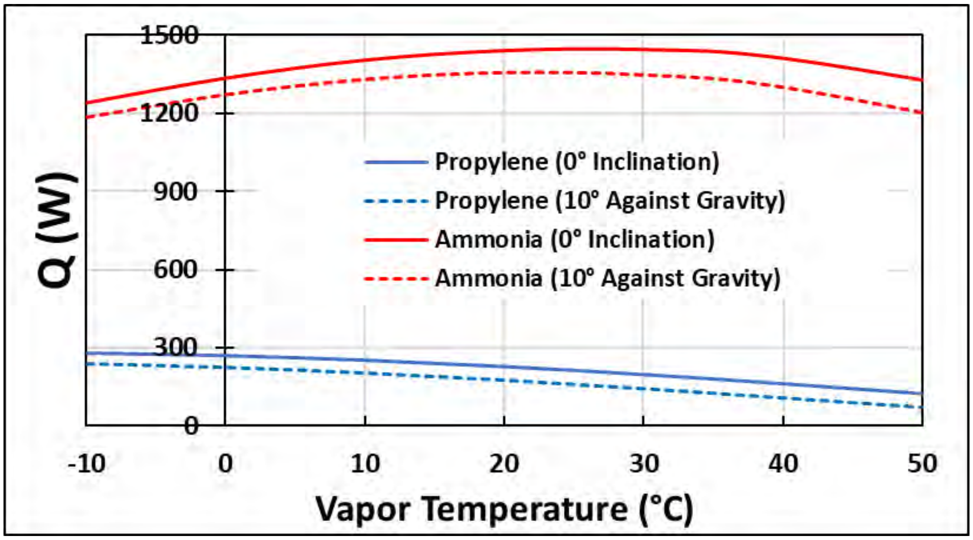

Figure 4. Heat transfer limit of FDU I, if propylene or ammonia is used as the working fluid, at different operating temperatures.

The operating temperature control range is calculated for FDU I (assuming the reservoir size is the same as that of the prototype developed under Phase II program “i.e., V_R=5.4V_c”). The following formula[7] represents a relation between the reservoir size, V_R, and the operating temperature control range, (ΔTv), at a certain nominal operating temperature and sink temperature range. That formula is derived based on the two extreme limits (i.e., fully-open and closed condenser). Please note that this formula is for hot reservoir VCHPs.

$$\frac{V_C}{V_R} = \left[\left(\frac{P_{v,max}-P_{s,max}}{P_{v,min}-P_{s,min}} \times \frac{T_{s,min}}{T_{v,max}}\right) - \frac{T_{s,min}}{T_{v,min}}\right] \quad (1)$$

where $T_{v,max}$ is the maximum operating temperature, $T_{v,min}$ is the minimum operating temperature, $T_{s,max}$ is the maximum sink temperature, $T_{s,min}$ is the minimum sink temperature, $P_{v,max}$ is the corresponding pressure at $T_{v,max}$, $P_{v,min}$ is the corresponding pressure at $T_{v,min}$, $P_{s,max}$ is the corresponding pressure at $T_{s,max}$, $P_{s,min}$ is the corresponding pressure at $T_{s,min}$. The maximum operating temperature is defined as $T_{v,max} = T_v + (\Delta T_v/2)$ while the minimum operating temperature is defined as $T_{v,min} = T_v - (\Delta T_v/2)$. For a reservoir volume of 5.4V_c, nominal operating temperature of 20˚C, and sink temperature that varies from -130˚C to 50˚C, the operating temperature control range (ΔT_v) can be calculated. Figure 5 shows the operating temperature control range for different working fluids under the same nominal operating temperature and sink temperature range. It can be seen that working fluids with lower saturation pressure provide better operating temperature control range. Please note that this analysis does not take into account the heat loss through the VCHP envelope.

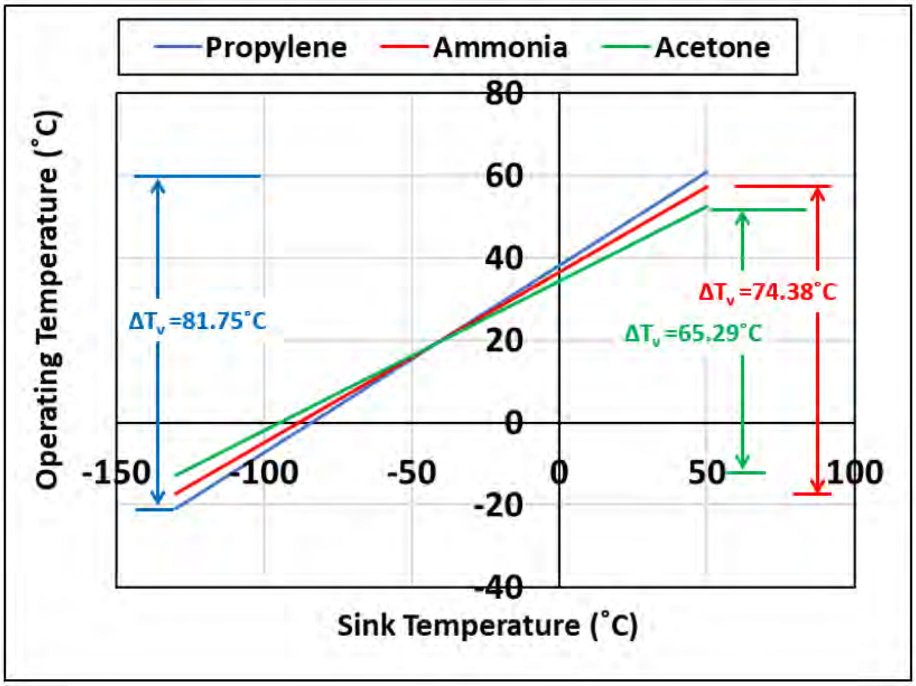

Figure 5. The operating temperature control range of FDU I under a certain nominal operating temperature and sink temperature range.

B. FDU II (Microgravity Testing on the ISS)

FDU II has the same overall design and dimensions as that of FDU I. However, FDU II will be made of copper. It would be challenging to have a determined interface between the NCG and working fluid in the condenser or the adiabatic sections when having a very high thermal conductive envelope material such as copper. Therefore, to minimize the heat losses via conduction when having very low sink temperatures (e.g., lunar night), the solid connection between the external NCG tube and heat pipe will be made thinner and will have holes or "*windows*" as shown in Figure 6. The design of FDU II is finalized and will be sent for fabrication. The reservoir and heat pipe will be fabricated by EDM. The fabricated parts will be assembled by brazing. The working fluid is water while the NCG is argon. Water is used for the ISS testing since it is not toxic nor flammable. In addition, other working fluids would need a lengthy safety approval process for usage on the ISS. The design requirements of FDU II are summarized in Table 3. Hybrid wick is considered for FDU II where the evaporator will have screens while the adiabatic and condenser sections will have axial grooves. Figure 6 shows the heat transfer limits of all-screens wick and all-grooves wick. It can be observed that both wick structures (either single wick type or hybrid) can easily satisfy the required power in Table 3. Generally, the HR-VCHP with axial grooves provides better thermal performance when compared to that with screen wick structure (Figure 7). For example, at an operating temperature of 50˚C, the heat transfer limit of the HR-VCHP with axial grooves is approximately twice that of the HR-VCHP with screen wick structure. Test results will be added to the final manuscript and will be presented at the conference.

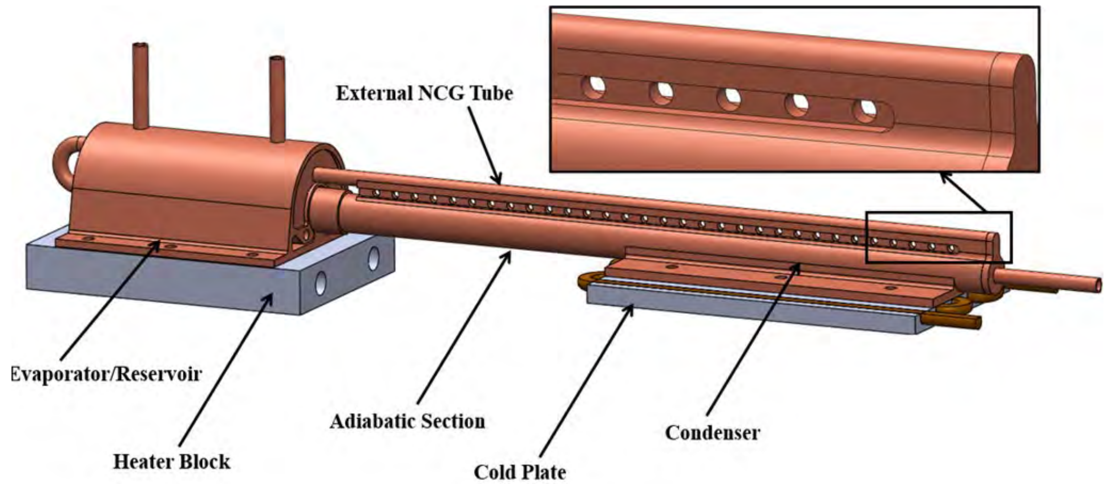

Figure 6. The CAD model of the FDU II design.

Table 3. Design requirements of FDU II.

Nominal Power (W)	100
Nominal Operating Temperature (˚C)	50
Maximum Sink Temperature (˚C)	20
Minimum Sink Temperature (˚C)	0
Payload Survival Temperature (˚C)	-10
Working Fluid	Non-toxic nor flammable

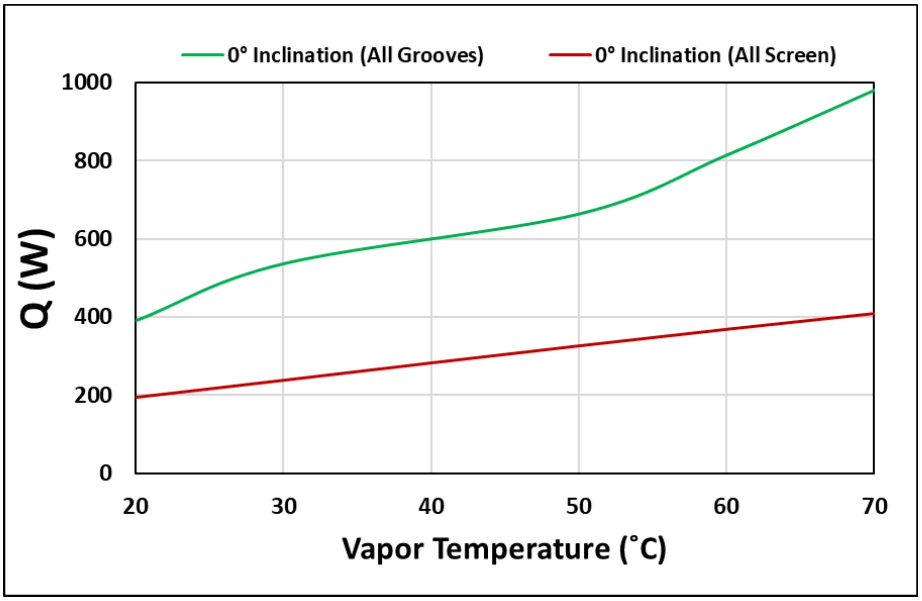

Figure 7. Heat transfer limit of FDU II, if water is used as the working fluid, at different operating temperatures.

Similar analysis is conducted to calculate the operating temperature control range for FDU II. The sink temperature control range for this case is from 0˚C to 20˚C. It was found that an operating temperature control range of 13.65˚C can be achieved. Please note that the sink temperature range has a significant effect on the operating temperature control range.

III. HR-VCHP Phase II Prototype Testing

While both FDUs are being fabricated, ACT continues performing testing on the aluminium HR-VCHP prototype developed under STTR Phase II program (shown in Figure 2(b) to predict the performance of FDU I since they are essentially similar. Successful purging and thermal control tests were achieved in a slightly against gravity orientation. The working fluid was toluene and acetone, and NCG was helium.[6] Figure 8 shows the experimental setup of the aluminum HR-VCHP, and the layout of 22 thermocouples. The objective of the new testing campaign is to demonstrate that (1) the VCHP can purge in gravity-aided orientation and (2) the VCHP can purge and startup using working fluids with higher saturation vapor pressure (e.g., propylene or ammonia).

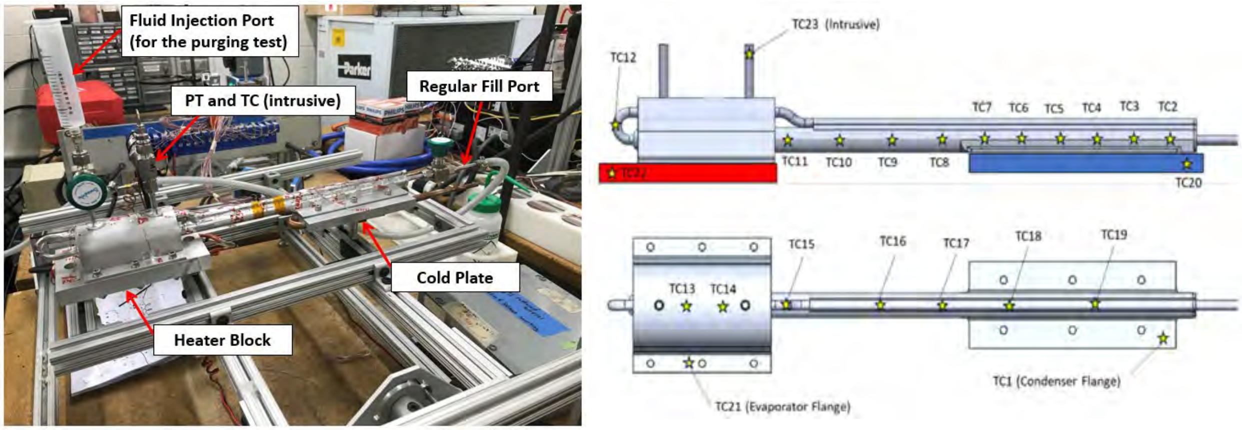

Figure 8. Experimental setup for the HR-VCHP purging test.

A. HR-VCHP Purging Test at Gravity-Aided Orientations

Figures 9-10 show an example of recent testing where a 5 cm^3 of acetone (a mass of about 4 g) was used as the working fluid. The first test was conducted to see whether a blockage, in the internal NCG tube, happens at different inclinations (see Figure 9). The pipe was initially positioned with 1° inclination and heated with 75 W of heat. The pipe reached a steady state. At t = 12,500 seconds, the inclination angle increased to 3°. The temperature difference (ΔT) slightly decreased, indicating that the pipe was slightly undercharged for 1° inclination. The inclination angle was increased incrementally from 3° to 75°. No blocking was observed. Vapor and NCG distributions were normal. The following test was performed to validate the purging performance at different orientations. The purging performance means the HR-VCHP's capability of removing any moisture in the reservoir, reconditioning, and reaching a steady state operation again. The purging test is conducted by injecting a small liquid amount of the working fluid (e.g., 0.5 cm^3) into the reservoir from the fluid injection port (see Figure 8) and then monitoring the temperature and pressure along the VCHP. Figure 10 shows the purging test results for a small inclination (< 5° inclination). First purging happened at t = 11,000 seconds with an inclination of 3°. It took 570 seconds to purge 0.1 cm^3 of liquid out from the reservoir. After the pipe reached a steady state, we increased the inclination to 5° and performed a 2nd purge where another 0.1 cm^3 of liquid acetone was injected. Similar purging time was observed.

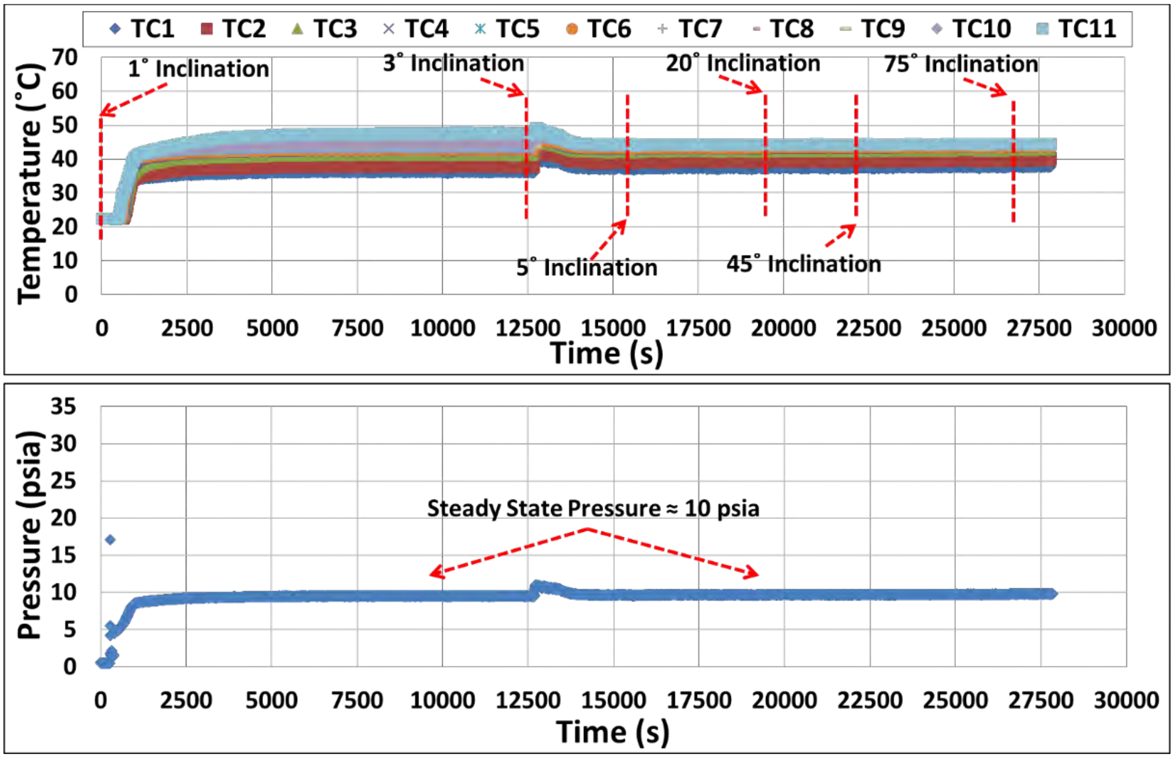

Figure 9. VCHP prototype operation at various inclination with a 5 cm^3 working fluid charge.

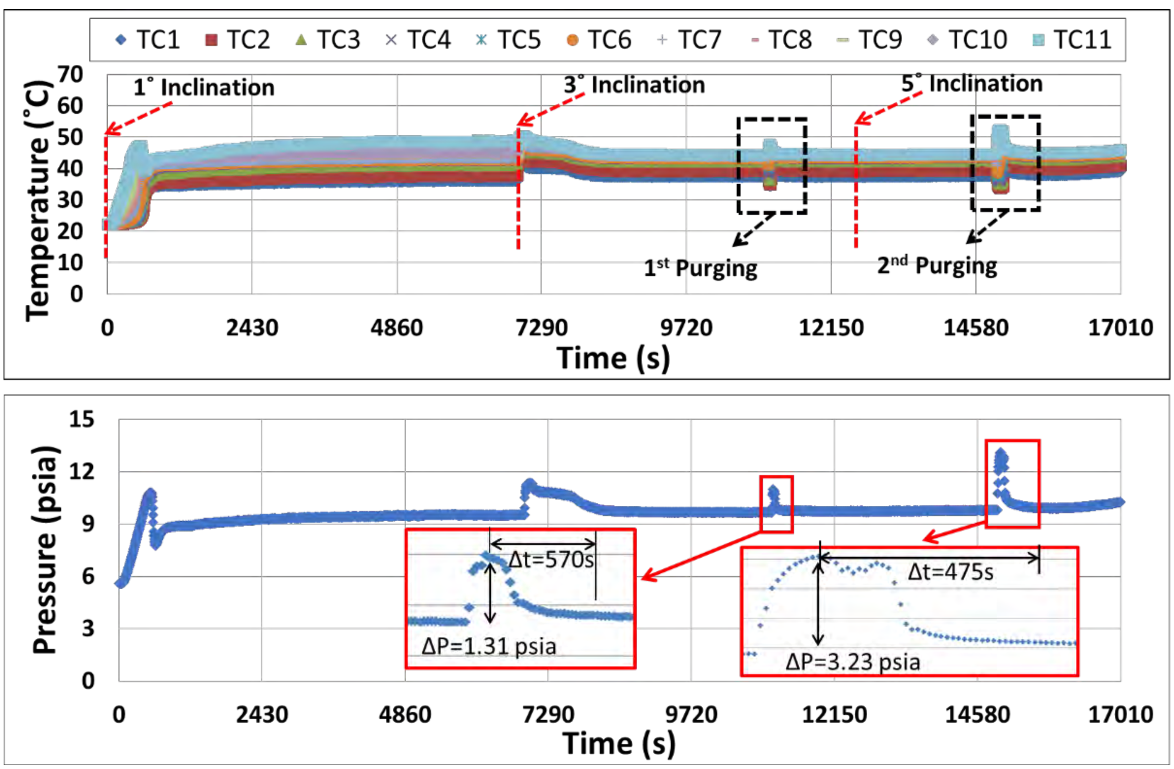

Figure 10. Purging test results at small inclination angles.

Figure 11 shows the purging test at a large inclination angle of 75°. Two purges with a 0.1 cm^3 working fluid addition were performed. As the figure shows, both purges were successful. It can be noted that the purging time at larger inclination angles is generally longer than that at small inclination angles. This is due to the adverse pressure gradient induced by the buoyancy force. It can be observed that, under regular operating conditions, the HR-VCHP takes around 18 min to reach the steady state condition from the startup (see Figures 9-11).

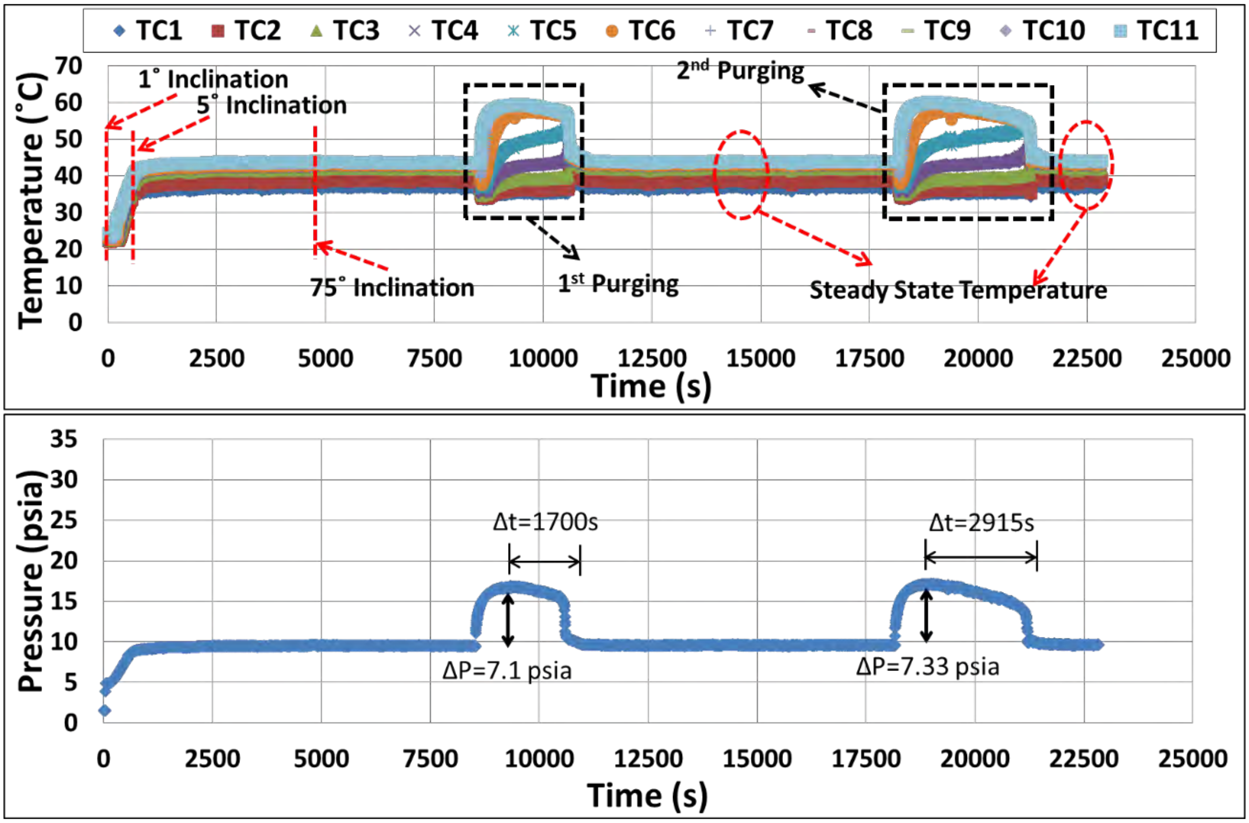

Figure 11. Purging test at large inclination angles.

B. HR-VCHP Thermal Control Test with High Vapor Pressure Working Fluid (Propylene)

Using propylene or ammonia as working fluid might result in a slower purge flow than acetone and toluene, mainly due to significantly higher vapor pressure, high density and high latent heat of vaporization. Table 4 below compares the kinetic energy (per unit volume), (K.E.), vapor density, (ρ_v), and operating temperature, (T), and pressure, (P), ranges of the acetone, toluene, water, propylene and ammonia. The kinetic energy is defined as:

$$K.E. = \frac{Q^2}{2h_{fg}^2 \rho_v A^2} \quad (1)$$

where Q is the power or heat rate, h_{fg} is the latent heat of vaporization, and A is the cross-sectional area of the vapor space in the heat pipe. It can be observed that the flow kinetic energy for both propylene and ammonia is an order of magnitude lower than acetone and toluene. When temperature increases, the kinetic energy further decreases and the pressure increases. Therefore, higher power and lower temperatures are selected for the next round of testing to recover as much kinetic energy as possible while having lower pressure values.

After preliminary testing, a power (heat rate input) of 125 W was selected for the thermal control testing. Figure 12 shows the transient temperature results, at different locations along the prototype, while gradually increasing the sink temperature from -85˚C to -19˚C. Please note that the power was kept constant at 125 W during the whole test. It can be seen that the temperature difference between the evaporator flange and heat sink decreases when the sink temperature increases. For example, the temperature difference is 64.5˚C and 31.4˚C when the sink temperature is -85˚C and -19˚C, respectively. The evaporator's temperature was passively maintained at ±16.2˚C while the sink temperature increased by 66˚C. As shown in Figure 12, no noticeable spatial temperature variation is observed along the adiabatic section (e.g., the temperature readings of TCs 8-11 at adiabatic section are almost the same).

Table 4. Vapor density, pressure, and kinetic energy values of acetone, toluene, propylene, and ammonia at different operating temperatures based on 75 W inputs and heat pipe ID 10.16 mm.

	Acetone			Toluene			Water		
T (˚C)	ρ_v (kg/m^3)	P (bar)	K.E. (Pa)	ρ_v (kg/m^3)	P (bar)	K.E. (Pa)	ρ_v (kg/m^3)	P (bar)	K.E. (Pa)
-50	0.01	0.003	115.01	0.0007	0.0001	2547	-	-	-
0	0.24	0.093	5.67	0.036	0.009	63.46	0.0048	0.006	14.2
40	1.31	0.566	1.21	0.28	0.079	9.32	0.051	0.074	1.44
	Propylene			Ammonia					
T (˚C)	ρ_v (kg/m^3)	P (bar)	K.E. (Pa)	ρ_v (kg/m^3)	P (bar)	K.E. (Pa)			
-50	2.13	0.91	1.026	0.38	0.41	0.56			
0	12.35	5.86	0.243	3.45	4.29	0.078			
40	35.71	16.52	0.13	12.03	15.55	0.029			

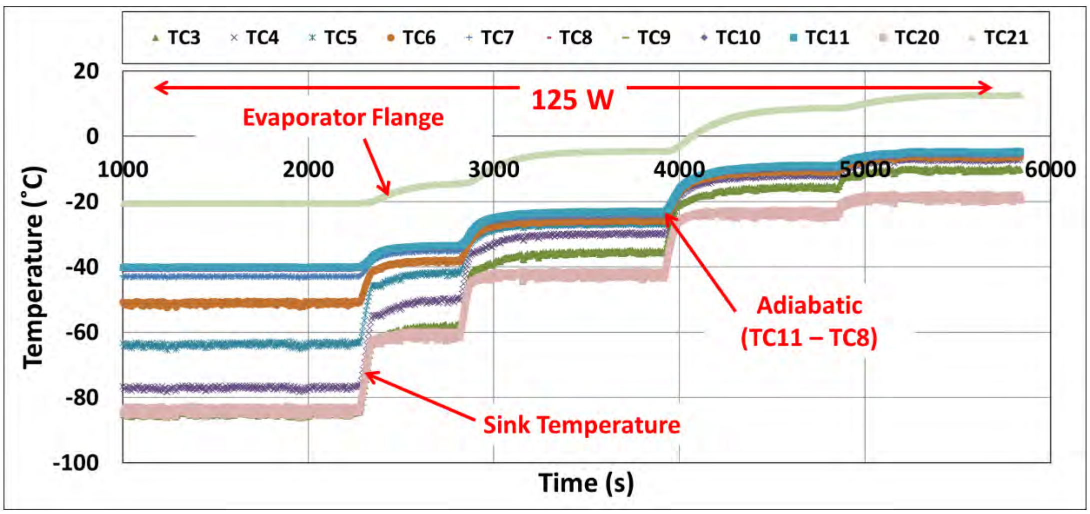

Figure 12. Thermal control testing results. 125W constant heat input was applied while the sink temperature was gradually increasing from -85˚C to -19˚C.

C. HR-VCHP Start-up Test with High Vapor Pressure Working Fluid (Propylene)

The most important objective of the developed FDUs is their ability to remove any moisture (e.g., NCG moisture or liquid working fluid) from the reservoir and quickly go back to normal operating conditions (i.e., purging) to avoid drastic increases in the evaporator temperature which may burn the electronic device that is being thermally controlled in the lunar lander. When acetone was used as the working fluid, the purging test was performed by intentionally injecting small known amounts of liquid acetone into the reservoir (see Figures 10-11). However, it would be challenging to control the amount of propylene injected into the reservoir since it will not stay as a liquid in ambient condition. As an alternative (as well as more close to the actual scenario), the following startup procedure was implemented to demonstrate propylene purging from the reservoir:

- Charged VCHP with designed amount of propylene and NCG (helium) and let the VCHP sit in ambient for over night, letting diffusion to create an uniform distribution of vapor/NCG mixture.
- Applied cooling to the HR-VCHP (e.g., a sink temperature of -50˚C) for more than 20 mins. This step is to ensure that an amount of liquid propylene can be formed within the reservoir. For quicker procedure, cooling can be applied to the reservoir as well.

- Heat was applied at the evaporator (125 W) while maintaining the same cooling condition at the condenser.

Figure 13 shows an actual example where the prototype was able to passively remove the naturally-formed moisture in the reservoir. After starting up the VCHP, it is observed that, during the first 30 min, the prototype started to experience a purging behavior (at t=1700 seconds) where the temperature difference between the evaporator and reservoir suddenly decreases. The VCHP reaches a new steady state condition (see Figure 13) within 200 seconds. The power and sink temperature were kept unchanged during that time period shown in Figure 13. Figure 14 shows the corresponding transient pressure results during the purging process. It can be seen that the VCHP took around 874 s (14.5 min) to startup and reach the steady state condition. It is difficult to experimentally evaluate the purging rate since the moisture amount is unknown. Figure 15 shows the thermal control capability of the propylene VCHP after experiencing the purging behavior. It can be seen that it successfully functioned after removing the moisture from the reservoir.

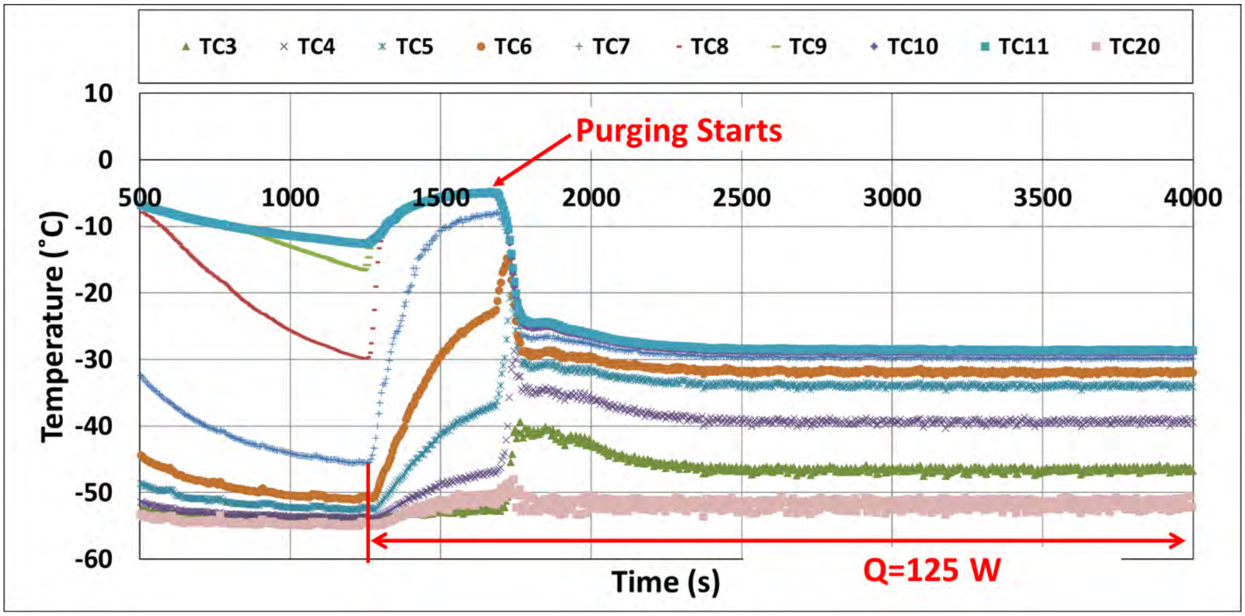

Figure 13. Transient temperature results during a purging behavior at a heat rate input of 125 W and sink temperature of -52˚C.

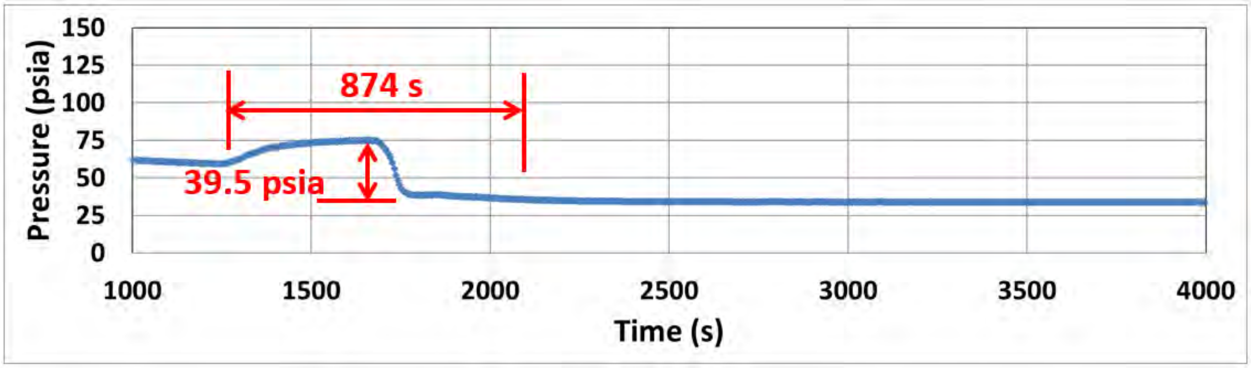

Figure 14. Transient pressure results during a purging behavior at a heat rate input of 125 W and sink temperature of -52˚C.

Figure 16 shows the kinetic energy and pressure values of some successful and unsuccessful purging tests for different working fluids. Please note that these data only represent whether the HR-VCHP was able to purge or not. As discussed above, it can be seen that the ability to purge depends on two main factors, kinetic energy which depends on the fluid properties (mainly vapor density) at the operating temperature and the pressure at that operating temperature. It can be seen that, for toluene and acetone, the purging was successful, even though the operating temperature was high, due to the relatively low vapor density and low pressure. On the other hand, for propylene, purging was only successful, with lower kinetic energy value when compared to that of acetone or toluene, at very low operating temperature (e.g., -28˚C) since propylene has much higher pressure and vapor density. It was observed that, approximately, for operating temperatures larger than -28˚C, the VCHP was not able to startup and remove the naturally formed moisture in the reservoir. In order to validate that speculation, acetone was tested at a higher operating temperature to reach high saturation pressure in order to mimic the conditions of the unsuccessful purging test of propylene. It was found that the HR-VCHP was not able to purge when acetone was tested at such high pressure and temperature (Figure 16). These results support the speculation that there is a limit where the HR-VCHP cannot purge (e.g., when the kinetic energy is very low, e.g., <0.5 Pa, and the pressure is high, e.g., >5 bars). During the unsuccessful purging (startup), at those limits (i.e., very low kinetic energy and high pressure), the evaporator's temperature suddenly increases significanlty resulting in a spike in the pressure as well. Based on the kinetic energy analysis and the test results, the following approaches can increase the kinetic energy:

- When using high saturation pressure working fluids such as propylene or ammonia, the HR-VCHP needs to work at low operating temperatures.
- Decrease the heat pipe diameter to accelerate the flow after the internal NCG tube's tip to increase the purging pressure.

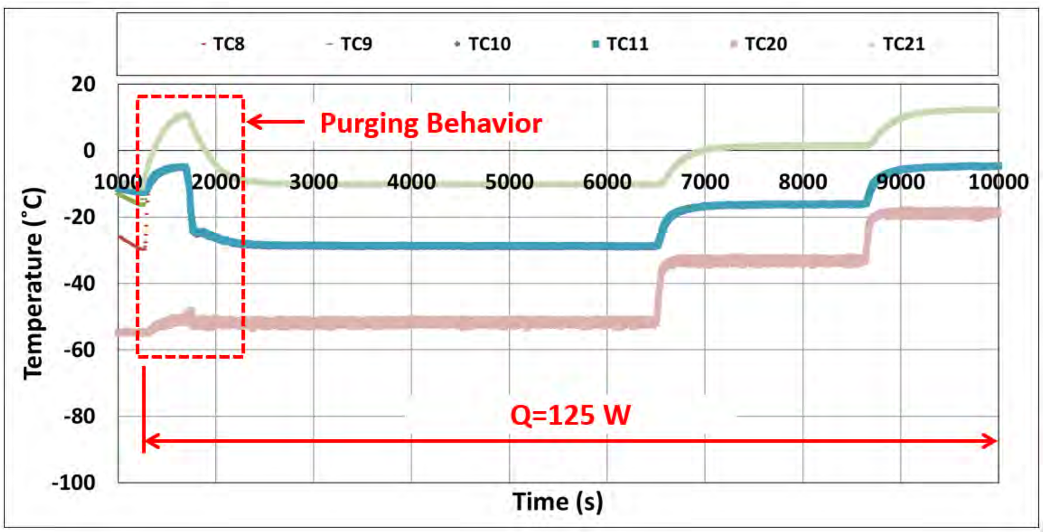

Figure 15. Thermal control testing after the occurrence of the purging behavior.

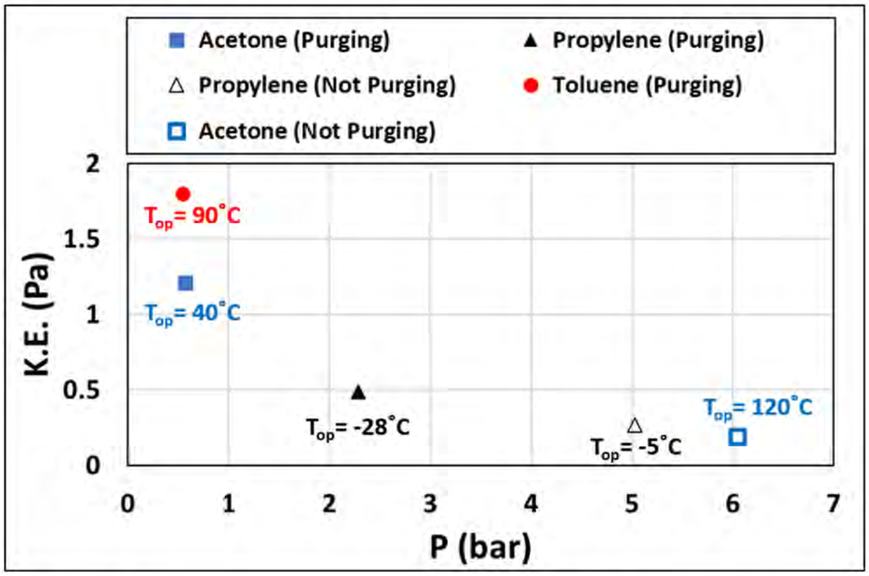

Figure 16. Kinetic energy and pressure values of successful and unsuccessful purging tests. Please note that helium was used as the NCG in all the tests. Solid symbols mean successful purging tests while open symbols mean unsuccessful purging tests.

IV. Conclusions

ACT in collaboration with CWRU is developing two HR-VCHP FDUs. FDU I is potentially planned to be used for near-future lunar landers while FDU II is planned to be used for microgravity testing on the International Space Station (ISS). The current design significantly improves the reliability and thermal control ability of the HR-VCHP. This paper presents the recent development activities of two HR-VCHP FDUs and testing results of the VCHP prototype developed under Phase II. The conclusions are summarized below.

- The aluminum HR-VCHP showed successful reliability tests (i.e., purging tests) under different orientations, injection amounts, and working fluids. For example, when the acetone/helium mixture is used, at an orientation of 5˚, the HR-VCHP was able to remove the injected liquid acetone amount (0.1 cm^3) from the reservoir and went back to the steady state operating conditions in about 8 min. Furthermore, at an orientation of 75˚, the purging time of the first purge was about 28 min while the purging time of the second purge was about 48 min.
- The aluminum HR-VCHP was observed to be functioning improperly during the first set of tests when propylene is used as the working fluid. A great deal of effort was dedicated to the troubleshooting process. Using higher power and lower sink temperatures seem to be a potential solution. Successful thermal control and startup testing was achieved when using propylene. The HR-VCHP was able to passively remove moisture from the reservoir during the startup process.
- The VCHP design analysis shows that for minimum and maximum operating temperatures of 20˚C and 70˚C, FDU II will be able to efficiently transport heat of up to 378 W and 950 W, respectively.
- The design phase of FDUs has been completed. Both FDUs are being fabricated. Some of the testing results of the two FDUs will be added to the final manuscript and presented at the conference.

Acknowledgments

This project is sponsored by NASA Marshall Space Flight Center (MSFC) under an STTR Phase III (Contract# 80NSSC22CA242) program and an STTR Phase II (Contract# 80NSSC20C0023) program. We would like to thank the program managers, Dr. Jeff Farmer and Mr. William Johnson for support and valuable discussions during the program. In addition, special appreciation goes to Philip Texter who has provided significant technical contributions to this project.

References

[1]Tarau C., Schwendeman C. L., Schifer N.A., Polak J. and Anderson W.G., "Optimized Back up Cooling System for the Advanced Stirling Radioisotope Generator", in *International Energy Conversion Engineering Conference (IECEC)*, 2015

[2]Tarau C., Schwendeman C.L., Anderson W.G., Cornell P.A. and Schifer N.A., "Variable Conductance Heat Pipe Operated with Stirling Convertor", in *IECEC, 2013*

[3]Tarau C. and Anderson W.G., "Variable Conductance Thermal Management System for Balloon Payload", *in 20th AIAA Ligher-Than-Air Systems Technology Conference*, 2013

[4]Lee K-L., Tarau C., Lutz A., Anderson W.G., Huang C-N., Kharangate C. and Kamotani Y., "Advanced Hot Reservoir Variable Conductance Heat Pipes for Planetary Landers", *in 50th International Conference on Environmental Systems (ICES)*, 2020

[5]Lee K-L., Tarau C., Adhikari S., Anderson W.G., Kharangate C., Huang C-H., Kamotani Y., "Hot Reservoir Variable Conductance Heat Pipe with Advanced Fluid Management" *in 51th International Conference on Environmental Systems (ICES)*, 2021

[6]Lee K-L., Tarau C., Anderson W.G., Huang C-H., Kharangate C., Kamotani Y., "Integrated Hot Reservoir Variable Conductance Heat Pipes with Improved Reliability" *in 52th International Conference on Environmental Systems (ICES)*, 2022

[7]Marcus B.D., "Theory and design of variable conductance heat pipes" *NASA-CR-2018*, 1972