24 Hours Consumable-based Cooling System for Venus Lander

Kuan-Lin Lee[1], Calin Tarau[2]*
Advanced Cooling Technologies, Inc., Lancaster, PA, 17601

To support NASA future Venus in-situ exploration missions, Advanced Cooling Technologies, Inc (ACT) is developing a Venus Lander thermal management system based on a cooling concept that uses venting of consumable fluids. This system will allow at least 24-hours of operation on Venus surface in the high temperature (460°C) and high pressure (~92 bar) environment. The consumable-based cooling system will reject both the electronics waste heat generated inside the vehicle as well as the incoming heat leaks from the hot Venus environment. The system consists of two pressure vessels (primary vessel and compressed gas vessel) and a network of flow channels that are embedded within the lander's structure for environmental heat guarding. The primary vessel will be charged with working fluid (ammonia) at saturation that is further pressurized by compressed gas (e.g. helium), such a way that the resulted fluid mixture can be vented into the environment at a pressure higher than the saturation pressure of the coolant that corresponds to the temperature of the payload. The venting will provide effective refrigeration of the electronics. In addition, as the vented fluid mixture travels through the heat guarding system, it can further collect environmental heat as sensible heat and exit into the Venus environment. This paper presents the feasibility study performed under a NASA SBIR program, that includes mathematical modeling and proof-of-concept prototype development.

Nomenclature

A	=	surface area of the primary vessel
h_i	=	enthalpy of components (v: vapor, l: liquid, g: gas)
h_{fg}	=	latent heat of vaporization
h_{IN}	=	enthalpy of compressed gas entering primary vessel
h_{OUT}	=	enthalpy of compressed gas leaving primary vessel
$\hat{h}_{loss}$	=	parasitic heat loss heat transfer coefficient
m_i	=	mass of components (v: vapor, l:liquid, g: gas)
mCp	=	equivalent thermal mass of the fluid and vessel
P	=	total pressure within the primary vessel
P_g	=	partial pressure of compressed gas
P_v	=	partial pressure of working fluid vapor
$\dot{Q}_{in}$	=	net heat input applied to the primary vessel
$\dot{Q}_{elec}$	=	total (electrical) power applied to the heater
T	=	temperature
T_0	=	initial liquid temperature for hypotherical temperature variation calculation (Eq. (7))
t_0	=	initial time for hypotherical temperature variation calculation (Eq. (7))
Δt	=	time duration of heat acquisition (Eq. (6))
ρ_i	=	density of components (v: vapor, l: liquid, g: gas)

I. Introduction

Venus in-situ exploration has been ranked as one of the highest priorities for future inner solar system studies [1]. Howerver, the extremely hostile Venusian environment presents significant challenges in designing of the thermal management system for a Venus lander. The Venus surface temperature can be as high as 460°C and the atmospheric pressure can be around 92 bar (1334 psi), making it extremely difficult to reject the waste heat generated

[1] R&D Engineer, Defense & Aerospace Products Group, 1046 New Holland Ave.
[2] Principal Engineer, Defense & Aerospace Products Group, 1046 New Holland Ave.

by the electronics inside a lander. To date, the longest survival duration on Venus surface was achieved by the Russian Venera lander 13 (127 minutes) by using Phase Change Material (PCM) to absorb the payload waste heat, and multi-layer insulation (MLI) to mitigate the incoming heat leaks from the environment [2] [3]. Future NASA Venus surface exploration missions request a light-weight and highly reliable thermal management technology that will enable at least 24-hour survival and operation of a Venus lander on the planatory suface.

Since the development of Venera lander 8 in 1972, PCM has been consistently included in the Venus lander thermal management system as a primary heat sink to absorb the heat load of the electronics. The PCM typically used for internal heat loads storage is lithium salts ($LiNO_3$), which has roughly a latent heat of fusion of 296 kJ/kg. The insulation against external heat leaks was MLI or aerogel. They were commonly applied on both interior and exterior surfaces of the Venus lander shell structure. A water shell structure based concept was proposed in the report of a Flagship mission described in [3]. Their trade study on a 0.9 m diameter Venus lander design shows that at least 45 kg of Lithium Nitrate, 50kg of water shell and 110kg of porous silica insulation layer are required to maintain the internal payload temperature under 88°C with an average heat load at 210W for 24 hour. Another concept for Venus lander cooling is by venting two-phase coolant (ammonia) into Venus ambient. The major challenge of venting ammonia vapor into Venus ambient is that the ammonia saturation vapor pressure at the payload set point (70°C) is not enough to overcome the high pressure on Venus environment. Therefore, the evaporative cooling of ammonia venting is only used to reject the incoming environmental heat leaks, maintinaing the lander shell temperature at 121°C while the payload waste heat inside the lander is cooled by senible heat of liquid ammonia from 0 to 70°C [4].

In order to address this thermal design challenge, Advanced Cooling Technologies, Inc. (ACT) developed an innovative cooling concept that is based on venting of consumable fluids into an environment with higher pressure than the vapor pressure that corresponds to the temperature of payload. This paper presents the feasibility study conducted under an SBIR Phase I program to develop a Venting-based cooling sytem for 24 hours-life Venus landers.

II. Consumable-based Cooling Concept

Figure 1 shows the thermal management system for Venus landers based on the proposed venting cooling concept, which can be divided into two subsystems: a venting-based refrigeration system to reject the internal heat load and a heat guarding system to manage the incoming enviornemntal heat leaks.

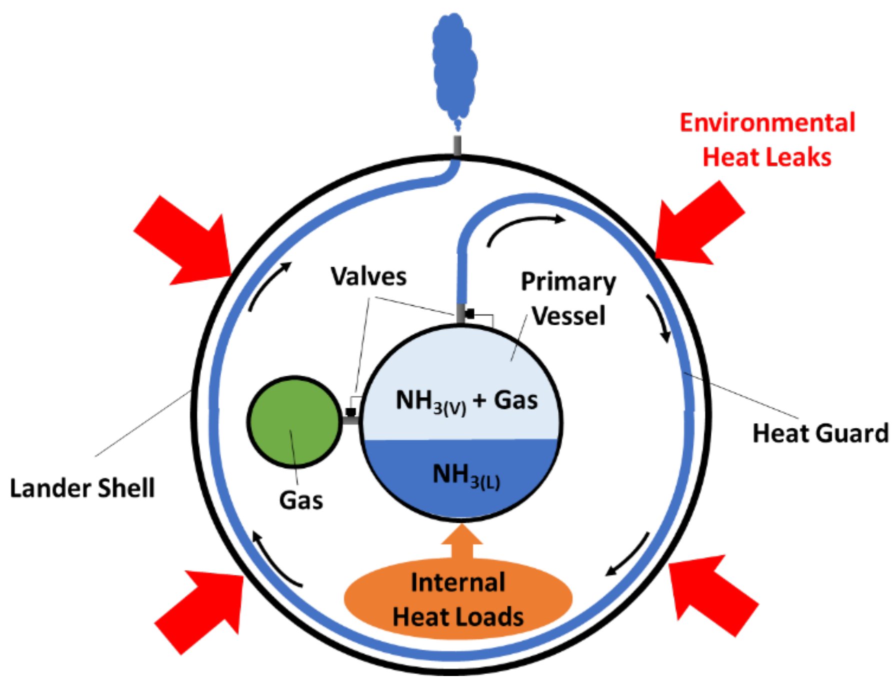

Figure 1. Venus lander thermal management system with consumable-based cooling

Venting-based Refrigeration System

The venting-based refrigeration system consists of two pressurized vessels (shown in Figure 1), the primary vessel (blue vessel) and the secondary vessel (green vessel). The primary vessel will contain two-phase working fluid where the vapor will be mixed with a secondary species (i.e. compressed gas such as argon or helium) that serves as pressurizer. The secondary vessel will contain only the compressed gas, initialy at a much higher pressure (~ 400 bar). The role of the secondary vessel is to pressurize the primary vessel, so that the total pressure consisting of working fluid vapor pressure at saturation and gas partial pressure is higher than the environmental pressure. As Figure 1 shows, internal heat load of payload will be transferred to the primary vessel through thermal links (heat pipes, thermal straps,other…) to vaporize the working fluid within the vessel. Two valves will be used to control system pressure and temperature. A venting valve will be mounted on the top of the primary vessel to control venting of the consumable fluid mixture. Another valve will be installed between the two pressure vessels to control recharging of the primary vessel with compressed gas. This system will operate in cycles:

1. *Heat Acquisition*

Heat load from electronics will be transfered to the primary vessel to vaporize the working fluid liquid. Vapor density will increase and so the total pressure within the primary vessel.

2. *Venting*

As the temperature of the primary vessel reaches the set point and the total pressure is higher than the Venus ambient, the venting valve will be opened. The mixture of the saturated consumable fluid and the compressed gas will be ejected, causing a sharp decrease of the total pressure. The reduction of the internal pressure make room for a new compressed gas charge.

3. *Gas Recharging and Evaporative Cooling*

After venting the consumable mixture, the primary vessel needs to be re-charged for next venting, which will be accomplished by opening the gas refill valve between two pressure vessels. As the valve opens, the compressed gas at much higher pressure will flow into the primary vessel collecting vapor from liquid phase and inducing evaporative cooling within the liquid pool. Once the internal pressure reaches the set point, the gas refill valve will be closed again.

Heat Guarding System

The consumable fluid mixture (working fluid vapor + compressed gas) leaving the primary vessel will be at payload set point (~70°C). Before being ultimately vented into Venus ambient at 460°C, there is a significant amount of sensible heat capacity which can be used to absorb incoming environmental heat leaks and then vented away. The flow paths (tubing) embedded within the lander structure that will allow the consumable fluid to collect incoming environmental heat leaks and ultimately rejected into the ambient is referred as the "heat gurading system". The heat guarding design resulted from the presented concept is the object of futher development and optimization. The current status however, is not presented in this paper.

III. Prototype Development

This research is to demonstrate that by addition of a secondary species (compressed gas) into a primary vessel that contains working fluid at saturation, the resultant fluid mixture can be vented into an environment that has a higher pressure than the working fluid vapor pressure corresponding to the set point. The work includes theoretical anlaysis, proof-of-concept prototype development and experimental measurement. For theoretical analysis, a thermodynamics-based model was established to describe the venting-based cooling process stated above and predict the required mass of both speices to achieve 24 hours operation. For experimental work, a proof-of-concept prototype was built and tested with several consumable fluid pairs (i.e. working fluid and compressed gas). The prototype was first tested with water as working fluid due to safety concerns and the easiness of handling. Later, the prototype was tested with ammonia as the working fluid, which will be used in actual applications (i.e. Venus lander). Parts of this research is to identify the beneficial characteristics of compressed gas for this application. Two inert gases (argon and helium) were tested and helium appeared to be the best choice due to its low density and high specific heat.

A. Mathmatical Model Development

A mathematical model for consumable-based refrigeration concept was developed based on thermodynamics laws. As Figure 2 shows, consumable-based cooling operation can be divided into three consecutive stages: heat acquisition, consumable fluid venting and compressed gas recharging. The corresponding thermodynamics states of each components (vapor, liquid and gas) at different stages such as temperature, pressure, density and enthalpy are calculated by solving a set of governing equations (conservation of mass, volume and ethanlpy). For example, during the heat acquisition process, fluid mass (liquid and vapor phases) and compressed gas mass within the primary vessel are conserved. The thermodynamics states (density and enthalpy) of liquid and vapor phases are determined by single variable (i.e. temperature) since they are in the satuation state. The thermodynamic states of compressed gas are determined by two variables (partial pressure of compressed gas and temperature). Based on Dalton's law, total pressure within the primary vessel consists of vapor saturation pressure and compress gas partial pressure. With given initial fluid and gas mass before heating (state 1), heat input ($\dot{Q}_{in}$) and the set point for venting (T_2), mass of vapor (m_{v2}) and liquid phases (m_{l2}), total venting pressure (P_2) and partial pressure of gas (P_{g2}) and duration of heating (Δt) can be determined by solving following equations.

$$m_{v1} + m_{l1} + m_{g1} = m_{v2} + m_{l2} + m_{g2} \quad \text{(total mass balance)} \quad (1)$$

$$m_{g2} = m_{g1} \quad \text{(gas mass balance)} \quad (2)$$

$$\frac{m_{v1}}{\rho_v(T_1)} + \frac{m_{l1}}{\rho_l(T_1)} = \frac{m_{v2}}{\rho_v(T_2)} + \frac{m_{l2}}{\rho_l(T_2)} \quad \text{(total volume balance)} \quad (3)$$

$$P_2 = P_v(T_2) + P_{g2} \quad \text{(Dalton's law)} \quad (4)$$

$$\frac{m_{v2}}{\rho_v(T_2)} = \frac{m_{g1}}{\rho_g(P_{g2}, T_2)} \quad \text{(gas volume balance)} \quad (5)$$

$$m_{v1}h_v(T_1) + m_{l1}h_l(T_1) + m_{g1}h_g(P_{g1}, T_1) + \dot{Q}_{in}\Delta t = m_{v2}h_v(T_2) + m_{l2}h_l(T_2) + m_{g1}h_g(T_2) \quad \text{(energy balance)} \quad (6)$$

Similar governing equation sets were established and solved for other two processes (venting and compressed gas recharging) to determine temperature, total and partial pressure within the vessel, mass of liquid, vapor and compressed gas within the vessel and corresponding thermodynamics states (density and enthalpy) at each stages. The venting mass of both species versus time can be calculated through iteration. Modeling results were validated by comparision with the proof-of-concpet prototype testing results.

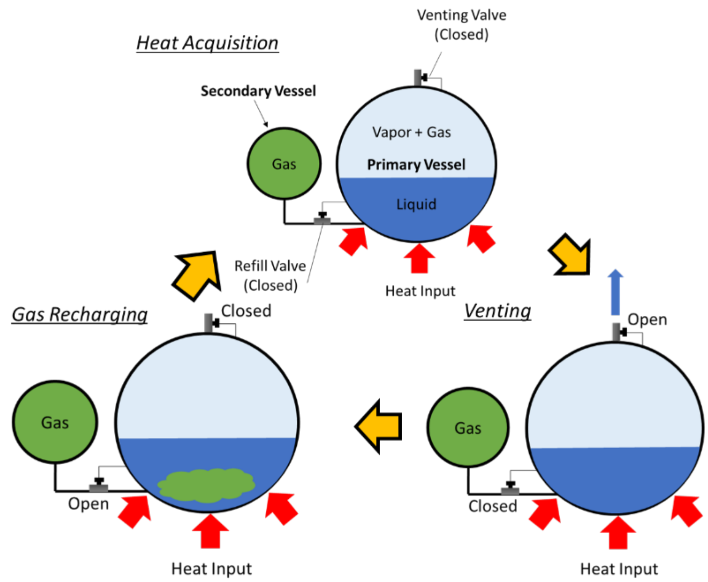

Figure 2. Venting-based refrigeration operation cycle

B. Proof-of-Concept Prototype Design and Testing

A venting-based cooling system prototype was designed and built to demonstrate concept feasibility. Due to various constrains in Phase I (budget, time, safety, complexitiy etc.), instead of 92 bar (~1300 psi) as Venus ambient, the proof-of-concept prototype was designed to vent into a lower pressure enviornement set at 110 ±10 psi (7.6 ± 0.7 bar). The net heat load 100W was continuously applied to the primary vessel for 3 hours to simulate the waste heat of payload inside the lander. The experimental results were be used to validate the mathematical model, which was further used to predict the full scale design operating in Venus conditions.

Two working fluids were tested: water with a set point of 147ºC and ammonia with a set point of 8.8ºC. The corresponding vapor pressure curves are shown in Figure 3 (a) and (b). Water saturation pressure at the set point of 147 ºC (purple dashed line) is 62 psi (~ 4.3 bar), which is lower than the environment pressure chosen as 110 psi (~7.6 bar). To fill up the gap between the environmental pressure and the saturated vapor pressure that corresponds to the set point, a compressed gas (e.g. argon or helium) was charged into the primary vessel to increase the total pressure to 150 psia (~10.3 bar) as shown as the red dashed line in Figure 3 (a), so venting can occur. Similary for ammonia tesing (Figure 3 (b)), vapor pressure at set point (8.8ºC) is 82 psi (5.7 bar) which is also lower than the environmental pressure of 110 psi (7.6 bar), so a compressed gas (helium) was added into the primary vessel to increase the total pressure to 150 psia (10.3 bar) for venting.

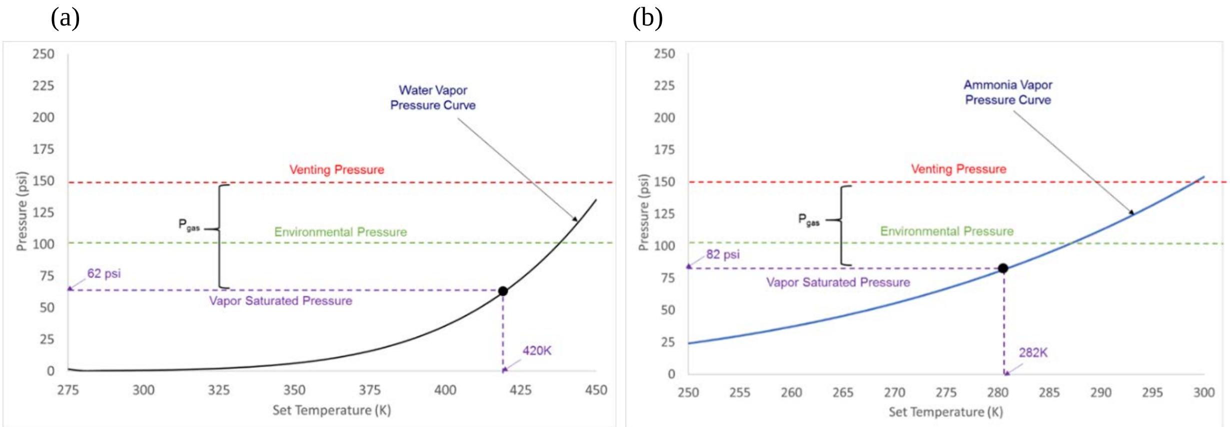

Figure 3. Operating conditions for proof-of-concept prototype (a) water as working fluid (b) ammonia as working fluid

A system diagram of the proof-of-concept prototype (using water as working fluid) is shown as Figure 4. In addition to the primary vessel and secondary vessel (i.e. compressed gas cylinder), a third pressured vessel called "Environmental Pressure Simulator (EPS)" was introduced to create a high pressure environment for the consumable fluid mixture to be vented in. Pressure within the EPS vessel is maintained at the constant level of ~110 psi (7.6 bar) by a pressure relief valve. T-type thermocouples and pressure transducers were installed in various locations of the system for temperature and pressure measurements. The venting valve and gas refill valve were controlled manually by tracking liquid temperature and pressure in the primary vessel. A fiberglass standard tape heater was wrapped around the primary vessel to simulate the heat load. The testing procedure is summarized as follows:

1. Pressurize EPS vessel (yellow vessel in Figure 4) to 110 psi (7.6 bar) via gas bypass line.
2. Charge working fluid into the primary vessel
3. Heat up the primary vessel until liquid temperature reaches set point (or slightly under)
4. Open gas refill valve to charge compressed gas into the primary vessel to rise total pressure to 150 psi (10.3 bar)
5. Apply 100W of net power input and start venting operation
6. Open the venting valve when liquid temperature exceeds the set point
7. Shut the venting valve when the primary vessel pressure drops below 118 psi (~8.1 bar)
8. Open the compressed gas refill valve to recharge the primary vessel back to nominal pressure of 150 psi (10.3 bar)
9. Repeat steps 6 through 8 for 3 hours

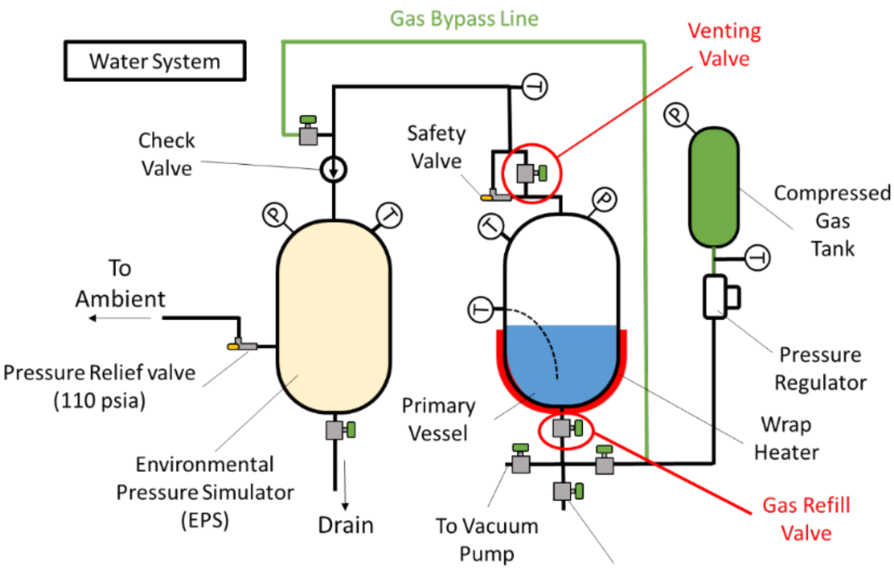

Figure 4. Proof-of-concept prototype system diagram (with water as working fluid)

Figure 5. Photograph of proof-of-concept system

IV. Proof-of-concept Prototype Testing Results

A. Water Test Results

Figure 6 shows the working fluid (liquid) temperatue measured during 3 hours of operation with 100W of net heat input. It can be seen from temperature data that liquid temperature (blue solid line) was successfully maintained below the set point temperature (420±1K) for 3 hours through venting. The effectiveness of consumable-based cooling can be observed by comparision with a hypothetical liquid temperature (yellow dashed line) in Figure 6, which was calculated by solving the differential equation below where mCp and $\hat{h}_{loss}$ are the equivalent thermal mass of the fluid and vessel and the parasitic heat loss from the primary vessel to the environment at set point, which were carefully determined through calibration testings. $\dot{Q}_{elec}$ is the total (electrical) heat applied to the tape heater. As shown in Figure 6, without venting-based cooling, liquid temperature will eventually reach 475K (202ºC) after 3 hours of 100W of heating.

$$mCp\frac{dT}{dt} = -\hat{h}_{loss}A(T - T_\infty) + \dot{Q}_{elec}$$

$$T = T_0 \; at \; t = t_0 \tag{7}$$

Mass consumption of water and argon is shown in Figure 7(a). After 3 hours of venting, the remaining working fluid within the primary vessel was collected from the drain and weighted to determine total working fluid mass that being vented out. The consumption of compressed gas was calculated by measuring the pressure differences of the compressed gas tank before and after tesing. The system vents a total mass of 1.49 kg of consumable fluid which consists of 0.38 kg of water and 1.11 kg of argon. When compared with model predictions (solid lines plotted in Figure 7(a)), it can be seen that the analytical model described in Sec.III.A can predict the vented mass (both total and components) reasonably accurate. Heat rejection performance can be further shown by the following energy analysis.

- Net heat input for 3 hours operation:

  $$90.6W \times 10916s = 989\ kJ$$

- Heat removed by argon sensible heat:

  $$1.11 \text{ kg} \times (h_{OUT} - h_{IN}) = 88.2\ kJ \text{ (8.91\% of the net heat input)}$$

- Heat removed by water latent heat:

  $$0.38 \text{ kg} \times h_{fg} = 802.7\ kJ \text{ (80\% of the net heat input)}$$

Where h_{OUT} and h_{IN} are the enthalpy of compressed gas leaving and entering, respectively, the primary vessel, which can be calculated by temperature and pressure data. Energy analysis shows that more than 80% of thermal energy input is removed by two-phase working fluid through vaporization and only 8.91% of heat is removed by the argon sensible heat. The remaining 11% of energy necessary to close the balance may be due to measurement errors, heat loss estimation and calculation errors.

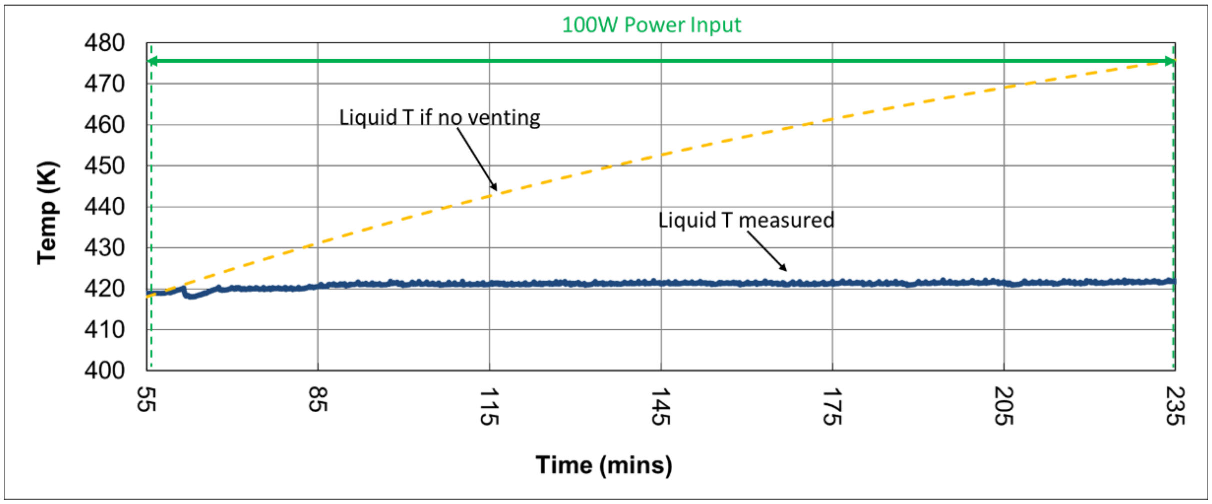

Figure 6. Working fluid (water) temperature during 3 hours of operation (blue solid line: actual liquid temperature measured by TC inserted inside the primary vessel ; yellow dashed line: hypothetical liquid temperature without venting-based cooling effect)

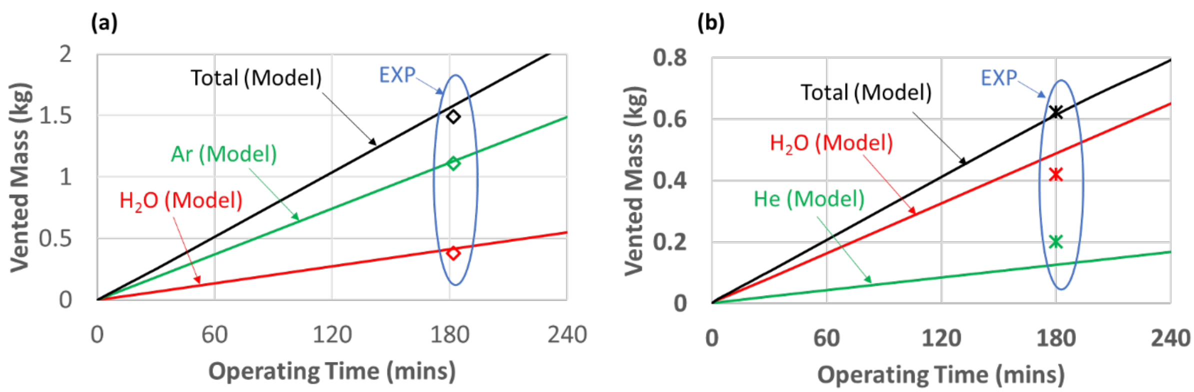

Figure 7. Comparion between vented fluid mixture mass resulted from the experiment and from the model for (a) water - argon system and (b) water - helium system

The same testing was performed using helium as the compressed gas, which has 10 times lower density and 10 times higher specific heat than argon. The comparison between the vented mass of both species resulted from the model and from the experiment is shown in Figure 7(b). For 100W applied during the 3 hours of operation, the total vented mass for water - helium system was 0.622 kg, consisting of 0.42 kg of water and 0.202 kg of helium. It is concluded that using helium as compressed gas can significantly reduce the total system mass due to its low density and high specific heat.

B. Ammonia Test Results

The prototype system was modified and tested with ammonia as working fluid. Only helium was used as the compressed gas since its superiority over argon was clearly established. As the liquid temperature measurement result (blue line) shows in Figure 8, the prototype system successfully demonstrated its cooling capability by maintining the liquid temperature at the set point (8.8°C) for 3 hours with 100Watts of electronics heat input. Again, without venting-based cooling, after 3 hours of heating, ammonia liquid temperature would reach 370K (96.85°C). Based on mass measurements, the system vented 0.859 kg of ammonia and 0.157 kg of helium. Again, the predicted mass consumption resulted from analytical modeling agreed well with the measured mass as shown as Figure 9. Note that the ammonia system, testing was performed at lower set temperature than ambient. In addition, the temperature of the injected helium was also ambient meaning that sensible heat was added to the system and further removed through venting. This being added to the environmental heat leaks into the system give the results a certain degree of conservativeness. The total heat input to the system is the summation of heat load provided by the electric heater and the compressed gas sensible heat. Since the system was well insulated, the environmental heat leaks into the system were assumed small and therefore they were not evaluated.

- Heat provided by heater for 3 hours operation:

$$99W \;\times 10652s = 1054.5\;kJ$$

- Heat provided by helium entering at ambient temperature:

$$0.157\;kg\;\times (h_{IN} - h_{OUT}) = 2.87\;kJ\;(h_{IN} >\; h_{OUT})$$

- Heat removed by ammonia latent heat:

$$0.859\;kg \times 1230.64\frac{kJ}{kg} = 1057.12\;kJ$$

This analysis shows that almost all (99.97 %) the heat provided to the system, including 99W electronic heat load and compressed gas sensible heat are removed by latent heat of the working fluid (ammonia). Again, the environmental heat leaks into the system were not evaluated.

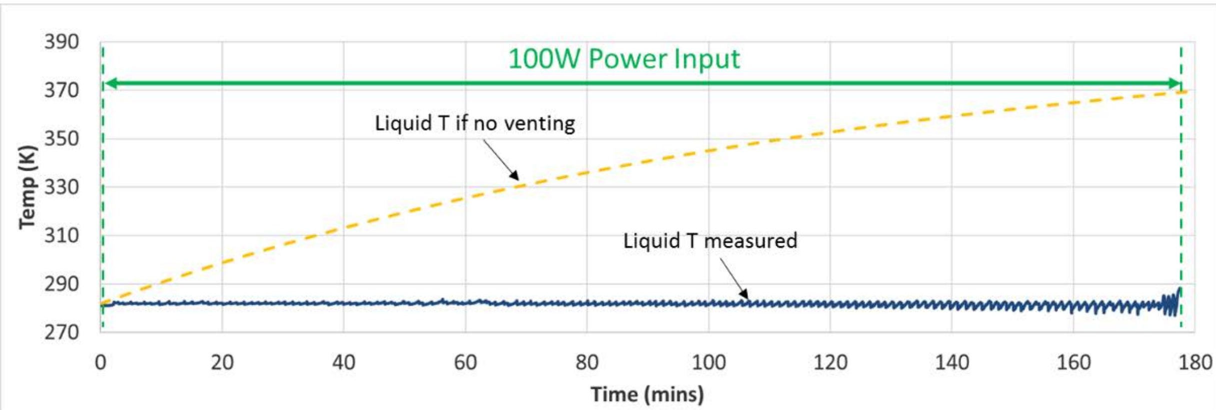

Figure 8. Ammonia liquid temperature variation with 3 hours 100W heat input (blue solid line: actual temperature measurement with venting-based cooling; yellow dashed line: hyphothetical temperature development without venting cooling)

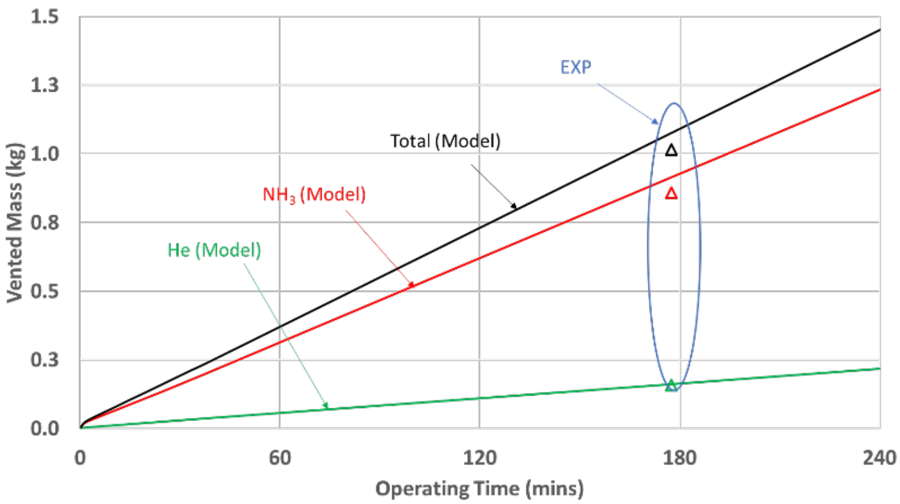

Figure 9. Vented mass of ammonia - helium mixture (experiment vs. prediction)

Table 1. Summary of proof-of-concept testing results

Consumable Fluid	H_2O-Ar	H_2O-He	NH_3-He
Set Temperature (°C)	147	147	8.8
Vapor Pressure (psia)	62	62	82
Working Fluid Vented Mass (kg)	0.378	0.420	0.859
Compressed Gas Vented Mass (kg)	1.113	0.202	0.157
Total Vented Mass (kg)	**1.491**	**0.622**	**1.016**
Heater Q_{in} (kJ)	989	1080	1055
Percentage of Heat Removed by Vaporization	**81.2%**	**82.5%**	**99.7%**

Proof-of-concept prototype testing results are summarized in Table 1, which leads to the following conclusions:

1. The prototype system is capable of cooling by venting two-phase working fluid - compressed gas mixture into an environment that has a higher pressure of 110 psi (~7.6 bar) than the saturated vapor pressure corresponding to the set temperature (for water is 62 psi (4.3 bar) and for ammonia is 82 psi (~5.7 bar)).
2. The system is able to provide effective two-phase cooling and remove 100W of heat for at least 3 hours. Energy analysis proves that majority of heat input (>80%) is indeed cooled by working fluid vaporization.
3. Using helium as compressed gas can save significant amount of fluid mass due to its superior physical properties (low density and high specific heat).
4. The analytical thermodynamic model was successfully validated by the experimental results for all three cases water -argon, water – helium and ammonia – helium.

V. Performance Prediction for the Full - Scale Venus Lander

The validated model was then used to predict the required mass of fluid mixture to achieve a 24 hour survival for the Venus lander. Dimensions and design parameters of the lander provided by NASA JPL [5] are summarized in Table 2. Two Venus ambient pressures (92 bar and 100 bar) were considered in this case study. The venting vessel pressure in this analysis was 5 bar higher than the ambient in each case. The consumable fluid used in this analysis are ammonia (working fluid) and helium (compressed gas). Since ammonia vapor pressure is much higher (~100 times) than water vapor pressure at the set point (70℃), the amount of compressed gas to fill up the gap between the vapor pressure and the venting pressure will be significantly reduced. Because of its low density and high specific heat, helium was established as the best pressurizer for this application.

Table 2. Design Parameters for 24 hours Venus lander [5]

Lander Vessel ID	112cm
Internal Heat Loads	150W
Duration	24 hours
Set Temperature	70°C
Enviornmental Temperature	460°C
Environmental Pressure	92 bar/100 bar
Venting Pressure	97 bar/105 bar

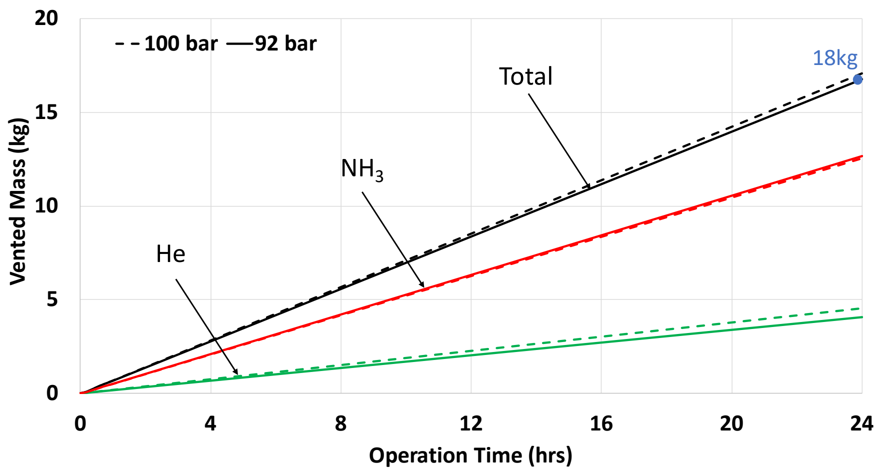

Figure 10. Accumulated vented mass for 24 hours Venus lander cooling using ammonia as working fluid and helium as compressed gas (solid line: ambient pressure at 92 bar; dashed line: ambient pressure at 100 bar)

It can be seen in Figure 10 that a total mass of 18kg of fluid mixture (13.5 kg of ammonia and 4.5 kg of helium) is needed to reject 150W of electronics heat loads and keep the system temperature at 70°C for 24 hours by venting in a 92 atm environment. For a potentially higher environment pressure (ex. in places on Venus where the altitude favorizes higher ambient pressure) the system can still work but a penalty of mass increase is needed. For example, the dashed lines in Figure 10 represent the total mass of consumable fluids required for operation in 100 bar of environmental pressure. It can be observed that the fluid mass penalty is minimal.

Note that in this case study, the initial temperature of the Venus lander cooling system is considered at set point of 70°C instead of 0°C. If precooling conditions are considered, the total required fluid mixture mass will be even lower.

Another note refers to the fact that the remaining sensible heat capacity of the 18 kg of vented fluid mixture (from 70°C to let's say 410°C) will be further used to collect and reject the incoming environmental heat leaks while traveling through the heat guarding system. A preliminary design of the heat guarding system has been developed and will be presented in a future paper.

VI. Conclusion

Under an SBIR program, ACT developed a consumable-based cooling system to achieve 24 hours survival and operation of Venus lander in extreme enviornenment. The consumable-based cooling concept will enable venting of two-phase working fluid into an enviornemnt that has higher pressure than saturation pressure of working fluid corresponding to temperature of payload. The concept was fully demonstrated through mathematical modeling and proof-of-concept prototype testing. Based on model prediction, the consumable-based cooling system will only need 18kg of consumable fluid (75% of ammonia and 25% of helium) to achieve 24-hours survival of Venus lander. The consumable-based cooling technology is considered to be a game changer due to the following advantages:

- Low mass: fluid mass that will be needed for 24 hrs Venus lander thermal management is less than 18 kg.
- Simple and reliable: the amount of moving parts is minimized, components involved in the proposed system are pressure vessels containing working fluid/compressed gas, pipelines integrated flanges and valves (can be automatically controlled).
- Effective cooling: payloads within lander will be cooled by evaporative cooling and incoming heat leaks can be removed by remaining sensible heat of consumable fluid.
- Passive: venting and gas recharge valves will open and close automatically based on either pressure or temperature set points.
- No energy consumption: except the negligible amount of actuation energy for valves, no energy will be needed.

Acknowledgements

This project is funded by NASA Jet Propulsion Laboratory (JPL) under a SBIR Phase I program (Contract 80NSSC18P2186). The technical monitor is Eric Sunada. Special appreciation goes to Philip Martin and Cheyenne

Jones for their technical support as well as the ACT safety committee members for their valuable input on ammonia handeling and testing.

References

[1] National Academy of Science, "Vision & Voyages Planetary Science Decadal Survey 2013-2022," National Academies, Press, 2011.

[2] NASA Goddard Space Center, "NSSDC Chronology of Venus Exploration," 2014. [Online]. Available: http://nssdc.gsfc.nasa.gov/planetary/chronology_venus.html.

[3] J. L. Hall, M. Bullock, D. Senske, J. Cutts and R. Grammier, "Venus Flagship Mission Study: Final Report of Venus Science & Technology Definition Team," NASA , 2009.

[4] M. T. Pauken, C. J. Fernandez and S. M. Jeter, "Expendable Cooling For a one-day Venus Lander," in *11th International Panetary Probe Workshop*, 2014.

[5] NASA JPL, "Venus Lander Mid-Duration Thermal Trade Study," 2018.