Variable Conductance Thermal Management System for Balloon Payload

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While continuously increasing in complexity, the payloads of terrestrial high altitude balloons need a thermal management system to reject their waste heat and to maintain a stable temperature as the air (heat sink) temperature swings from as cold as -90°C to as hot as +40°C. The current solution consists of copper-methanol Constant Conductance Heat Pipes (CCHPs). The problem with these devices is that the conductance cannot effectively be reduced under cold operating or cold survival environment conditions, so an active heater requiring significant energy is required to maintain the instruments in their normal operating range. This paper presents the development of a low cost Variable Conductance Heat Pipe (VCHP) that allows the thermal resistance to increase passively under cold operating or cold survival environment conditions, keeping the instrument section warm with minimal electric heating. This VCHP is based on smooth-bore, thin-wall stainless steel tubing, with methanol, toluene or pentane as working fluids, and is capable of passively maintaining a relatively constant evaporator (payload) temperature while the sink temperature varies between -90°C and +40°C. Two configurations were developed, a cold reservoir one (reservoir is attached to the condenser) and a hot reservoir one (reservoir is attached to the evaporator). Both configurations were tested with the above mentioned working fluids and the experimental results were consistent with the modeling results. In all experimental cases, the evaporator temperature was maintained within the required interval of -10ºC…+50ºC while the sink temperature varied between -90°C and +40°C. The hot reservoir configuration showed the tightest temperature control. For example, the pentane based hot reservoir VCHP allowed the evaporator temperature to change only 3.7ºC from the coldest to hottest heat sinks. The largest temperature variation observed was 32.6ºC for the pentane based cold reservoir VCHP, still meeting the design requirements. Survival tests were also carried out but only for the toluene based cold reservoir VCHP. A duration of 13,000 seconds was needed by the evaporator to cool from 49ºC down to 20ºC while the power was shut down and the sink (condenser) was continuously as cold as -90ºC.

I. Introduction

NASA's Scientific Balloons provide practical and cost effective platforms for conducting discovery science, development and testing for future space instruments, as well as training opportunities for future scientists and engineers. Balloons can reach altitudes above 36 kilometers and can stay afloat for several weeks. It is intended in the Balloon Program to introduce an advanced balloon system that will enable 100 day missions at mid-latitudes and thus provide similar performance to a small spacecraft at a fraction of the cost.

While continuously increasing in complexity, the payloads of terrestrial high altitude balloons need a thermal management system to reject their waste heat and to maintain a stable temperature as the air (heat sink) temperature swings from as cold as -90°C to as hot as +40°C. In the past, constant conductance, copper-methanol heat pipes have been utilized on balloon payloads to effectively move the waste heat over significant distances. The drawback of this thermal solution is that the conductance cannot effectively be reduced under cold operating or cold survival environment conditions, so an active heater requiring significant energy is required to keep the instruments warm.

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As discussed below, a Variable Conductance Heat Pipe (VCHP) can be used to increase the thermal resistance as the sink temperature drops, keeping the instrument section warm.

Modeling, designing and testing of low-cost VCHPs are presented in this paper. The design is based on smooth-bore, thin-wall stainless steel tubing, with methanol, pentane or toluene as working fluids. It is capable of passively maintaining a relatively constant evaporator (payload) temperature while the sink temperature varies between -90°C and +40°C. The thin wall is used to save mass, and to provide better temperature regulation due to its lower thermal conductivity. The combination of working fluid and envelope material results in a heat pipe that is much less expensive to manufacture than standard grooved aluminum VCHPs. An additional change from a spacecraft VCHP is the location of the reservoir. Spacecraft VCHPs normally have the gas reservoir at the end of the condenser, and maintain its temperature with electrical heaters. The proposed VCHP moves the reservoir near the evaporator, eliminating the need for electrical energy to regulate the heat flow and, consequently, the payload temperature. However, the analyses, design and testing are done for two configurations, a hot reservoir configuration and the (standard) cold reservoir configuration.

II. Background - Variable Conductance Heat Pipes

A simple VCHP is shown below in Figure 1. It is similar to a conventional heat pipe but has a reservoir and controlled amount of non-condensable gas (NCG) inside the reservoir. When the heat pipe is operating, the NCG is swept toward the condenser end of the heat pipe by the flow of the working fluid vapor. The NCG then blocks the working fluid from reaching a portion of the condenser. The VCHP works by varying the amount of condenser available to the working fluid. As the evaporator temperature increases, the vapor temperature (and pressure) rises, the NCG compresses (Figure 1 top) and more condenser is exposed to the working fluid. This increases the conductivity of the heat pipe and drives the temperature of the evaporator down. Conversely, if the evaporator cools, the vapor pressure drops and the NCG expands (Figure 1 bottom). This reduces the amount of available condenser, decreases the heat pipe conductivity, and drives the evaporator temperature up (Marcus, 1972).

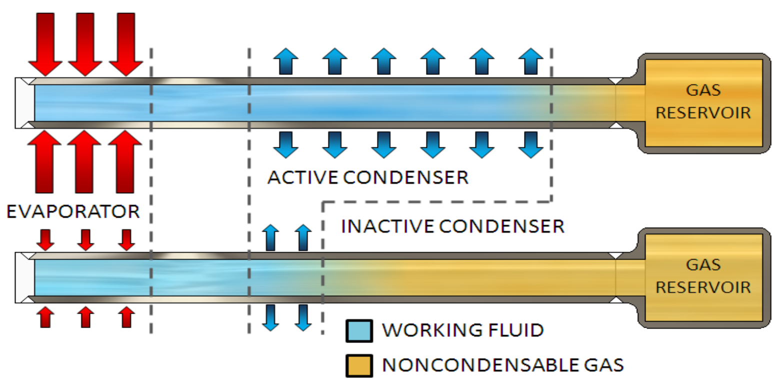

Figure 1. The working of a variable conductance heat pipe (VCHP) is illustrated. At high heat load the temperature dependent saturation pressure of the working fluid is high and compresses the non-condensable gas (NCG) into the reservoir. At lower heat input the working fluid temperature and pressure is lower, and the non-condensable gas expands into the condenser.

For the VCHP shown in Figure 1, the degree of control depends primarily on two factors: the slope of the working fluid vapor pressure curve and the ratio of reservoir and condenser volumes. Working fluids having steeper vapor pressure curves at the particular operating temperature result in tighter temperature control. Small changes in temperature result in large changes in pressure and subsequently large changes in the NCG volume/condenser length. Similarly, large reservoir volumes improve control because a given pressure change results in a larger change in the position of the gas/vapor interface in the condenser.

III. VCHP Modeling and Design

Schematics of the two VCHP configurations, hot and cold reservoir, are shown in Figure 2. Configuration 1 (hot reservoir VCHP) has the reservoir attached to the evaporator and the reservoir temperature will mainly follow the evaporator (payload) temperature. Configuration 2 (cold reservoir VCHP) has the reservoir attached to the condenser and the reservoir temperature will follow the condenser (or sink) temperature.

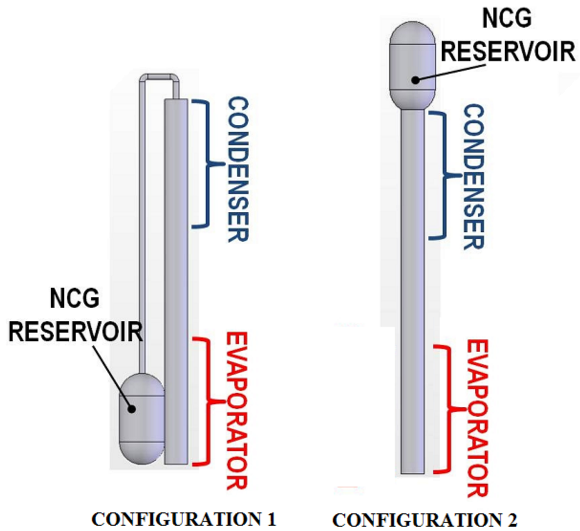

Figure 1. Potential VCHP configurations: Configuration 1 – reservoir attached to the evaporator (hot reservoir); Configuration 2 - reservoir attached to the condenser (cold reservoir).

A. Design Requirements

The VCHP must be capable of rejecting the waste heat from the balloon payload during the entire mission when exposed to the wide range of the sink temperatures (-90 to 40ºC). During operation, it will passively adjust its thermal resistance to maintain the evaporator (payload) temperature within an acceptable temperature range. The VCHP will shut down to protect the payload from experiencing low temperatures during survival periods. Based on a set of detailed temperature ranges for potential/typical balloon payload components and operating conditions that was provided by the New Mexico State University (NMSU) Physical Science Laboratory the following temperature intervals resulted as design requirements:

1) LTI = -5…50ºC (Limiting Temperature Interval for Instruments)
2) STI = -20…50ºC (Survival Temperature Interval)
3) HSTI = -90…40ºC (Heat Sink Temperature Interval)

The power rejection requirement for these two VCHP prototypes was 70-100W.

B. VCHP Performance Limitations and Preliminary Geometry

Heat pipe performance limitations were calculated for a preliminary geometry that is presented below in Table 1. Five working fluids were investigated in the context of this VCHP geometry to determine their suitability for the application. The five working fluids investigated are: pentane, methanol, ammonia, toluene and propylene, which are all known to be compatible with the stainless steel envelope. The VCHPs are thermosyphons that only contain screen in the evaporator to enhance priming of the evaporator during startup. The adiabatic and condenser sections are bare tubes that only experience returning fluid film flowing down the envelope back to the evaporator. Since the VCHP will function as a thermosyphon, the capillary limit was not a concern and, therefore, it was not included in the performance calculations.

Table 1. VCHP parameters for heat pipe performance calculations.

PARAMETER	VALUE
Outer Diameter	0.50in (1.27cm)
Wall Thickness	0.020in (0.0508cm)
Inner Diameter	0.460in (1.1684cm)
Evaporator Length	6.00in (15.24cm)
Condenser Length	12.00in (30.48cm)
Adiabatic Length	12.00in (30.48cm)
Total Pipe Length	30.00in(76.2cm)
Minimum Operating Temperature	-90°C (183.15K)
Maximum Operating Temperature	50°C (323.15K)

An overall summary of the minimum and maximum powers for all working fluids is presented in Table 2. Ammonia shows the best power transport capabilities however its elevated melting point (-78°C, above the lower temperature limit) and high vapor pressure would dramatically decrease its ranking among the five fluids investigated. Methanol also shows a high power transport capability.

Table 2. Summary of minimum and maximum powers for all working fluids.

Working Fluid	Minimum Power	Maximum Power
Pentane	2.5W @ -90°C	120W @ 50°C
Methanol	0.097W @ -90°C	300W @ 50°C
Ammonia	N/A @ -90°C	539W @ 16°C
Toluene	0.00825W @ -90°C	100W @ 50°C
Propylene	90W @ -90°C	152W @ -17°C

C. VCHP Modeling and Analysis

A VCHP model based on flat front theory (Marcus, 1972) was developed and used to analyse both VCHP configurations for all five potential working fluids. The most relevant results are presented below where VCHP performance (evaporator temperature control) is shown as a function of sink temperature and reservoir size.

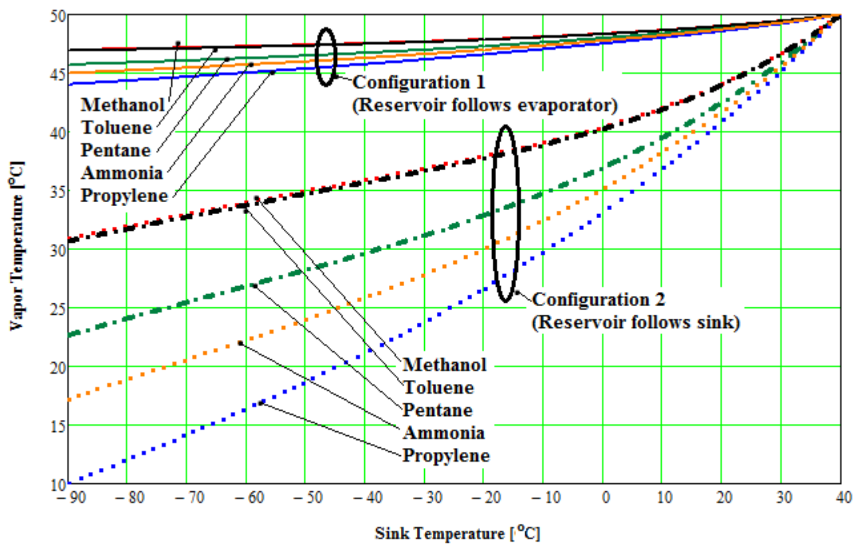

Figure 3. Evaporator temperatures variation as the sink temperature sweeps the entire HSTI (Heat Sink Temperature Interval).

Figure 3 shows the evaporator temperature variation as the sink temperature sweeps the entire HSTI (Heat Sink Temperature Interval = -90…40ºC) defined above. As expected, Configuration 1 (reservoir attached to evaporator) provides a better (tighter) temperature control than Configuration 2 (reservoir attached to condenser). From the working fluid point of view, methanol is the best fluid, very closely followed by toluene. In addition, both the higher heat pipe merit number (which ranks heat pipe fluid performance, Reay and Pew, 2006) and the vapor pressure show that methanol is a better fluid than toluene. A fluid with a higher merit number would allow a smaller heat pipe inside diameter, for the same transported power. Also, the lower the vapor pressure, the smaller the differential pressure across the heat pipe walls, which allows thinner walls. Smaller VCHP size (diameter) and thinner VCHP walls also minimize heat leaks through the metallic structure. This fact is beneficial during extreme cold sink temperature exposure and survival periods because it allows the payload components to stay longer at temperatures above the survival value without using heating.

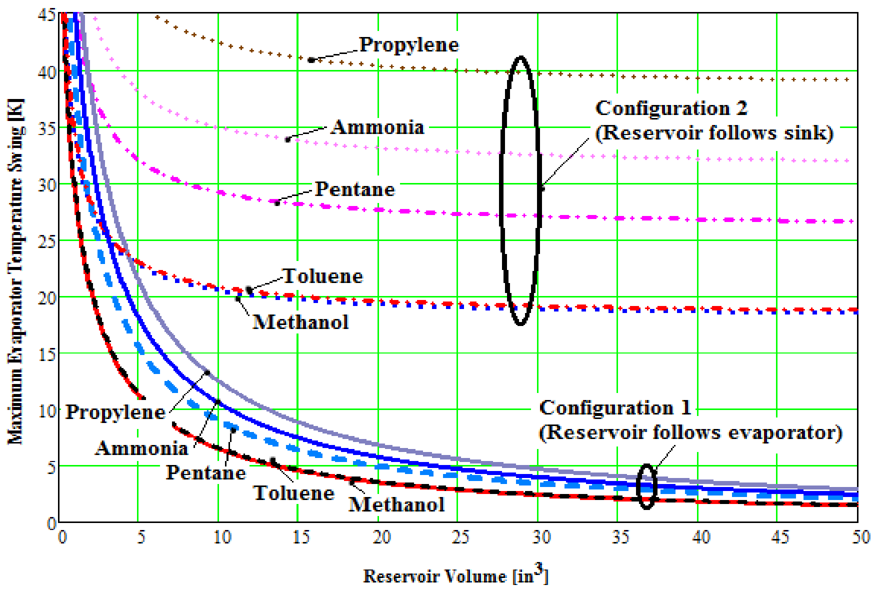

Figure 4. Maximum evaporator temperature swings (as the sink temperature sweeps the entire HSTI) as a function of reservoir size.

Additional VCHP modeling results are shown in Figure 4 where the maximum evaporator temperature swing is presented as a function of sink temperature, fluid, configuration, and reservoir size. In other words, the ordinate axis shows the size of the temperature range the evaporator will experience while the sink conditions vary along the entire HSTI, as a function of the VCHP reservoir volume. Again, Configuration 1 (hot reservoir) shows the best (tightest) temperature control, while methanol, toluene and pentane are the best fluids. For example, a methanol or pentane charged VCHP with a reservoir volume of 30 in^3 will allow only 2.5-3ºC of evaporator temperature change while the heat sink swings from -90 to 40ºC (HSTI). It has to be noted that the VCHP geometry impact on the performance is strongly dominated by the reservoir size. The actual geometry used for the two configurations is presented in Table 3.

Table 3. VCHP geometry.

VCHP section	Length	Inner diameter	Volume	Wall thickness
Evaporator	L_{ev} = 15 cm	ID_{ev} = 1.2 cm	Vev = 14.2 cm^3	t_c = 0.05 cm
Adiabatic	L_c = 30 cm	ID_{ad} = 1.2 cm	Vad = 27.2cm^3	t_c = 0.05 cm
Condenser	L_c = 30 cm	ID_c = 1.2 cm	Vc = 32.6 cm^3	t_c = 0.05 cm
Condenser-Reservoir Tube	L_o = 81.3 cm (Config. 1) L_o = 7.5 cm(Config. 2)	ID_o =0.37 cm	Vo = 9.17 cm^3 Vo = 1.4 cm^3	t_{co} = 0.09 cm
Reservoir	H = 15 cm	ID_r = 6.17 cm	Vr = 455.5 cm^3	t_r = 0.081 cm

D. Payload Survival and Heat Leak Analysis

During extreme survival times when heat sink temperature is as low as -90°C, the NCG blocks the condenser and part of the adiabatic section, shutting down the heat pipe. However, , heat leaks still occur by conduction through heat pipe envelope in the adiabatic section. Assuming that no power is supplied to the instruments, the instrument temperatures will gradually, eventually drop below the lower limit of the STI (Survival Temperature

Interval). Additional modeling results (see Figure 5) estimate the survival time with conduction through a non-operating VCHP. As shown in Figure 5, the unpowered instruments will cool down to the cold survival temperature limit over roughly 1.5 days.

This period can be increased with the addition of a phase change material (PCM), which keeps the instrument temperatures fairly high until all of the PCM is frozen. The PCM used in the model is Rubitherm® RT-4 (with melting point of -4ºC).

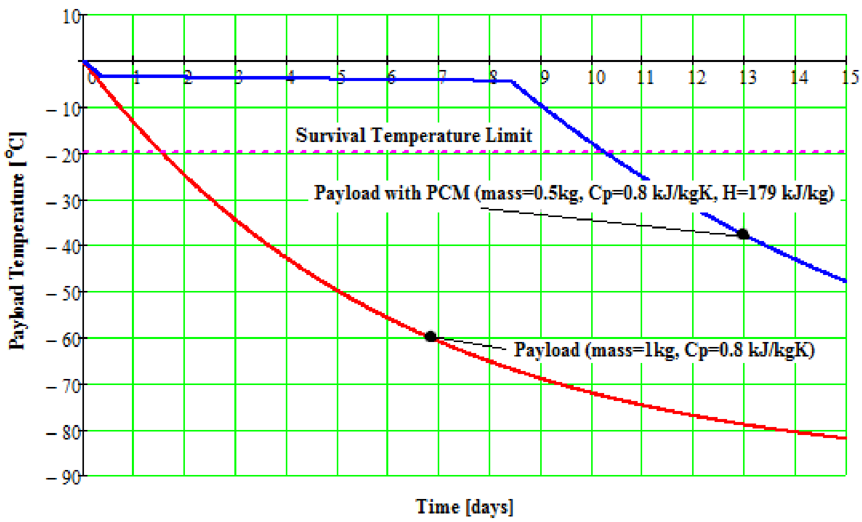

Figure 5. Payload temperature during 15 day operation of payload at cold survival temperatures.

The same virtual payload but with 0.5kg of PCM was also examined and the result can be seen in Figure 5. The payload with the 0.5kg of PCM is capable of maintaining its temperature relatively constant and above the cold survival temperature limit for approximately 8.5 days. After 8.5 days the temperatures begins to decrease, however, it is still warmer than the cold survival temperature limit until a little after 10 days of operation. This example shows that by using such a VCHP, with only 0.5kg of PCM, the payload temperature can be maintained above the cold survival temperature limit for 8.5 days longer then without PCM.

E. VCHP Design

CAD designs and thermocouple maps for the two VCHP configurations are shown in Figure 6. The thermocouples are spaced every 2.54 cm (1 in.) starting with the exit of the evaporator and up to the entrance of the reservoir. These thermocouples are attached to the tubes (adiabatic zone and condenser-reservoir connecting tube) and inserted within the condenser body 0.035 inches from the vapor space. The evaporator has two inserted thermocouples while the reservoir has two intrusive thermocouples inserted in thermo wells. The VCHP Configuration 1 has extra thermocouples on the connecting tube between the condenser and the hot reservoir that is integrated with the evaporator. As seen both VCHPs have valves for working fluid and Non Condensable Gas (NCG) charge (these are left on to allow changing the fluids and NCG charge, and would be removed in the application).

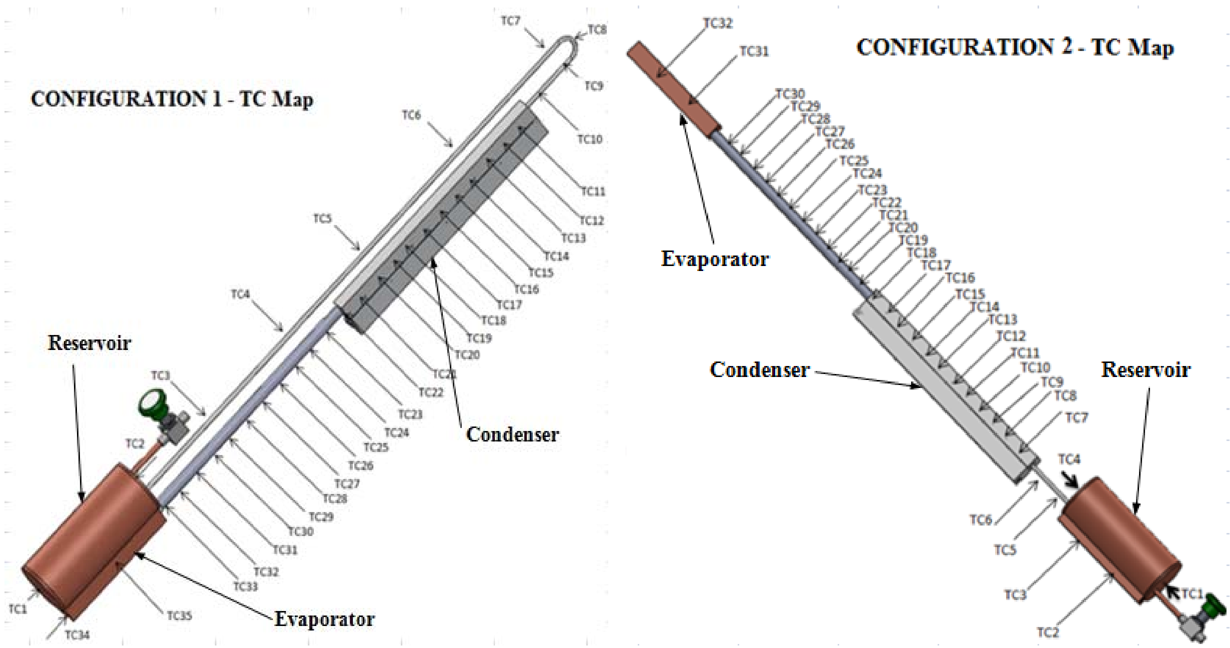

Figure 6. Thermocouple maps on the two experimental VCHPs.

IV. VCHP Testing Conditions and Experimental Results

Both VCHP configurations were tested in ambient conditions using liquid nitrogen to cool the condenser and cartridge heaters to heat the evaporator. For the VCHP Configuration 2, the reservoir temperature was also controlled by using liquid nitrogen for cooling and cartridge heaters for heating. The reservoir temperature in Configuration 1 was not controlled since it was both thermally and physically coupled to the evaporator and thus closely followed the vapor temperature. Both VCHP Configurations were tested with three selected working fluids: methanol, toluene and pentane. The tests conducted are described within the next four sections of the paper.

A. Test1 – Power Capability

The first test was to examine the maximum power carried by the heat pipe without an NCG charge. The heat sink temperature was kept constant at 15 ºC while the power was incrementally increased to 310W. This test was performed only for VCHP Configuration 2 charged with methanol. Figure 7 shows the results of this initial test.

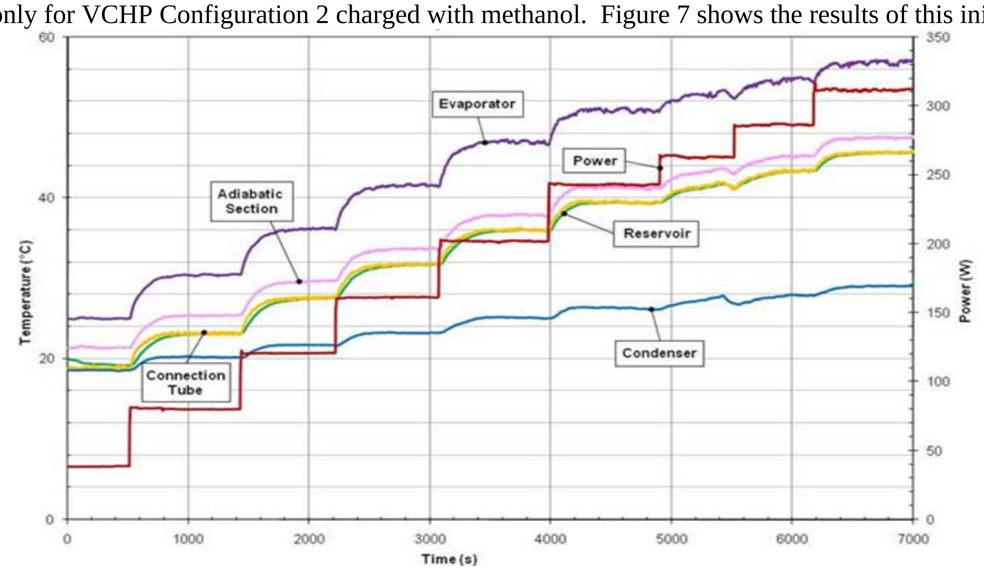

Figure 7. Preliminary testing of the VCHP Configuration 2: power capability.

As shown, the power was ramped up to 310 W and the VCHP acting as a CCHP has not reached its power capability. The experiment ended because of cooling limitations, not due to the limits of the heat pipe. A conclusion of this experiment is that the predicted power limits in Table 2 are validated, and that the predictions were conservative. The conclusion also applies to Configuration 1 since the vapor paths are identical in both VCHP configurations.

B. Test2 – Thermal Control with Constant Power

As mentioned above, all the combinations (six) with the two VCHP configurations and the three working fluids were tested. Detailed results however are shown only for the VCHP Configuration 1 with methanol in this paper. The power was maintained constant at 100W while sink temperature was incrementally decreased along the entire HSTI. Figure 8 below shows temperature profiles along the VCHP as a function of the sink temperature. Note that the evaporator (payload) temperature only varies from 50 to 44ºC as the sink temperature varies between 40 and -90°C, demonstrating the ability of the VCHP to maintain the evaporator temperature over the entire sink temperature range.

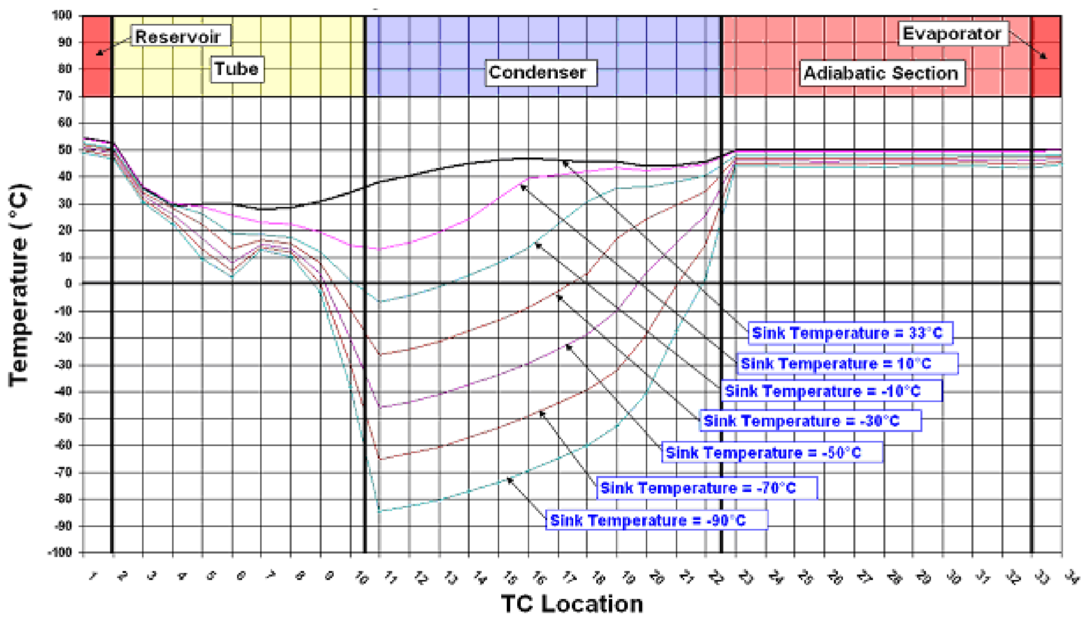

Figure 8. VCHP Configuration 1 (hot reservoir) with methanol - steady state temperature profiles for several sink temperatures and a constant power of 100W.

Figure 9 shows the transient temperatures for the same experiment. The green curve is the vapor temperature and was considered as reference. As seen the evaporator vapor temperature changes only slightly, while the end of the condenser closely follows the sink.

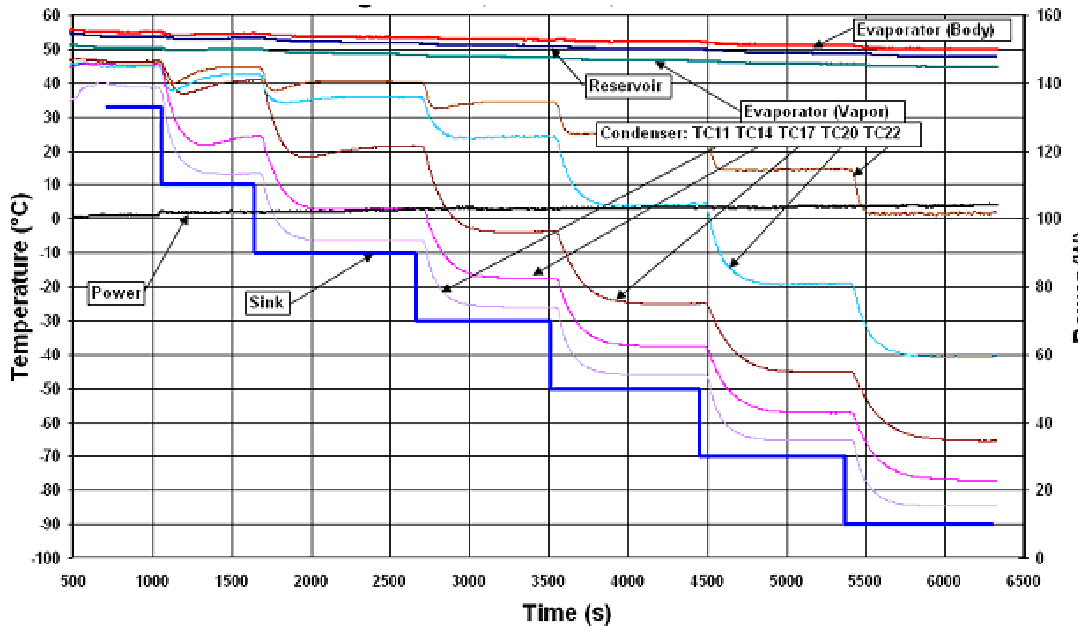

Figure 10. VCHP Configuration 1 - methanol - transient temperatures at several relevant locations as the sink temperature sweeps the entire HSTI.

A summary of the "Thermal Control at Constant Power" test is shown in Figure 11 where the evaporator steady state temperatures are shown for both configurations and all three fluids as a function of heat sink temperature.

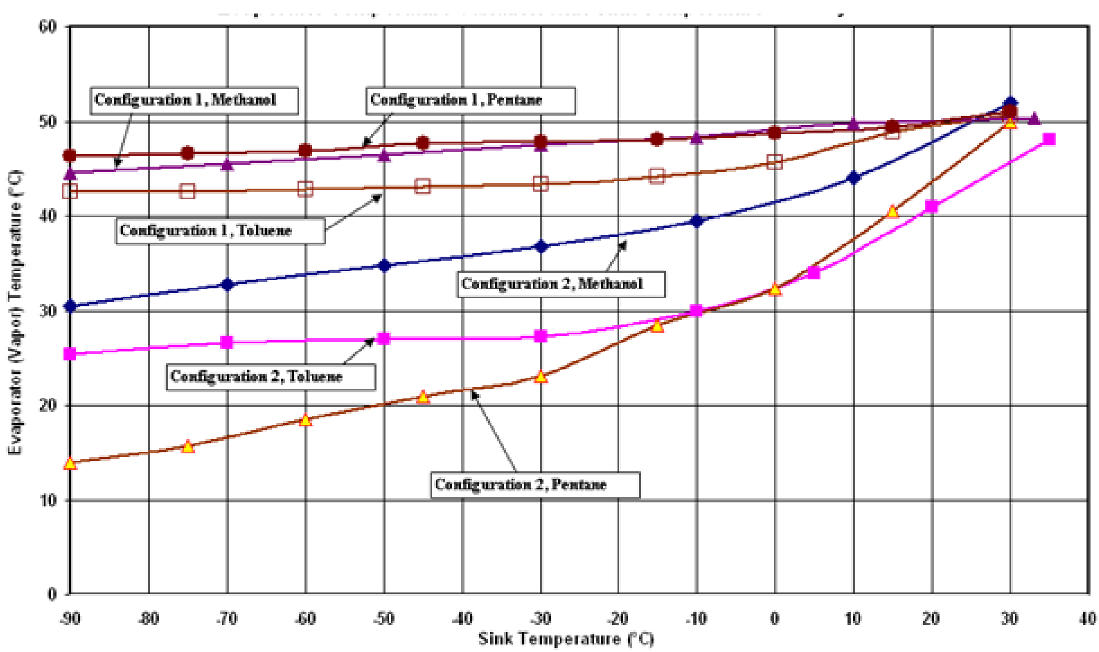

Figure 11. Steady state evaporator temperatures for both VCHP configurations and all three working fluids when sink temperature sweeps the entire HSTI.

It can be concluded that Configuration 1 (hot reservoir) shows better temperature control than Configuration 2. Moreover, both configurations with all three working fluids provide a temperature control tight enough satisfying the design requirements. The tightest temperature control was shown with pentane in VCHP Configuration 1 with only a 3.7ºC (46.3… 50ºC) temperature swing. The loosest temperature control was measured for the VCHP Configuration 2 with pentane, which was only 36ºC (14...50ºC). All other temperature swings are included in the 14… 50ºC range, which is conservative with respect to the requirements provided by the LTI = -5 …50ºC. A comprehensive summary of these results is presented in Table 4.

Table 4. Summary of the modeling and experimental evaporator temperature intervals as the heat sink sweeps the HSTI.

Working Fluid →	**Methanol**		**Toluene**		**Pentane**	
Configuration	Predicted	Measured	Predicted	Measured	Predicted	Measured
VCHP Configuration 1	47...50ºC	45.3...50ºC	46.9...50ºC	43...50ºC	45.2...50ºC	46.3...50ºC
VCHP Configuration 2	30.8...50ºC	30.4...50ºC	30.3...50ºC	26.2...50ºC	17.4...50ºC	14...50ºC

C. Test3 – Thermal Control with Constant Heat Sink Temperature

Next, the power was varied while the sink temperature was kept constant at the lower limit of the HSTI (-90ºC) and at 15ºC. Only the VCHP Configuration 1 with methanol was tested. It can be observed in Figure 12 that the evaporator temperature variation was reasonably small for the most of the power range. The evaporator temperature was close to the predicted value for 100 W at the respective sink temperatures. Note that these temperatures are well above the lower allowable temperature limit.

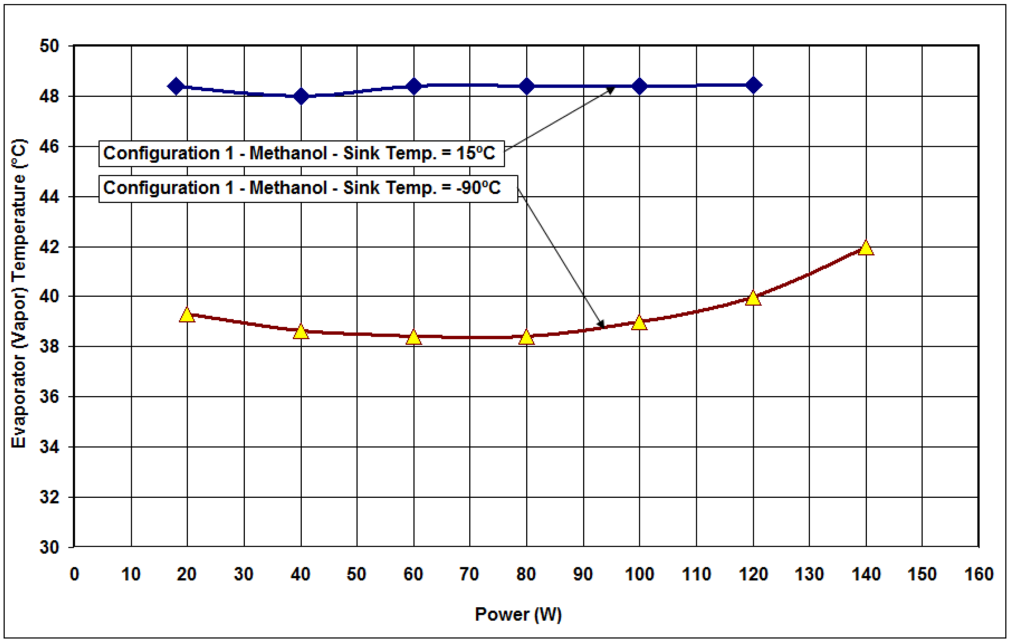

Figure 12. Steady state evaporator temperatures for VCHP Configuration 1 with methanol when sink temperature kept constant and power varied between 20 and 140W.

D. Test4 – Survival

The survival test was carried only for the VCHP Configuration 2 charged with toluene. The power was shut down when the evaporator temperature was 49ºC. The system was continuously cooled by a -90ºC heat sink. The thermal mass of the system consisted of the actual VCHP and a part of the insulation material. These conditions were considered as conservative since the real thermal mass (payload) is expected to be larger. As seen in Figure 13, the evaporator body reached 20ºC after 13000 seconds. This result shows that the lower side of the STI (Survival Temperature Interval) of -20ºC would have been reached significantly later. Both the experimental and the modeling results demonstrated that the presence of the VCHP does not create significant heat leaks during survival times and the payload can stay warm for extended periods of time (days).

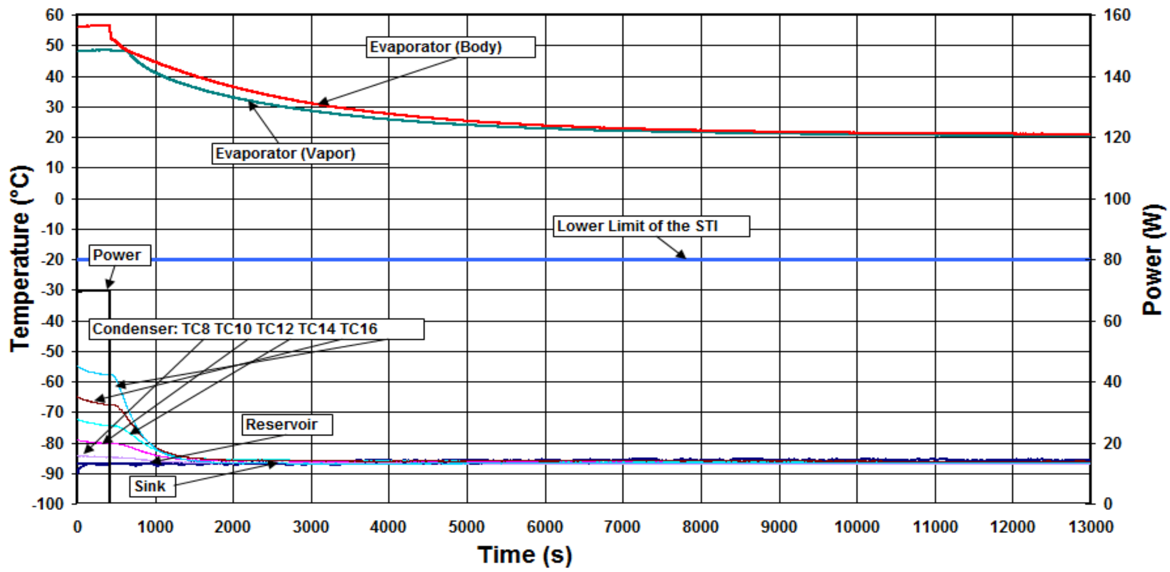

Figure 13. Survival testing results where the VCHP Configuration 2 with toluene was exposed to the most extreme environment conditions (-90ºC) while the power was shut down.

V. Conclusion

A low-cost Variable Conductance Heat Pipe (VCHP) based on smooth-bore, thin-wall stainless steel tubing was developed for high altitude balloon applications. This two-phase heat rejection device is capable of passively maintaining a relatively constant evaporator (payload) temperature while the sink temperature varies between -90°C and +40°C. The VCHP development included the modeling, designing, fabricating and testing of two fundamentally different VCHP configurations, a hot reservoir one (Configuration 1) and a cold reservoir one (Configuration 2). Two proof of concept VCHPs were designed, built (stainless/copper) and tested, one for each configuration. Both VCHPs (Configuration 1 and Configuration 2) were charged and tested with all three working fluids: toluene, methanol, and pentane.

Four types of tests were conducted:

- Power Test
- Thermal Control with Constant Power and Variable Heat Sink Temperature
- Thermal Control with Constant Heat Sink Temperature and Variable Power
- Survival Test.

The results of all four tests validate the modeling, and demonstrate the ability of the VCHP to passively control the balloon payload temperature as the sink temperature changes is summarized in Table 4. In each case, the VCHP was supplied with constant power (100 W for methanol cases and 70 W for the toluene and pentane cases) while the heat sink temperature (liquid nitrogen controller set point) was varied systematically from 40ºC all the way to -90ºC (along the HSTI). While the hot reservoir VCHP (Configuration 1) provides tighter thermal control than the cold reservoir VCHP (Configuration 2), both configurations can provide a balloon payload temperature control within the requirements. Moreover, the VCHP can protect the payload against exceptionally low temperatures during survival. The survival times (1-2 days) can be significantly extended (8 days) if a small amount of Phase Change Materials is used.

Acronyms

CCHP	Constant Conductance Heat Pipe
HSTI	Heat Sink Temperature Interval
LTI	Limiting Temperature Interval for Instruments
NCG	Non-Condensable Gas
NMSU	New Mexico State University
PCM	Phase Change Material
STI	Survival Temperature Interval

VCHP Variable Conductance Heat Pipe

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