Design and Thermal Vacuum Testing of a Propylene Miniature Loop Heat Pipe (MLHP)

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ABSTRACT

The paper presents the design and thermal vacuum testing of a Miniature Loop Heat Pipe (MLHP) with propylene as working fluid. It is for cooling a prototype lunar power device and so needs to work against lunar gravity. The target operating condition was to convey 20W in the +20 °C to -30 °C temperature range. All wetted materials were stainless steel, while an aluminum saddle and radiator panel were used to enhance heat spreading. The outer diameter of the LHP primary wick is 5mm and the length is 55mm. The bubble test showed a pore radius of 1.2 micrometer. The radiator is 265mm x 270mm. The MLHP was tested at different heat loads, different orientations in the gravity field and two sink temperatures of +20 °C and -30 °C. The MLHP thermal performance test included startup and steady state operation. Maximum heat transport limit was found to be 30W and peak conductance 6.6 W/C.

Nomenclature

mLHP	=	Miniature Loop Heat Pipe
TVAC	=	Thermal Vacuum Testing
W	=	Watts, the unit of measure for power and heat
Q	=	Heat Load (Watts)

INTRODUCTION

The NASA JPL Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE) project was a 3-year effort to develop passive thermal management tools necessary for future instrument/system operation in extreme environments. The overarching goal is to ensure that a full palette of TRL6 or higher "thermal toolbox" elements is available so that engineers can create passive, ultra-isolative thermal designs for science instruments on a variety of carriers in lunar/planetary extreme environments. One of the "thermal toolbox" elements included in PALETTE was the Loop Heat Pipe (LHP). LHPs have gained worldwide acceptance as passive cooling devices in space applications[1]; however, the design was not in a miniature form factor. This paper presents the design and test results obtained for development of a miniature LHP operating in different orientations under two different sink temperatures.

PHYSICAL DESCRIPTION

Figure 1 is a drawing showing the overall dimension of the MLHP. Figure 2 is a photograph of the overall unit. Overall, it weighed 544.3g, uses a stainless-steel loop charged with propylene, with an aluminum Saddle and Radiator panel for improved conductance at the heat inflow and outflow stations. Table 1 summarizes the design of the MLHP. The Evaporator primary wick used sintered stainless-steel powder. The Wick outer diameter is 15.6mm, bore diameter 6.5mm, and length 109mm. The outer surface of the Wick is scored with circumferential and longitudinal vapor grooves. The Wick is embedded in a stainless-steel Sleeve, which in turn is embedded in the aluminum Saddle. The Reservoir is mounted on-center to the Wick. The Liquid Return Line enters on that center at the back end of the Reservoir and passes through the Reservoir and into the central bore of the Primary Wick. There it delivers returning liquid to the Primary Wick. There is a screen wick assembly that lines the interior of the Reservoir and wraps tightly around the Liquid Return Line in the central bore of the Primary Wick. This Secondary Wick delivers liquid to the Primary Wick in situations when the massflow of vapor out exceeds the massflow of liquid in through the Liquid Return Line.

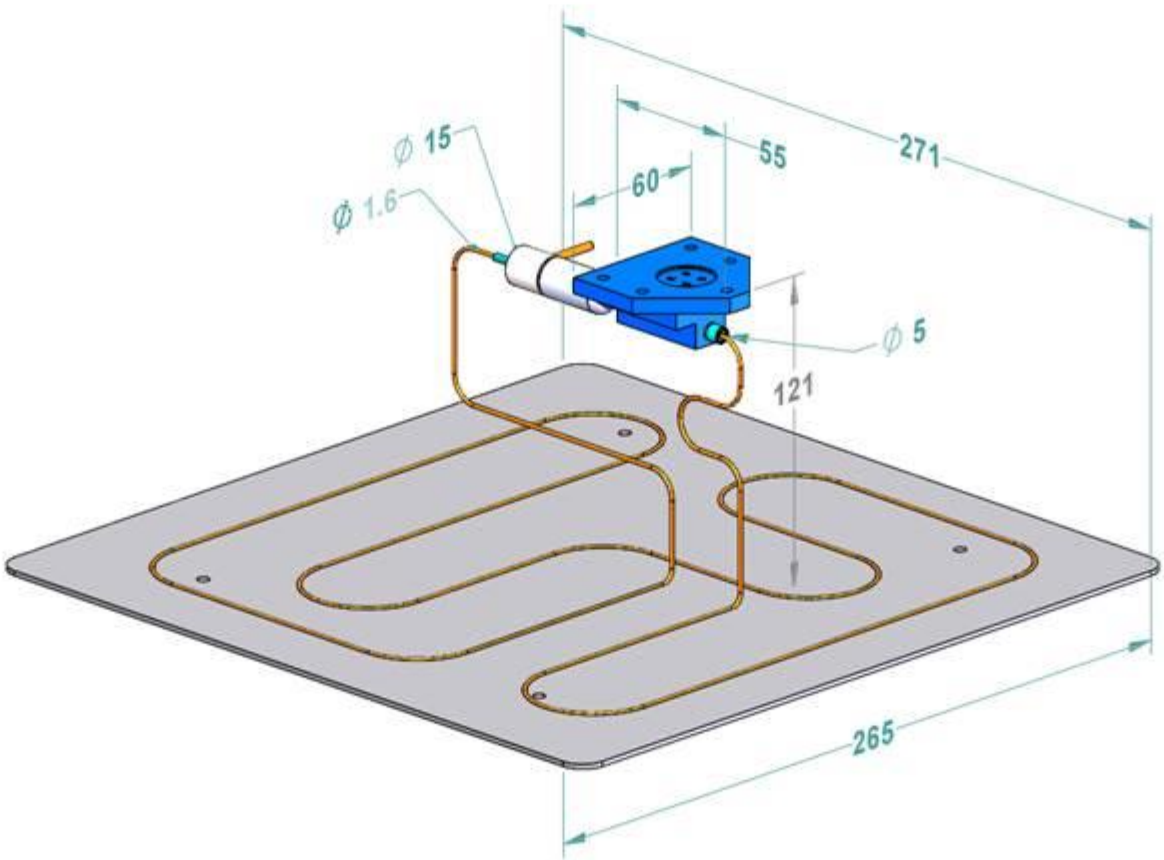


Figure 1. Mini-LHP Overall Dimensions

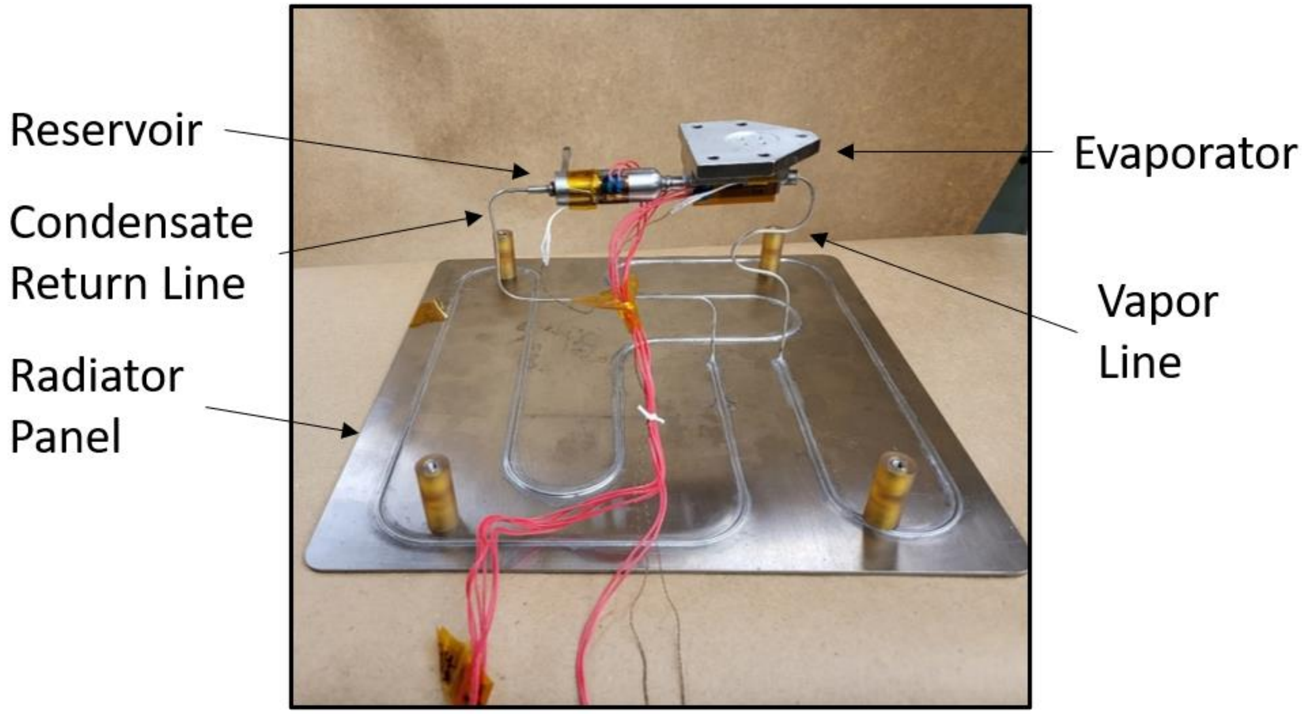
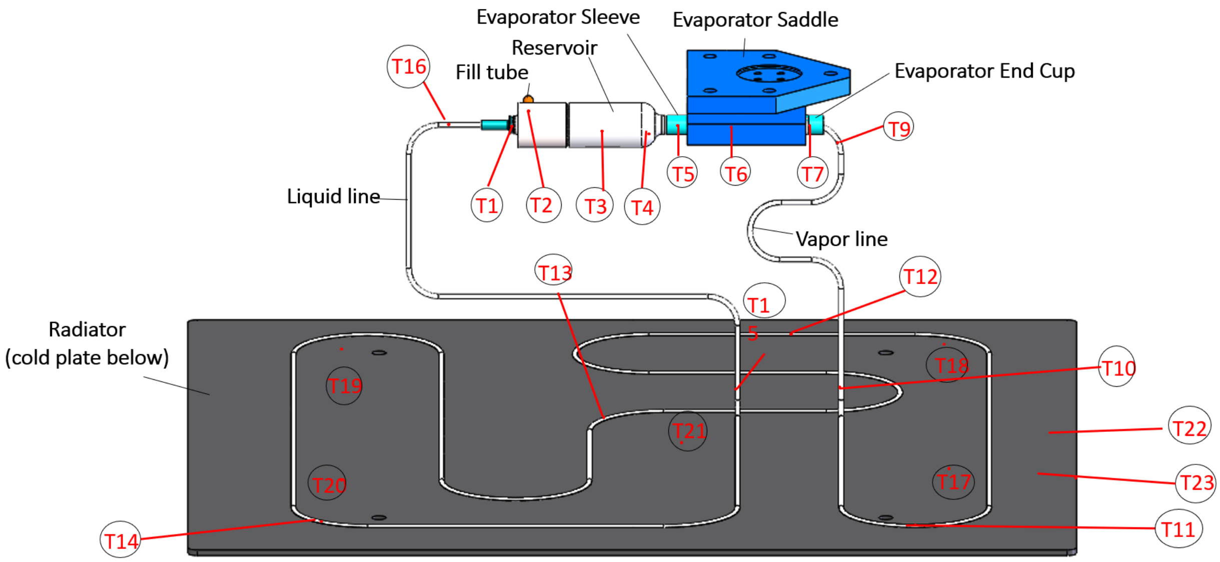


Figure 2. MLHP Design

TEST ARTICLE AND EXPERIMENTAL SETUP

Figure 3 shows the thermocouple locations for testing. The secondary wick is made from stainless steel screen wrapped tightly around the bayonet tube in the central bore of the primary wick and extended outward into the compensation chamber. The vapor line had an inside diameter of 1 mm and a length of 117 mm while the liquid line had an inside diameter of 1 mm and a length of 226 mm. The condenser line had an inside diameter of 1 mm and is serpentine into three passes to yield total length of 1665 mm. This line is soldered to the aluminum radiator panel. Anhydrous propylene is used as the working fluid since the condenser temperature range would be below193K.



Reservoir	Evaporator	Vapor line	Condenser	Liquid Line	Radiator	Coolant In-Out	MLI	VC Wall
T1-T4	T5-T7	T9-T10	T11-T14	T15-T16	T17-T21	T22-T23	T24	T25

Figure 3: Configuration of the miniature LHP with the Thermocouple Locations

Table 1: Significant Parameters of the MLHP

Working Fluid	Propylene	**Liquid Line Length**	226 mm
Wick Material	Stainless steel	**Liquid Line ID**	1 mm
Wick Pore Radius	1.2 µm	**Condenser Length**	1665 mm
Wick Permeability	1.4×10^{-14} m^2	**Condenser ID**	1 mm
Evaporator OD	6.4 mm	**Volume of Reservoir (compensation chamber)**	6.75 cc
Wick Heated Length	40 mm	**Dimensions of Cold Plate for testing**	200 mm× 265 mm
Vapor Line Length	117 mm	**Radiator dimensions**	200 mm× 265 mm
Vapor Line ID	1 mm	**Secondary wick screen mesh**	200×1150
Total Mass	544.3g	**Liquid Line OD**	1.6mm

A copper block with two Minco resistance heaters was attached to the LHP evaporator to provide heat input. Each heater had a variable power up to 24.4 W. For heat removal, the radiator is mounted on a copper cold plate with imbedded coolant channels that was cooled by a coolant circulated from a chiller. A total of 24 thermocouples were installed to monitor temperatures. No startup heater and compensation chamber heater were used. A chiller-cooled cold plate is mounted to the radiator, with a simple bolted interface, with Chomerics Chotherm Thermal Interface Material mounted between the cold plate and Radiator. MLI (Multilayer Insulation blankets) were wrapped around evaporator, reservoir, transport lines and radiators/cold plate for insulation.

The tests were performed in a thermal vacuum chamber and comprised measurement of the various mLHP temperatures as a function of heat load, for two different sink temperatures (-20 °C and 30 °C) and five mLHP orientations (Figure 4): two horizontal positions and three vertical positions where "horizontal" and "vertical" indicate that evaporator is perpendicular and aligned with gravity respectively. The tests included start-up, maximum heat load capability and steady-state heat transfer performance.

Test Results

A. Startup Testing

Different head loads starting from 1 Watt were applied to the evaporator while the sink temperatures were held at -30°C or 20 °C. Coolant was passed through cold plate until the temperature of the radiator (TC21) were chilled to -30°C or 20 °C. Once the TCs readings were stable, heat load was applied to the copper heater block attached to the evaporator. The tests started from 1W heat load and if the LHP can't be started after 30 minutes, then power would be increased to 5W, 10W, 15W and so on.

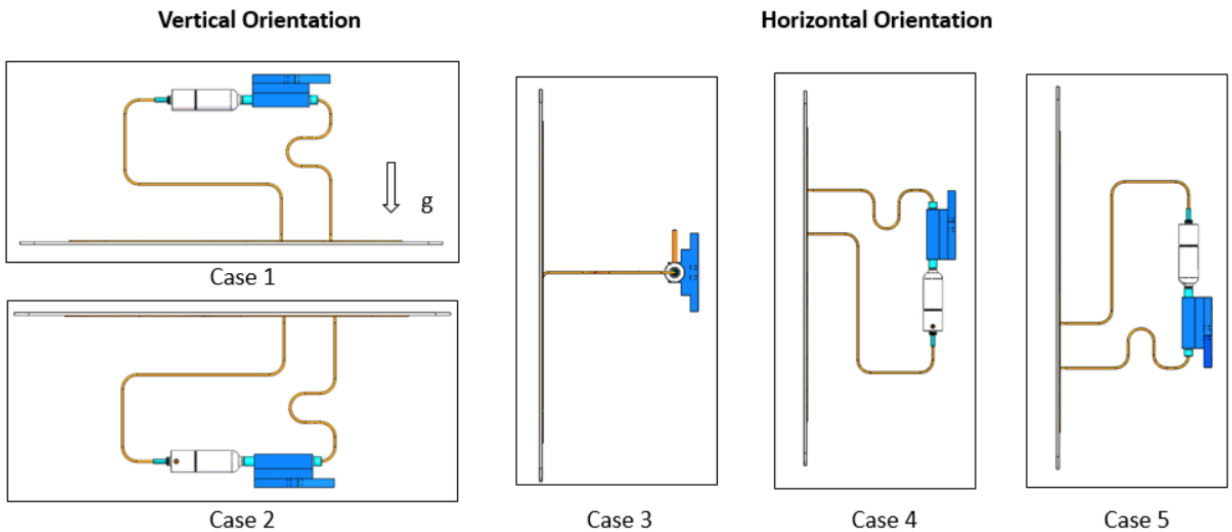


Figure 4: Two vertical orientations and three horizontal orientations.

Figure 5 shows the starting behavior for vertical orientation case 2 for sink temperature of 20 °C during a 1 Watt start-up test. Each temperature value shown in the figure is the average of TCs readings. The temperature of the vapor line increased while the liquid return line entering the evaporator body dropped rapidly towards the sink temperature after the power was applied to the evaporator. This indicates that cold fluid in the condensers is starting to flow back to the compensation chamber and then evaporator as a result of the power input. This indicated that the LHP has successfully started.

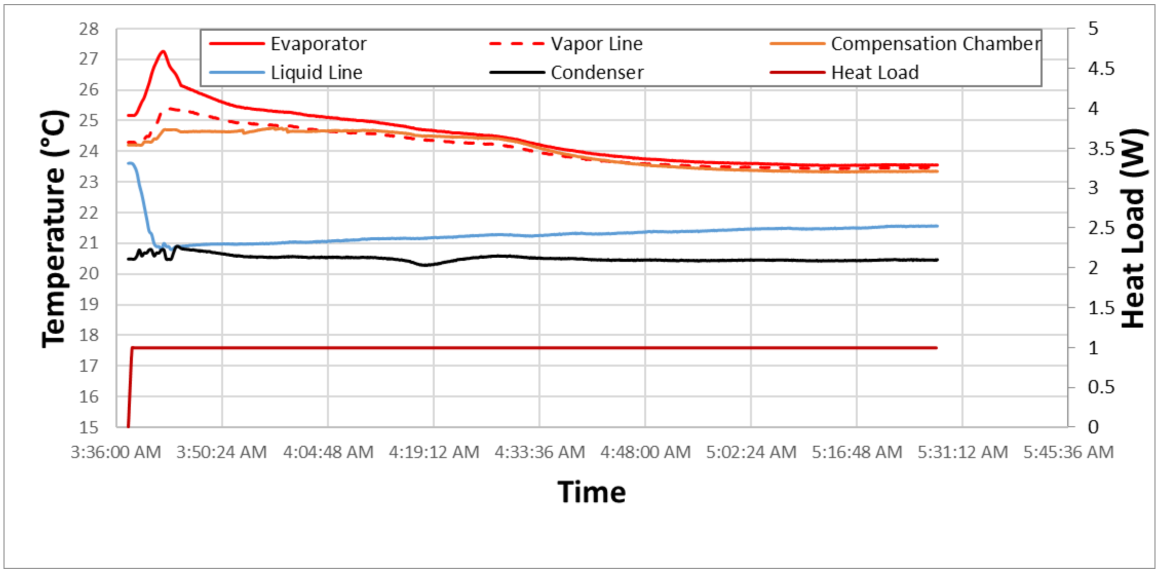


Figure 5: Vertical orientation case 1 Hot startup profile.

Table 2 shows the minimum evaporator heat load for successful startups for different orientations. For vertical orientations (case 1 and case 2), LHP started up successfully when 1 Watt heat load was applied for both hot and cold case. Similarly, 1 Watt head load is enough for successful start-up for horizontal case 3 and case 5 for cold case. For hot case of horizontal case 3 and case 5, LHP didn't show indication of start-up after 1 Watt was applied for 30 minutes. Then heat load was increased to 5 Watt, successful start-up was observed for the above cases.

But for horizontal case 4 where reservoir is located above the evaporator, LHP can't be started at all for both sink temperatures. Power level started from 1 Watt, then 5 Watt, 10 Watt and finally 20 Watt applied. For each heat load, 30 minutes passed for both sink temperatures and there is no indication of startup.

Table 2: Minimum Heat Load for Successful Start-Up for Different Orientations

Power (w)	**Vertical**		**Horizontal**		
	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Hot[a]	1	1	5[b]	No[c]	5[b]
Cold[a]	1	1	1	No[c]	1

[a] Hot: sink temperature= 20 °C; Cold: sink temperature=-30 °C.
[b] After 1 Watt applied 30 minutes, no indication of starting; then heat load increased to 5 Watt.
[c] Four heat loads were applied: 1 Watt, 5 Watt, 10 Watt, and 20 Watt. For each heat load, 30 minutes passed and no indication of starting.

B. Maximal Heat Transport Capability

Maximum power testing was performed immediately after startup testing. The power was increased stepwise in 5 Watt increments every 20 minutes. The results are summarized in Table 3. It should be noted that above 25 watt was not performed for testing for horizontal case 3 for sink temperature of -30°C due to time constraint.

Table 3: Maximal Heat Transport

	Vertical		Horizontal		
	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Hot	20[a]	20[a]	20[a]	N/A[c]	20[a]
Cold	20[a]	30[b]	20[a]	N/A[c]	25[d]

[a] deprime at 25W heat load; [b] deprime at 35W heat load; [c] LHP didn't start up; [d] 30 W or higher heat load was not tested.

C. Steady-State Heat Transfer Performance

The current LHP performance was tested under different heat load cycles to validate its operational reliability. Considering the hysteresis[2] and failure of startup for certain orientations at 1 Watt heat load, the tests were conducted with decrease of heat load: with power cycle of 20-10-5-1 in sequential order.

A plot of the power cycle test data is shown in Figure 6. The current LHP responded well to the change of heat load and showed no sign of instability. When the sink temperature is lower than ambient temperature, the typical trend of steady-state evaporator temperature as a function of heat load is U-shaped[3]: that is, the evaporator temperature first decreases until it reaches a minimum and then increases with heat load. The heat load corresponding to the minimum evaporator temperature is affected by ambient temperature, sink temperature, physical setup of the LHP, the operating conditions, and most importantly the design of the condenser. With increase of heat loads (1W, 5W,10W and 20W), the condenser is opened more and thus average condenser temperature increases. However, the condenser is not fully utilized, and part of the condenser is used to cool the liquid phase of the working fluid propylene rather than to condense vapor. Since the mass flow rate increases with heat load and temperature of liquid propylene coming out of condenser still is close to sink temperature, the liquid temperature entering the reservoir and evaporator temperature decreases as mass flow rate increases.

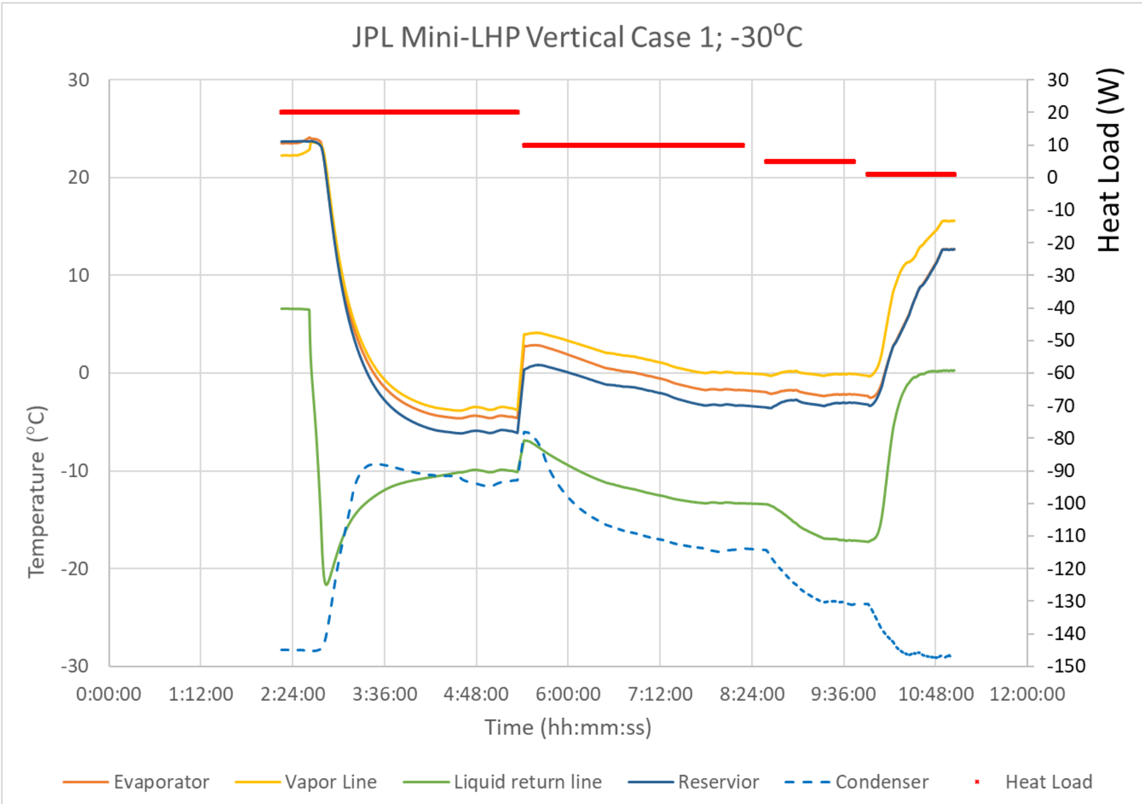


Figure 6: Temperature profiles for vertical orientation 1 for cold case (-30 °C) at four heat loads: 20W, 10W, 5W and 1W.

Figure 7 shows the averaged evaporator temperature against evaporator heat load for two different sink temperatures and different orientations. For the cold sink temperature, the evaporator temperature decreases then increases with heat load. For 20 W heat load, slight increase in the evaporator temperature was observed for two horizontal cases. The difference of temperature values between different orientations decreases with increase of heat load. In contrast, for the hot sink temperature, the evaporator temperature increases with heat load. Also, the difference of temperature values between different orientations increases with increase of heat load.

The effect of the sink temperature on the evaporator temperature is clearly observed in Figure 7. When sink temperature was lower than ambient temperature, evaporator temperature decreased with increase of heat load. But when sink temperature is close to ambient temperature, evaporator temperature increased with increase of heat load. These different trends of evaporator temperature between two sink temperatures are related to heat exchange between the liquid line and the ambient[2].

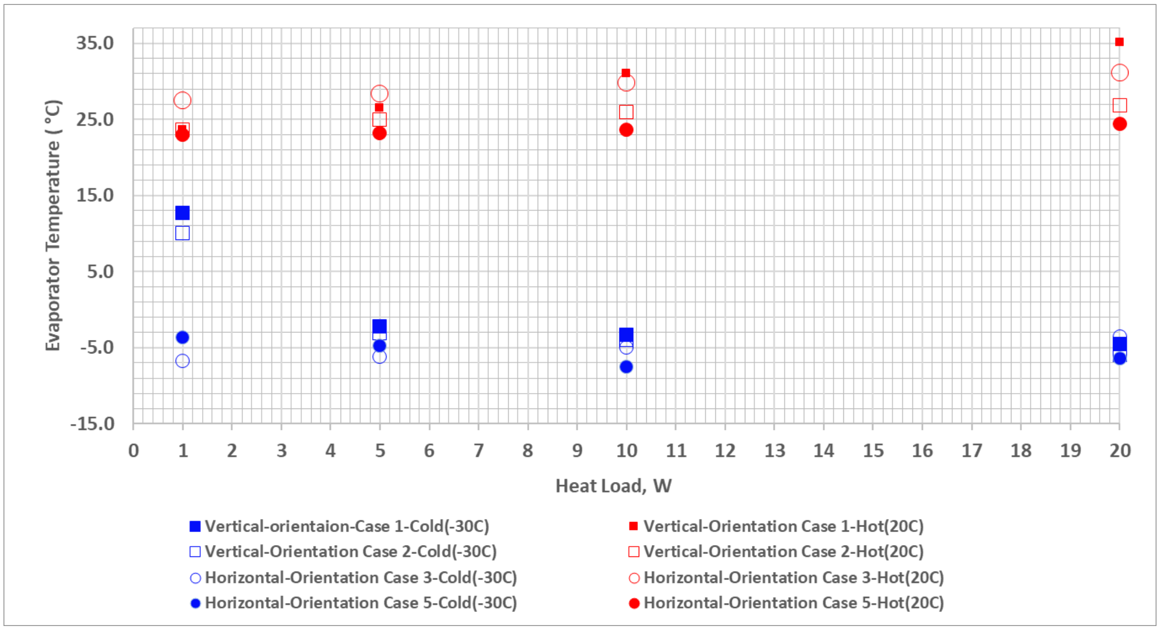


Figure 7: Comparison of evaporator temperature for different orientations at different sink temperature.

Fig. 8 shows the thermal conductance of the unit where conductance was calculated as heat load divided by the difference between average evaporator temperature and condenser temperature. As can be seen, the thermal conductance for hot sink temperature is higher than that of cold sink temperature. For both sink temperatures, thermal conductance increases almost linearly with increase of heat load. Among all the orientations, the peak value of thermal conductance is achieved at 6.6 W/C for horizontal case 3 where compensation chamber is located above the evaporator.

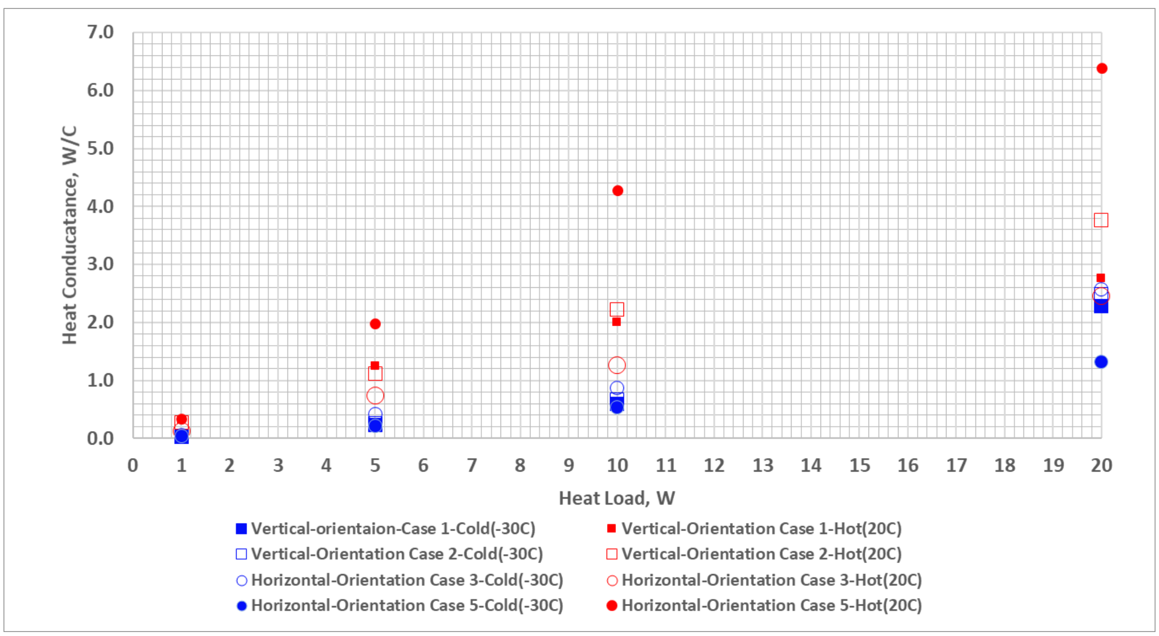


Figure 8: Comparison of thermal conductance for different orientations at different sink temperature.

DISCUSSION

LHP start-up process involves very complex transient phenomenon in the LHP operation. Four possible situations exist inside the evaporator/compensation chamber prior to loop startup[2]: (1) evaporator vapor grooves contain vapor while evaporator core is completely filled with liquid. This is the most favorable case for LHP startup; (2) Both the evaporator core and evaporator vapor grooves contain vapor. Similar to (1), LHP can start up easily but with a larger heat leak between evaporator and compensation chamber; (3) liquid occupies both the evaporator core and vapor grooves. LHP will start up once vapor is generated in vapor groove, which means liquid in vapor grooves needs to be superheated to initiate nucleate boiling; (4) vapor grooves are flushed with liquid and the evaporator core contains vapor. This is most difficult case for LHP startup since heat leak is large.

LHP start-up failed for horizontal case 4 for evaporator heat load up to 20 Watt, which is believed to similar to the scenario (4) described above. During the testing, it was observed that compensation chamber temperature increased simultaneously with evaporator temperature due to the large heat leak. Evaporator temperature increase was not faster than the compensation temperature, the required superheat was not achieved to initiate the nucleate boiling, so the loop didn't start successfully.

The relative larger heat load (5 Watt) required for LHP startup in the horizontal case 3 and case 5 for hot case is confusing since low heat load (1 Watt) can start up LHP for cold case. This needs further investigation.

The maximum heat transport capability of LHP is mainly determined by the primary wick pore radius and permeability. Theoretical analysis estimated the maximum power of 26.6 W and 25.8 W for cold case and hot case under 0-G condition. The smaller value of 20 W for vertical case 1 for both hot and cases are expected considering the high adverse elevations where condenser is above the evaporator. Following the same rationale, larger heat transport values were achieved for vertical case 2 for cold case. Considering the complex routing of condenser lines, the relatively smaller power limits are thought to be the effects of gravity for horizontal case 3 and 5 for both hot case and cold case. However, for vertical case 2 and cold case, only 20 W was achieved, similar to vertical case 1 and cold case. Considering LHP deprimed at 25 W for both cases and no values between 20 W and 25 W were tested, it is guessed that slightly higher power limit is achieved for vertical case 2/cold case than vertical case 1/cold case.

CONCLUSIONS

A miniature loop heat pipe with propylene as working fluid was tested for different orientations under two sink temperatures. The test results can be summarized as follows:

- The unit performed well to meet the requirements of the system under different orientations for the two sink temperatures except Horizontal Case 4 where LHP can't be started.
- Elevation and tilt have strong effects on the startup of LHP. The unit can be started with as low as 1W power for vertical orientations (case 1 and case 2). For horizontal oriental case 4 where reservoir was located below evaporator, LHP couldn't be started with power as high as 20W.
- Evaporator temperatures with increase of heat load showed different trends for the two sink temperatures: evaporator temperatures decreased with increase of heat load for sink temperature of -30°C, but increased for sink temperature of 20°C.
- With increase of evaporator heat load, the difference of thermal conductance of the unit for different orientations increased. For all the orientations, the thermal conductance is higher for sink temperature of 20°C than sink temperature of -30°C. Particularly, the unit has peak conductance 6.6 W/°C for Case3 for sink temperature of 20°C.

The current miniature loop heat pipe was developed for NASA GCD (Game Changing Development)-funded PALETTE project where thermal designs/technologies were developed to enable lunar instrument overnight survival without radioisotopes. The LHP in series with reverse-operation differential thermal expansion thermal switch (ROD-TSW) constitutes the variable conductance thermal link. The LHP is designed to start up when ROD-TSW is turned off at 273K. The maximal heat load is 20W and minimum conductance is required as 5 W/K. JPL has tested the LHP in vacuum chamber in December 2021 and the LHP performed as expected.

ACKNOWLEDGMENTS

The work presented in this paper was funded under NASA JPL PO 1656240.

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