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Thermal Performance Evaluation of a Small Loop Heat Pipe for Space Applications

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ABSTRACT

A Small Loop Heat Pipe (SLHP) featuring a wick of only 1.27 cm (0.5 inches) in diameter has been designed for use in spacecraft thermal control. It has several features to accommodate a wide range of environmental conditions in both operating and non-operating states. These include flexible transport lines to facilitate hardware integration, a radiator capable of sustaining over 100 freeze-thaw cycles using ammonia as a working fluid and a structural integrity to sustain acceleration loads up to 30 g. The small LHP has a maximum heat transport capacity of 120 Watts with a thermal conductance ranging from 17 to 21 W/°C. The design incorporates heaters on the compensation chamber to modulate the heat transport from full-on to full-stop conditions. A set of start up heaters are attached to the evaporator body using a specially designed fin to assist the LHP in starting up when it is connected to a large thermal mass. The total mass of the small Loop Heat Pipe, including the evaporator body and the radiator, is only 1.4 kg.

This paper describes the steady state and transient performance of the small LHP in four different orientations: vertical, horizontal, adverse and reflux. The tests include start up and shut off results for the four orientations at hot and cold case conditions. The results of the test program indicate that the small LHP can successfully transport moderate heat loads for many space related applications.

INTRODUCTION

The original motivation for the Small Loop Heat Pipe design was for removing waste heat on a Mars surface mission application. However, the design of the SLHP can be adapted to a wide variety of spacecraft thermal control schemes. The previous generation of Loop Heat Pipes used a 2.54 cm diameter evaporator wick and was capable of transporting several hundred watts of waste heat. But the thermal loads of many electronic components is on the order of 100 watts or less. Therefore, the large LHPs can be considered oversized for the heat loads they are required to carry. The Small Loop Heat Pipe uses a wick that is half the diameter of the large LHPs (1.27 cm diameter). Thus the mass of the evaporator, compensation chamber and transport lines can be significantly less in a small LHP compared to a large LHP. The SLHP was designed and developed by Dynatherm Corporation Inc. (DCI), which is now a part of Swales Aerospace. The tests conducted on SLHPs have demonstrated that they can meet heat removal requirements and all other mission requirements in many spacecraft applications.

The fundamental theory of LHP operation and descriptions of applications can be found in many papers.[1, 2] They were developed in the former Soviet Union in the early 1980s, and have flown successfully in a number of space missions. These include the ALYONA flight experiment launched in 1989 and the OBZOR optical instrument launched in 1994.[3, 4] Loop Heat Pipes are being used in a number of space missions currently under development such as the Geoscience Laser Altimeter System Instrument[5] and the Tropospheric Emission Spectrometer Instrument.[6] A description of the SLHP designed for use with the Mars Exploration Rovers can be found in Reference 7.

MAIN SECTION

SLHP DESIGN REQUIREMENTS

The SLHP is a low-weight means of removing excess heat from electronic components at a high conductance between the heat source and sink. It is a single evaporator, single condenser "classical" design except that the size of the evaporator is about half of the typical size used in standard LHPs. The evaporator was designed to operate well beyond the lower and upper allowable flight temperatures of typical electronic components. The condenser was sized to reject the heat load from the electronics with a high emissivity – low solar absorptivity surface coating. The condenser was also designed to withstand over 100 cycles of freezing and thawing ammonia since the night temperatures on Mars are lower than the freeze point of ammonia, -78°C. This represents a three-month long operating lifetime. This also demonstrates the potential for using the SLHP in other space applications in which it condenser may freeze during either normal or safing mode operations. The SLHP was also designed to withstand the pressure developed at a maximum operating temperature of 70°C. Additional unique design requirements include the capacity to withstand the transient g-loads generated by an airbag landing on Mars and flexible transport lines to facilitate integration into the spacecraft component during assembly operations.

Thermal Performance Requirements

The mini-LHP was designed to remove from 20 to 120 watts of heat with a source-to-sink conductance exceeding 10 W/°C for a fully active condenser. It had to start reliably from a heat load of 20 watts while attached to a 3-kg aluminum mass. Furthermore, it had to shut-off with a 1-watt heater attached to the compensation chamber. The start-up and shut-off requirements had to be met at both the typical upper and lower allowable flight operating temperatures (AFT) of electronic components attached to the SLHP.

Flight Qualification Requirements

A flight qualification program was developed and successfully implemented to bring the SLHP to flight readiness. The program included mechanical testing for proof pressure, landing loads, random vibration, vapor and liquid transport-line flexibility and ammonia leakage. The thermal qualification tests included demonstrating reliable start-up and shut-off, determining steady state heat transport, transient response on variable evaporator heat loads and condenser sink temperatures, and surviving non-operational temperature cycling between AFT extremes. The temperature cycling included bringing the condenser across the freeze/thaw point of ammonia over 100 times to demonstrate its survivability for three months on Mars. The start-up, shut-off, steady state performance and the transient response tests were performed for the vertical, adverse, and reflux orientations shown below in Figure 3. In the horizontal orientation only the start up and shut off tests were performed.

HARDWARE DESCRIPTION

A photograph of the SLHP is shown in Figure 1. The materials used in constructing the SLHP are common to the larger units flown on other spacecraft. The aluminum evaporator houses a porous sintered nickel wick. The evaporator has a fin at one end to accommodate two start-up heaters that provide a locally intense heat flux as far away as possible from the compensation chamber. The heaters are simply wire-wound power resistors. The stainless steel compensation chamber accommodates a film heater with redundant circuits for shutting off the fluid circulation within the LHP. The fill port attached to the compensation chamber is coplanar with the vapor outlet tube on the evaporator.

The radiator is an aluminum panel bonded to a stainless steel condenser line. It features a slot cut between the liquid and vapor lines to reduce liquid reheating from the vapor line. The liquid and vapor lines are heavy wall tubing that is sufficiently strong to withstand the pressures developed by the thawing ammonia after the radiator is frozen.

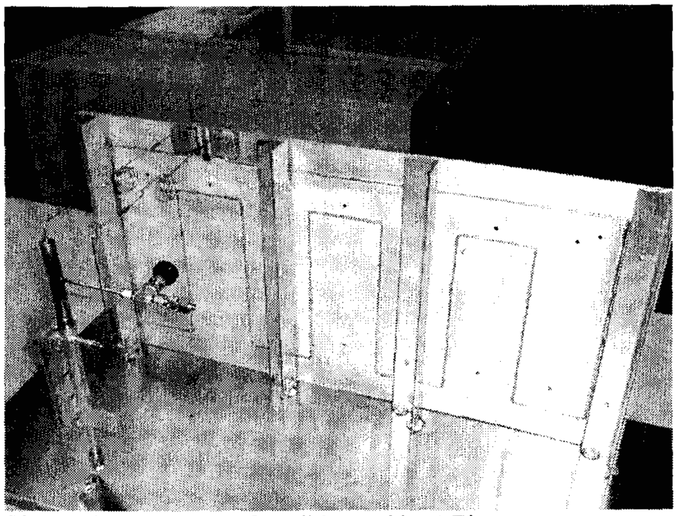

Figure 1. Prototype Small Loop Heat Pipe

DISCUSSION OF TEST RESULTS

MECHANICAL TESTS

Flexibility/Flexural Cycle Test

To facilitate integration purposes, the SLHP was subjected to a flex cycle test. This test was conducted while the SLHP was charged with ammonia. The test consisted of rotating the evaporator about the transport line coils to a set angle of rotation. The direction of travel and the angles of rotation are shown in Figure 2. The condenser was secured to a frame during the test with the transport line coils, and transport lines left unsupported. One cycle consisted of rotating the evaporator from its starting position to +90°, rotating back in opposite direction toward the condenser to -45°, and back over to starting position. The SLHP was cycled in this manner 50 times.

Most of the flexing occurred at the transport line coils as the evaporator was rotated over and back. The transport lines did distort and bend slightly during the test, but did not permanently set in a manner that would adversely affect its performance. The transport lines also did not kink or twist. The transport lines were left as is and were not adjusted following the test. A final adjustment to the transport lines was made during final inspection and preparations for shipping to JPL.

The SLHP was subjected to an ammonia leak test following the flexural cycle test and passed with no leaks detected. The test was conducted using a colorimetric developer with a sensitivity up to 1×10^{-7} scc/sec.

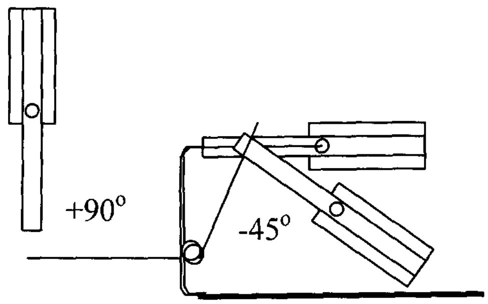

Figure 2. Flex Cycle Test Orientations

Landing Load Testing

The evaporator and condenser were subjected to a landing load test. The landing load to each component was simulated with a static load, and each component was tested separately. The landing load acceleration levels for the evaporator and condenser were above 30g.

To test the evaporator, a point load was applied to the surface of the compensation chamber. The compensation chamber is welded to the evaporator saddle and cantilevered. The point load was applied at the end of the compensation chamber where the liquid return line enters the compensation chamber, and in two orthogonal directions (parallel and perpendicular to the axis of the compensation chamber fill tube). The amount of force applied to the compensation chamber was determined by calculating the mass of the compensation chamber parts.

The evaporator was rigidly supported to a frame and leveled. A depth gauge was used to measure deflection of the compensation chamber during the test. The load was cycled three times in each of the two directions.

The compensation chamber and evaporator were visually inspected for damage following the test, and ammonia leak tested. There was no reported damage, or leaks to the compensation chamber, evaporator, or evaporator-to-compensation chamber bi-metal. The deflection of the compensation chamber was completely elastic.

The SLHP radiator was statically loaded by uniformly distributing a predetermined amount of lead shot over the surface of the radiator. The load was applied to both the front (condenser side of panel) and back surfaces of the radiator. A depth gauge was used to measure deflection of the panel during the test.

The amount of lead shot distributed over the surface of the radiator was determined by calculating the total mass of the radiator.

For the setup, the radiator was secured to a vibration test plate with spacers. The spacers, measuring 1.27 cm in diameter and 5.08 cm long, were placed at each mounting hole in the radiator. Fasteners were then used to secure the radiator to the vibration test plate. This setup lifted the radiator from the vibration plate and provided a stable and secure method of applying a static load to the radiator surface.

To contain the lead shot, a Styrofoam barrier was constructed and placed around the edges of the radiator. A slit approximately 0.3 cm deep was cut into the Styrofoam and the radiator edges were pushed into the Styrofoam. This setup covered approximately 0.3 cm of the radiators outer perimeter, and provided a stable barrier to contain the lead shot during the test. The lead shot was applied slowly and uniformly over the surface of the radiator and removed by vacuum once the test was complete.

Inspection of the radiator following the test revealed superficial cracks in the solder-to-condenser, and solder-to-radiator panel bond. The condenser line however remained firmly bonded to the radiator panel. The loop was helium leak checked following the test and passed.

Random Vibration Testing

The SLHP was successfully vibration tested at the Applied Physics Lab (APL) to typical random vibration levels associated with a Delta II launch vehicle. The SLHP test setup was visually checked following each test in each orientation. No damage was discovered during or following each test.

THERMAL TESTS

The SLHP was thermal performance tested to determine heat transport capability, thermal conductance, start-up and shut-off behavior, and the transient response of the SLHP.

All thermal performance tests were conducted in a temperature controlled environmental chamber. Temperature controllers were used to maintain and control chamber temperatures to ±3°C. Liquid nitrogen was used to cool the chamber and an internal heater was used to heat the chamber. The SLHP was tested in four orientations; the four test orientations are illustrated in Figure 3. The SLHP was placed in a test orientation before the start of each test and the evaporator and condenser were leveled. The type of thermal tests performed in each orientation is detailed in Table 1.

The evaporator, evaporator heater block, compensation chamber, liquid transport line, and vapor transport line were separately thermally insulated from ambient sink temperatures to minimize parasitic heat leaks during thermal performance testing. To eliminate large air gaps between the transport lines and the insulation and heat exchange between the transport lines, each transport line was individually wrapped in foam insulation.

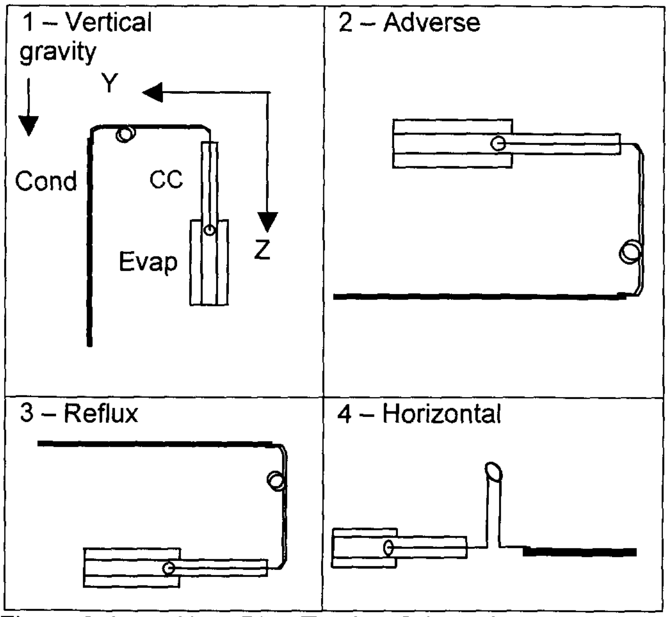

Figure 3. Loop Heat Pipe Testing Orientations

Table 1. Thermal Performance Test Type, Orientations, and Sink Temperatures

Orientations	Thermal Tests	Sink Temp
1 - Vertical 2 - Adverse 3 - Reflux	Startup	Hot Sink (0°C)
		Cold Sink (-5°C)
	Shutoff	Hot Sink (30°C)
		Cold Sink (-20°C)
	Steady State	Hot Sink (37°C)
		Cold Sink (-50°C)
	Transient	Hot Sink (37 °C)
		Cold Sink (-50°C)
		Sink Transient (37°C → -50°C)
4 - Horizontal	Startup	Hot Sink (0°C)
		Cold Sink (-50°C)
	Shutoff	Hot Sink (30°C)
		Cold Sink (-20°C)

The evaporator was also equipped with startup and shutoff heaters as shown in Figure 4. The startup heaters were bolted to the vertical flange located on the evaporator body. A film/strip heater with an adhesive backing was wrapped around the compensation chamber.

The evaporator was bolted to a standard heater block during steady state and transient response tests. This heater block consisted of an aluminum block ½ inch thick with a footprint the same size as the evaporator saddle, and a cartridge style heater. The heater block was unbolted during shut-off and start-up tests and replaced with a 3 kilogram thermal mass. The thermal mass was also equipped with a cartridge heater. Both the heater block and thermal mass were thermally insulated during all thermal performance tests. Thermal grease was applied to interface of the heater block/thermal mass and evaporator.

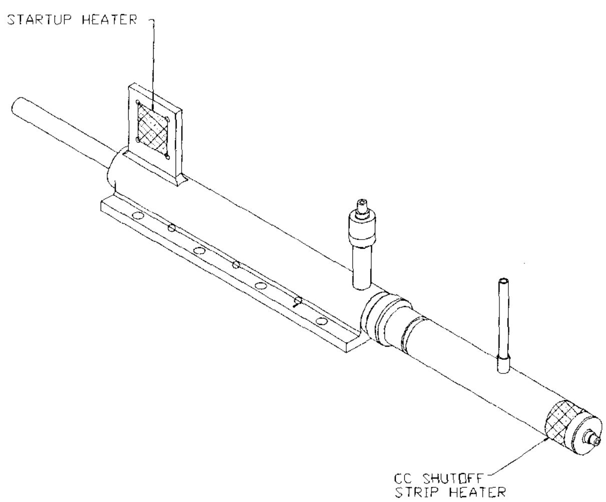

Figure 4. Evaporator shown with Shut-off heater, and Start-up Heater

Startup Tests

The SLHP started successfully in all four orientations when exposed to both hot and cold sink conditions with the evaporator never exceeding a typical maximum flight allowable temperature limit of 50°C. All start-up tests were conducted with the evaporator saddle bolted to the 3 kilogram thermal mass.

The compensation chamber was preconditioned at the start of each start-up test by applying 10 watts of power to the compensation chamber strip heater for a minimum of 5 minutes. Sink conditions were set in the test chamber following preconditioning of the compensation chamber. Once condenser and evaporator initial temperature conditions were reached and the SLHP reached steady state, 10 watts of power was applied to both thermal mass heater and evaporator startup heaters (20 watts total power). Power to the heaters was applied until a successful start was achieved and maintained until steady state.

Power to the compensation chamber heater was applied, following preconditioning, during cold case startup in orientation 3 (reflux), and hot case startup in orientation 1 (vertical). The compensation chamber heater was applied to keep the SLHP from starting during the sink transition.

Table 2 below lists each startup test with the approximate time for loop startup once start-up power was applied the evaporator. It also lists the initial condition of the evaporator and the temperature of the evaporator at startup.

Table 2. Start-up Test Results of the SLHP

Test Configuration	Initial Temp		Time to Start	Evap temp at start up
	Evap	Sink		
1 – vertical	20°C	0°C	5 min	21°C
1 – vertical	0°C	-50°C	330 min	18°C
2 – adverse	20°C	0°C	17 min	27°C
2 – adverse	0°C	-50°C	225 min	22°C
3 – reflux	20°C	0°C	40 min	30°C
3 – reflux	0°C	-50°C	2 min	-3°C
4 – horizontal	20°C	0°C	60 min	38°C
4 – horizontal	0°C	-50°C	25 min	4°C

Shutoff Thermal Tests

One of the desirable features of the SLHP is the capability of shutting off the heat transfer by applying a small heat load to the compensation chamber. On a Mars Rover application for example, this feature is attractive for retaining heat within the Rover so that the nighttime heat requirements may be somewhat reduced. One test was performed with the SLHP in the vertical orientation to compare the amount of energy removed from a 3 kg aluminum mass when the compensation chamber heater was used versus not used to stop the SLHP. The temperature of the thermal mass after a 50-watt heat load was stopped while the SLHP was operating is shown in Figure 5.

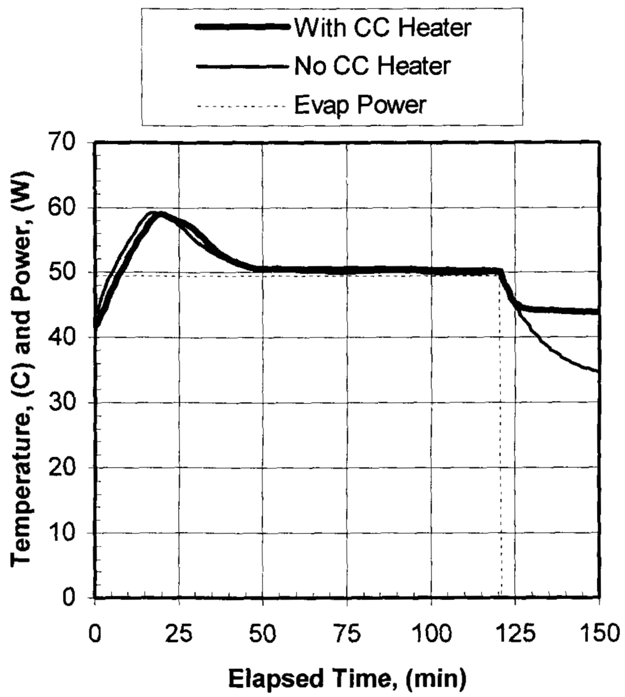

Figure 5. Temperature of the Thermal Mass in a Comparison of LHP Shut Off With and Without Using the Compensation Chamber Heater.

When the compensation chamber heater is applied after the electronic component is shut off, the SLHP stops removing heat in a few minutes, thus conserving energy by storing it in the thermal mass. If the compensation chamber heater is not activated, the SLHP continues to remove energy for a longer period of time. In the test shown, the SLHP brought the thermal mass down an additional 10°C before it finally stopped removing heat from it. This resulted in removing 27 kJ of energy that could possibly have been required from the battery during nighttime heating. This is equivalent to operating a 10-watt heater for 45 minutes. During the colder phase of a mission, the compensation chamber heater could be activated when the electronics are turned on to prevent the SLHP from operating and removing energy that should be conserved as heat within the Rover.

The shutoff tests were performed in hot and cold sink conditions, and in all four orientations. All shutoff tests were conducted with the evaporator saddle bolted to the thermal mass. All shut-off tests were successful with the compensation chamber temperature remaining above the evaporator temperature, and the SLHP remaining non-operational. Hot and cold sink temperature conditions for the shutoff tests is listed in Table 3 below.

Sink temperature conditions were set at the start of each test, and condenser temperatures were allowed to reach equilibrium (±3°C) for a minimum of 15 minutes before applying power. Once equilibrium was reached, 100 watts of power was applied to the evaporator thermal mass. Power to the thermal mass was maintained until the system reached equilibrium (±1°C) at which time power to the thermal mass was shutoff, and ≤1 watt of power was applied to the compensation chamber strip heater. The SLHP was then monitored until shut-off and system equilibrium was reached. Table 3 lists each shutoff test with the approximate time for loop shut-off once power to the compensation chamber was applied.

Table 3. Shut-off Test Results

Test Configuration	Sink	Time To Shutoff
1 - vertical	30°C	12 min
1 - vertical	-20°C	15 min
2 - adverse	30°C	8 min
2 - adverse	-20°C	12 min
3 - reflux	30°C	52 min
3 - reflux	-20°C	68 min
4 - horizontal	30°C	10 min
4 - horizontal	-20°C	12 min

Steady State Thermal Tests

The thermal performance of the SLHP was tested at maximum and minimum sink conditions. Each test consisted of applying an increasing power step change sequence to the evaporator heater and measuring thermal conductance at equilibrium in each sequence. Steady State tests were performed in orientations 1, 2, and 3.

The thermal mass used in the start-up and shut-off tests was removed during the steady state tests and replaced with a standard heater block. Once the SLHP was oriented and prepared for testing, the environmental chamber sink temperature was set and stabilized. Condenser thermocouple temperatures were monitored and the condenser temperature was allowed to stabilize to (±3°C) for a minimum of 15 minutes before power was applied to the evaporator heater. The power step changes during each test started at 20 watts and incrementally increased by 20 watts to dryout, or until a maximum evaporator temperature of 70°C was reached. With each 20 watt increment of power to the evaporator temperatures were monitored and allowed to stabilize (±1°C) for a minimum of 15 minutes before the next power increment.

Maximum power for the SLHP was determined from hot case steady state tests. Unlike cold case steady state tests, hot case power increments were limited by a maximum allowable flight qualification temperature of 70°C. Cold case power increments were limited by dryout conditions. Maximum temperature of the evaporator during hot case tests was reached at 140 watts in test orientations 1, 2, and 3.

Dryout conditions were reached at 180 watts during cold case tests. Dryout is defined as an evaporator temperature greater than 20°C above the vapor saturation temperature. The vapor saturation temperature was measured at the compensation chamber. Maximum power was then determined to be 80% of 140 watts reached during hot case tests, or 112 watts.

Overall thermal conductance was calculated and is listed in Table 4 for power increments of 40, 60, 80, and 120 watts. Evaporator thermal conductance was also calculated and is listed in Table 5 for power increments of 40, 60, 80, and 120 watts.

Table 4. Overall Conductance, Steady State Hot and Cold Case

Power	Hot Case Orientations Overall Conductance		
	1-Vertical (W/°C)	2- Adverse W/°C	3-Reflux W/°C
40 W	20	17	20
60 W	20	19	19
80 W	20	21	19
120 W	19	18	19
	Cold Case Orientations Overall Conductance		
40 W	2	1	1
60 W	3	2	2
80 W	2	2	2
120 W	3	4	5

Table 5. Evaporator Conductance, Steady State Hot and Cold Case

Power	Hot Case Orientations Evaporator Conductance		
	1-Vertical (W/°C)	2- Adverse W/°C	3-Reflux W/°C
40 W	39	40	43
60 W	40	42	37
80 W	41	42	38
120 W	37	36	38
	Cold Case Orientations Evaporator Conductance		
40 W	16	20	18
60 W	15	20	19
80 W	20	20	21
120 W	23	23	23

Transient Response

The SLHP response to both a power transient and to a sink transient was tested. Power transient tests were performed at both hot and cold sink conditions. All sink transient tests were performed at a set evaporator heater power. Like the steady state thermal tests, the transient response tests were performed without the thermal mass bolted to the evaporator saddle to demonstrate the SLHP can accommodate rapid changes in conditions. Transient response tests were performed in orientations 1, 2, and 3.

Power transient response tests were performed at hot case and cold case sink temperatures. Hot case sink temperatures were set to 37°C, and cold case sink temperatures were set to -50°C. One cycle during each power transient test consisted of the following power increments: 0, 20, 112, 20, and 0 watts. Cold case power transients were performed with the same power increment but in two consecutive cycles. An example of one of these cycles is shown in Figure 6.

Sink transient tests were performed with 50% of the maximum power applied to evaporator or 56 watts. Power was maintained during the tests while the sink temperature was reduced to -50°C at an average rate of ≥4°C. Sink temperatures were set to 37°C at the start of each test and allowed to stabilize. The temperature of the condenser was monitored once sink temperatures were reached and allowed to stabilize (±3°C) for a minimum of 15 minutes. Once condenser temperatures stabilized 56 watts of power was applied to the evaporator and temperatures once again were monitored and allowed to stabilize (±1°C) for a minimum of 15 minutes. The environmental chamber temperature controller was then set to –50°C and the sink transient was monitored as the temperature reduced at an average rate of ≥4°C to –50°C. Loop temperatures were monitored and allowed to stabilize (±1°C) at minimum sink temperatures for a minimum of 15 minutes. An example of one of these transients is shown in Figure 7.

The SLHP was monitored during both power and sink transient tests. The SLHP temperatures did not overshoot or undershoot during these tests, and the SLHP did not shutdown during any of the tests.

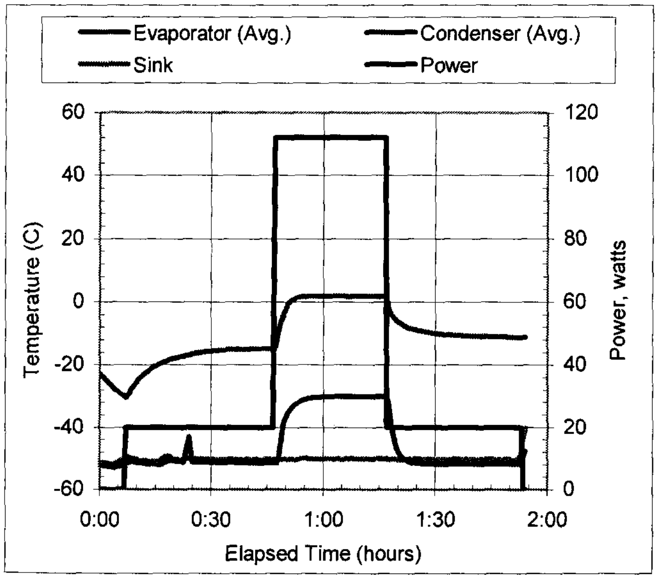

Figure 6. SLHP in Adverse Orientation with Cold Sink Power Transient.

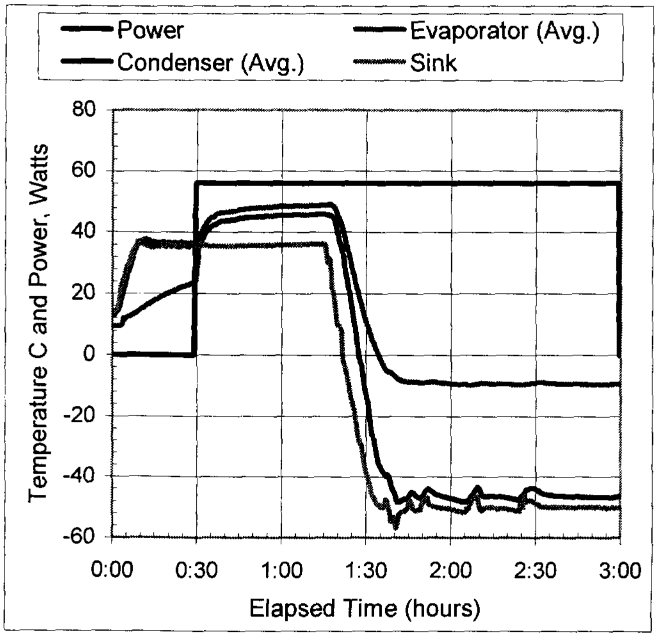

Figure 7. SLHP in Adverse Orientation with Rapid Sink Transient Response.

Temperature Extreme/Thermal Cycling

Following transient performance testing, the SLHP was exposed to a thermal cycle test/temperature extreme test. The evaporator and condenser were exposed, separately, to ten (10) cycles of the temperature extremes as described below. The exposure time at each temperature limit was no less than 30 minutes.

To test the evaporator the entire SLHP was placed in a thermal cycle chamber and the temperature was cycled to the evaporator's extremes of -45°C to 70°C. The SLHP was instrumented with thermocouples to monitor temperature during the test.

The condenser was tested, separately, by attaching it to a plate equipped with cooling lines and strip heaters. The temperature limits for the condenser temperature extreme test were -120°C to 70°C. Thermocouples, distributed over the surface of the radiator, were used to monitor the temperature of the condenser and ensure uniformity during the test.

The SLHP was leak tested with a colorimetric developer following the test with no leaks detected.

Freeze/Thaw Cycling

A major concern by many thermal engineers is the freezing of ammonia in a condenser and alternative fluids have been investigated that have lower freezing points as one solution to this problem.[8] A freeze/thaw cycle test was conducted on the SLHP for over 100 cycles. The performance of the SLHP was not adversely effected by the end of the test. Each 6 hour test cycle consisted of starting the condenser sink at 40°C and dropping the temperature linearly to -120°C in 2.5 hours. The sink dwelled at -120°C for 30 minutes then ramped back up to 40°C in another 2.5 hours. Lastly, the sink dwelled at 40°C for 30 minutes to complete the cycle. The evaporator was attached to a 3 kg aluminum mass for these tests. A heat load of 50 watts was applied to the thermal mass when the radiator temperature was above 0°C. The heat load was on for approximately 90 minutes in each cycle. When the radiator temperature was below 0°C, the heat load was turned off and the compensation chamber heater was activated at 1 watt. There were never any problems starting the SLHP in the freeze/thaw cycles.

A summary of the temperatures of the key components during a typical freeze/thaw cycle is shown in Figure 8. The figure shows the power levels of both the evaporator heater and the compensation chamber heater. The figure also shows reliable start up and shut down of the LHP. An interesting feature in the figure is the sudden drop in the radiator inlet temperature, which occurs when the radiator temperature reaches the melting point of ammonia.

One reason the freezing and thawing of ammonia works in this radiator design is because the transport lines are only 1.6 mm in diameter and have a relatively thick wall. Thus the stresses within the condenser lines are comparatively smaller than traditional LHP condenser lines where the diameter is typically about 6.4 mm.

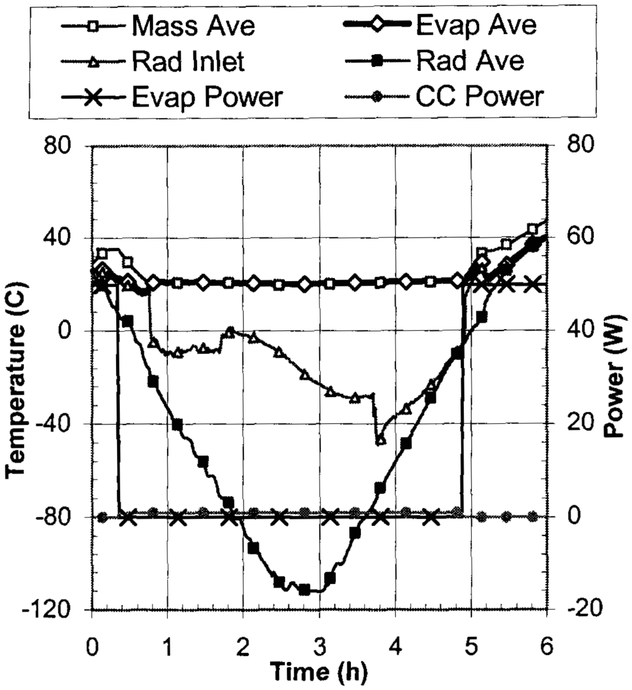

Figure 8. A Summary of Component Temperatures During a Typical Freeze/Thaw Test on the Condenser.

CONCLUSION

The SLHP described in this paper has successfully demonstrated its capacity for removing heat loads generated by typical electronic components on many spacecraft. The unit has a mass of only 1.4 kg and offers several desirable features such as flexible transport lines to facilitate integration, able to withstand freeze/thaw cycles within the condenser, and can handle the acceleration loads experienced on typical Mars surface landings using airbags. Furthermore, the SLHP starts up and shuts off reliably and the compensation chamber heater can be used to modulate the heat transport through the loop. Since it has successfully passed a rigorous flight qualification program, the SLHP is suitable for thermal control in a variety of spacecraft applications.

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