A Mini Loop Heat Pipe Suitable for Mars Rovers

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Abstract

Rovers used in exploration of Mars have significant challenges for thermal control of electronics and instruments. Seasonal and daily temperature variations create conditions in which heat rejection and heat retention must be accommodated in the Rover thermal design. The Loop Heat Pipe (LHP) allows excess heat to be rejected during the warmest phase of the mission while allowing heat to be retained during the coldest phase of the mission. This paper describes the thermal design requirements, the thermal performance characteristics and the flight qualification program of a mini-LHP suitable for the Mars Rovers. It was qualified to operate over a temperature range of –15°C to +70°C at the evaporator and -120°C to +65°C at the condenser. Ammonia was used as the working fluid. The performance was evaluated with a heat load ranging from 20 to 90 watts. The LHP demonstrated satisfactory performance during start-up with an attached thermal mass of 3 kg of aluminum and successful shutdown with a 1-watt compensation chamber heater. The condenser operated successfully through 100 freeze-thaw cycles without any physical damage or permanent deformation.

Key Words: Mini-Loop Heat Pipe, Mars Rovers, Thermal Performance

INTRODUCTION

There are significant challenges for thermal control of electronics and instruments on Rovers used for exploration of Mars. Surface temperature variations from -100°C to +30°C create conditions in which daily heat rejection and heat retention must be accommodated in the Rover thermal design. High-power electronics dissipate significant amounts of heat during daytime operations and this needs to be removed to keep them below maximum allowable flight operating temperature and not limit the science return during the mission. The LHP selected for Mars Rovers was based on a miniature heat pipe designed and developed by Dynatherm Corporation Inc. (DCI), which is now a part of Swales Aerospace. The tests conducted on mini-LHPs have demonstrated that they can meet heat removal requirements and all other mission requirements.

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]

LHP Design Requirements

The mini-LHP is a low-weight means of removing excess heat from Rover electronics 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 condenser is sized to reject the heat load from the electronics to the Mars daytime ambient environment with a high emissivity – low solar absorptivity surface coating. The evaporator was designed to operate well beyond the lower and upper allowable flight temperatures of typical electronic components. The condenser must 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. The mini-LHP was also designed to withstand the pressure developed at the maximum expected operating temperature of 70°C. Additional unique design requirements include the capacity to withstand the transient g-loads generated by an airbag landing and flexible transport lines to facilitate integration into the Rover during assembly operations.

Thermal Performance Requirements

The mini-LHP was designed to remove from 20 to 100 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 upper and lower allowable flight operating temperatures (AFT) of the LHP.

Flight Qualification Program

A flight qualification program was developed and successfully implemented to bring the mini-LHP 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 four orientations shown below in Figure 1. The remaining tests were performed in the vertical orientation shown in Figure 1. This is the preferential orientation for a LHP on a Rover.

DESCRIPTION OF HARDWARE

A photograph of the qualification mini-LHP is shown in Figure 2. The materials used in constructing the mini-LHP 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.

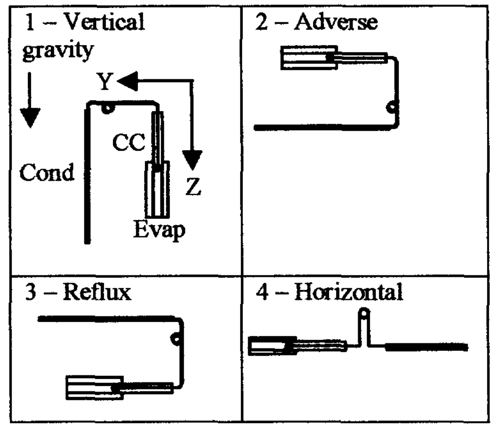

Figure 1. Loop Heat Pipe Testing Orientation Nomenclature

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 during the Martian night.

Figure 2. Photo of the mini-LHP Developed for use on Mars Rovers.

TEST PROGRAM DESCRIPTION

An engineering mock up (EM) of the mini-LHP was tested at JPL to develop specifications for a flight qualification test program. The EM unit was installed in a test stand shown in Figure 3. The condenser was mounted to a cold sink that used liquid nitrogen as a coolant. The temperature of the condenser was controlled by regulating a solenoid valve in the liquid nitrogen supply line. The condenser could be maintained at a fixed temperature or it could track predictions for daily diurnal temperature variations of the Mars ambient environment. The condenser and cold sink were insulated and sealed from the ambient environment (as shown in Figure 3) and kept dry with a gaseous nitrogen purge.

Figure 3. Mini-LHP on the Test Stand; the evaporator is in the foreground box and the condenser is in the background box.

The evaporator was attached to a bracket and a heated aluminum mass to simulate an electronic component. A box with an embedded heat exchanger was placed around the evaporator. The box simulated the boundary conditions of the Rover Warm Electronics Box (WEB). A recirculating chiller was connected to the heat exchanger in the WEB to maintain specific boundary conditions. This could be set to maintain a specific temperature or it could be used to mimic the diurnal temperature variation in the WEB boundary condition. The box was also insulated and sealed from the ambient environment. A nitrogen purge was used to keep moisture from condensing on cold surfaces. The LHP was instrumented with 45 thermocouples as shown in Figure 4.

The EM unit was used to determine the thermal conductance between the evaporator and condenser over a range of heat loads, sink conditions and orientations. While making these measurements, the heat leaks from the evaporator were minimized by setting the WEB temperature equal to the evaporator temperature. A guard heater on the mounting surface of the thermal mass minimized the heat leak through this path. The temperature of the mounting surface was set to equal the temperature of the thermal mass.

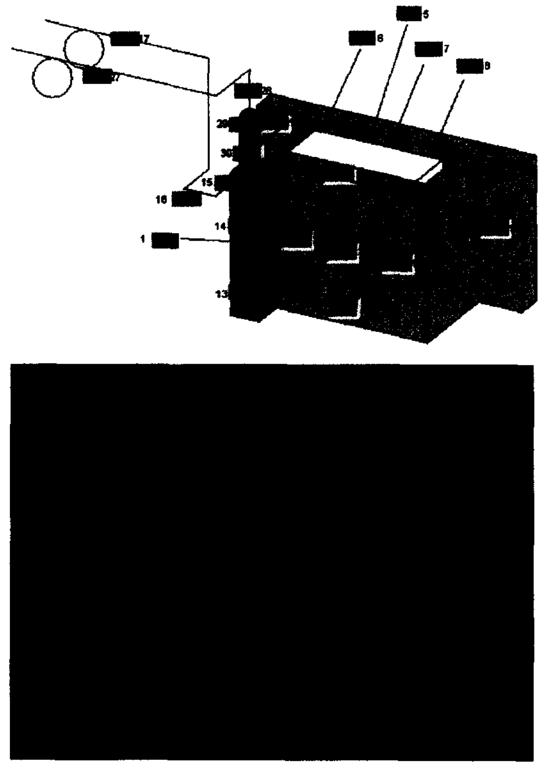

Figure 4. Schematic of Thermocouple Instrumentation on LHP Components and Thermal Mass.

In start-up tests, the evaporator was pre-conditioned to a hard liquid fill of the vapor grooves by using the compensation chamber heater to warm it a few degrees above the evaporator temperature for about five minutes. This provides the LHP with the most difficult starting condition.

The general procedure used for the freeze/thaw test of the condenser consisted of cycling it between +40° and -120°C. The temperature was changed from one extreme to the other in 2.5 hours followed by a 0.5 hour dwell at both temperature extremes. It took 6 hours to complete one cycle. A heat load of 50 watts was applied to the evaporator to verify that the LHP was functional when the condenser temperature was above 0°C during the cycle. When the condenser was below 0°C, the evaporator heater was turned off and the compensation chamber heater was turned on with 1 watt. This ensured that the evaporator was preconditioned every cycle in the same way.

DISCUSSION OF TEST RESULTS

An important parameter required in designing a thermal system in a Mars Rover is the overall thermal conductance of the LHP. This allows the radiator to be properly sized for removing the excess heat load during daytime operations. The thermal conductance between the evaporator and condenser was calculated for a 36-watt heat load. This was the highest heat load from any of the electronic components in the Rover.

The results of this test are shown in Figure 5. For an electronic component with a maximum AFT of 50°C, the conductance at an evaporator temperature around 45°C is most important. This allows for a 5°C temperature drop across the interface between the evaporator and the heat source. Thus for a 36-watt heat load, the temperature drop from the evaporator to the condenser is only about 1.5°C at the component AFT. The conductance at lower component temperatures is not that important because there is plenty margin available for heat removal.

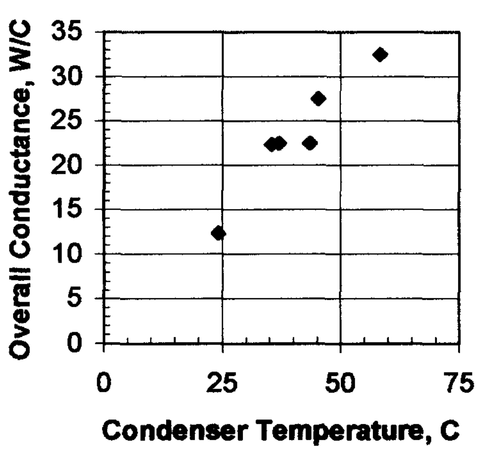

Figure 5. Effect of Condenser Temperature on the Mini-LHP Source to Sink Conductance.

The heat transfer performance of the LHP was also tested over a range of power levels to broaden the scope of applicability. Power was applied to the evaporator in the following sequence: 50, 70, 90, 70, 50, 30, 20, 30, and 50 watts. This scheme checked for hysteresis in the LHP but none was observed in any of the tests. The thermal performance test was done with condenser sink temperatures of 0°, 10°, 20°, 30° and 40°C. A typical time plot (in minutes) of the average evaporator and condenser temperatures for a thermal performance test is shown in Figure 6. The oscillations (usually less than ±0.5°C) in the temperatures are due to the controller that regulated the liquid nitrogen flow to the heat sink.

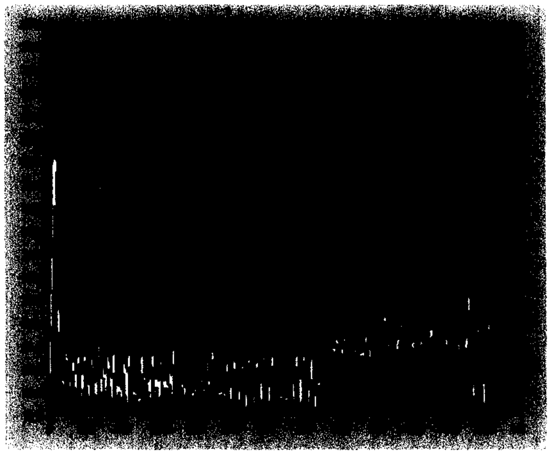

Figure 6. A Typical Performance Test of the LHP with an Evaporator Load Range of 20 to 90 Watts with a 20°C Condenser.

The results of the heat transfer performance testing are shown in Figure 7. The general trend is that the conductance increases for both increasing heat loads and increasing sink temperatures. An anomaly was observed between the 30° and the 40°C sink data. The conductance of the LHP was significantly higher at the 30° sink than at the 40°C sink. This was not observed in the conductance test in which the power was fixed while the sink temperature was varied. The cause of this anomaly is under investigation. It was also observed that the LHP would stop working for heat loads less than about 20 watts except when the sink temperature was at least 30°C. It is shown in Figure 7 that heat loads of 10 watts were sustainable for 30° and 40°C sink temperatures.

The heat transfer performance test was run with a 20°C sink before and after testing the freeze/thaw cycling of the condenser over 100 times. There was no significant difference in the performance of the LHP after the freeze/thaw cycling. 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. It is difficult to see when the CC heater was turned on in the figure because it was only powered with 1-watt. Basically, it was turned on when the evaporator heater was turned off. The figure also shows reliable start up and shut down of the LHP. An interesting feature in the feature is the sudden drop in the radiator inlet temperature, which occurs when the radiator temperature reaches the melting point of ammonia.

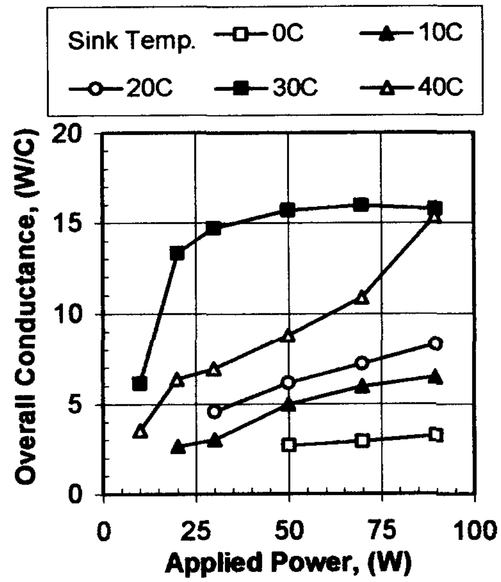

Figure 7. The Thermal Conductance of the Mini-LHP for a Range of Heat Loads and Sink Temperatures.

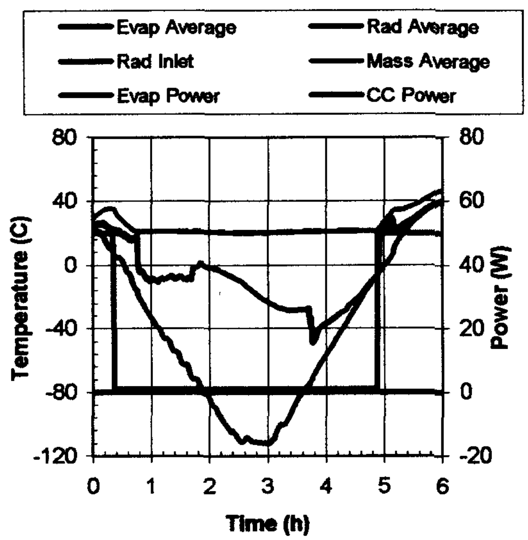

Figure 8. A Summary of Component Temperatures During a Typical Freeze/Thaw Test on the Condenser.

CONCLUSIONS

Electronic equipment used in Mars Rovers must be contained in a well-insulated chassis because of the extremely cold Martian environment. However, this "thermos bottle" packaging can cause overheating of the equipment during daytime operations. The excess heat must be either rejected to the ambient environment or put into a thermal storage device. The mini-LHP described in this paper can be configured to move excess heat to either the ambient environment or a thermal storage device. These options are discussed further in a companion paper.[7] Restrictions on mass allocations discourage using thermal storage, thus the mini-LHP development has favored the heat rejection configuration.

The mini-LHP has successfully demonstrated that it meets the mechanical and thermal requirements for flight on a Mars mission.

Acknowledgements

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