Thermal Control of Mars Rovers and Landers Using Mini Loop Heat Pipes

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Abstract

Effective thermal control of Mars surface vehicles and their equipment is key to their long-term survival on the Martian cold surface. Two miniature loop heat pipe (LHP) designs consisting of ½ diameter wicks and 1/16 inch diameter transfer tubes were investigated for their suitability for the thermal control of future Mars rovers. The first LHP concept used a single evaporator, two condensers and a thermal control valve to transfer about 10 Watts of heat. The second LHP concept used a single evaporator and a single condenser to transfer about 50 watts of heat. The results of this investigation are described in the paper.

Key Words: Miniature loop heat pipes, Mars rover, Thermal control

1. INTRODUCTION:

The long-term survival and operation of Mars landers and rovers depends critically on the thermal control of their batteries, electronics and the science instruments. The thermal environment on the Martian surface is harsh where the ambient temperatures range from +10 C during the day to –100 C at night Without a proper thermal control, the inside equipment temperatures can drop down below – 60 C at night even with a highly efficient thermally insulated enclosure for the equipment whereas the daytime temperature can go above 60 C. The low inside temperature at night is due to the cold ambient conditions along with most of the heat dissipating rover equipment not operating while the hot temperature during the day is a result of the hot ambient conditions along with the most of the rover equipment operating during the daytime. Several advanced thermal technologies are being investigated for application to rover and lander thermal control. One of the heat transfer devices that is critical for the effective thermal control of the rover is a heat switch. Among the several technologies considered for this function, loop heat pipe (LHP) is a very promising technology. The LHP, which is a passive two-phase device, not only functions as an efficient device to transfer heat over long distances in adverse gravity environment but also as an effective heat switch. These two functions make the LHP a very attractive to Mars rover and lander thermal control.

The LHP was originally developed in the former Soviet Union and has flown on several Russian spacecraft [1, 2]. It is being increasingly used during the last five years for the thermal control of spacecraft. It has been used on communication satellites and earth orbiting spacecraft that are currently operating in space. The key thermal control functions performed by LHPs on these spacecraft are: 1) removing excess heat from the electronics and other high heat dissipating equipment to an external radiator and 2) stopping transferring heat when the equipment temperatures fall below a pre-determined value. However, most of the LHP devices that are being flown are large ones that transfer over 100 Watts and as much as 1000 Watts of heat. These typically have an evaporator wick of one inch or larger diameter and weigh 2 kg to 5 kg depending on the power level and transfer distance. For most of the rover and lander thermal control applications, the need is for a miniature loop heat pipes that can transfer upwards of 5 Watts but less than 100 Watts. The heat transfer distances are less than one meter long. The miniature LHPs can be defined as those with an evaporator wick diameter of less than ½ inch and transfer lines that are less than 1/8 inch diameter The advantages of a miniature LHP are that it operates efficiently at low power levels and that it is very light and its transfer lines are flexible and can easily conform to the rover's tight interior dimensions. The LHP was chosen for investigation over another capillary pumped two-phase device, the capillary pumped loop (CPL), due to the LHP's simplicity of operation for the Mars rover surface operations

2. THERMAL CONTROL OF MARS ROVERS AND LANDERS

The key challenges of thermal control for Mars rovers and landers on the Martian surface is to keep the sensitive engineering and science equipment within their allowable flight temperature (AFT) range during their diurnal operations. The current generation of Mars rovers typically weighs less than 150 kg and has peak power levels of less than 200 Watts. The most temperature sensitive equipment inside the rover are the secondary batteries, electronics, and the science payload. Typically the Li-ion batteries, which are currently used in the rover, have an allowable temperature range of –20C to +30 C. The electronics have a range of –40 to +50 C, whereas the AFT for science equipment is in the range of –40 C to +60 C. A typical Mars rover configuration consists of a warm electronics box (WEB) inside of which all the temperature sensitive equipment such as batteries, electronics, and science instruments are housed. The WEB provides both structural enclosure and also a thermal insulation for inside equipment. A typical rover is shown in Figure 1 with key components.

The key thermal control functions needed for rover and lander are 1) minimizing the heat losses from the rover equipment enclosure at night, 2) removing heat from high heat dissipating equipment, 3) keeping the equipment within the AFT limits during Mars operations. The typical thermal control design of a rover consists of: super thermal insulation to minimize the heat leaks to ambient during the night, an efficient heat switch that can transfer heat from high heat dissipating equipment to outside during the hot part of the day, and a heat source to keep the inside equipment above the minimum AFT at night. Besides the internal components, the external components also need to be controlled to their AFT temperatures.

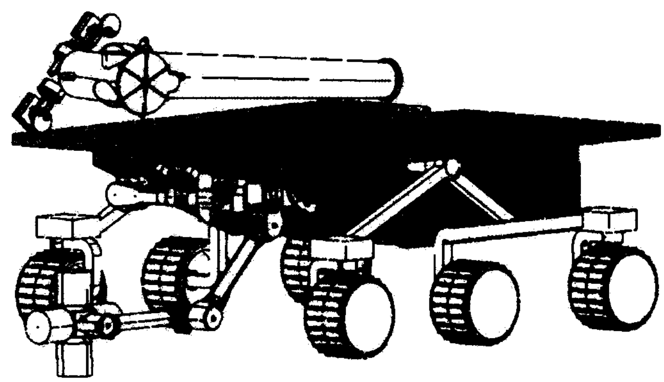

Figure 1. Mars Rover Conceptual Configuration

Aerogel has been used as the super thermal insulation in the enclosure. A thermal conductivity of 0.015 W/mK can be achieved with this material. Some other insulation materials that can be used are batt and Eccofoam. Some of the thermal control technologies that can be used for the heat switch are; mechanical switches, two-phase devices such as loop heat pipes, and a mechanically pumped liquid loop. Each of these has certain advantages and disadvantages compared to the other. A comparison of these technologies is shown in Table 1. The thermal control of the external components is typically accomplished by the use of thermal insulation material or appropriate thermal coatings on the surfaces and heater elements that would keep the equipment above their minimum AFT at night.

The thermal hardware that can be used for the Mars rover and lander is restricted due to Martian surface conditions and the mobility operations. Some of the thermal control devices used in earth orbiting or deep space spacecraft cannot be used in Mars vehicles due to the constraints on the surface. Some of these constraints include: the existence of a gravity environment, the presence of atmosphere, dust storms that are present during significant part of the year on the surface, the need to keep the hardware mass as light as possible, and the vehicle mobility and its dynamics. For example, multiplayer insulation (MLI) and mechanical louvers typically used on spacecraft are not suitable for Mars rovers and landers because of the dust and the presence of a gaseous atmosphere.

3. LHP for MARS EXPLORATION ROVER

As part of the Mars Exploration Rover (MER) mission, NASA will be sending two identical rovers in May and June of 2003. The two rovers will arrive on Mars in January of 2004 for a 90 sol mission. In terms of the thermal control design of MER rover, two key challenges have been to keep the Lithium-Ion secondary battery and the Solid State Power Amplifier (SSPA) of the telecom transmitter within their AFT. Both these applications needed an efficient heat switch that could remove heat to external radiators during the hot conditions and thermally isolate the radiator from the components during the cold conditions. The maximum heat transfer capacity needed for the battery was about 8 Watts whereas for the SSPA it was 60 Watts. After evaluating several concepts for heat switch applications, two miniature LHP configurations were identified for these two components. The LHPs using ammonia as a working fluid were designed, built and tested.

There are several characteristics of a mini LHP that makes it especially applicable to the MER rover. The first one is that ammonia LHP can be used even though the night-time ambient temperatures on the Martian surface drop below the freezing point of ammonia (- 78 C). The need for the usage of the LHP in the MER rover is during the day-time when the outside ambient temperatures are above –40 C. The thin condenser tubes can be allowed to freeze and thaw without any damage for the duration of MER rover operation (90 sols). Secondly, the thin transfer lines make it very easy to configure and install the LHP in the tight space inside the rover. Thirdly, thin transfer tubing that connects the radiator to the evaporator can be coiled to make the radiator deployable during integration and testing and also on the Mars surface.

In the case of the battery thermal control, a miniature LHP with two condensers and a by-pass valve was designed and evaluated. The LHP consisted of a single evaporator containing a ½ inch diameter nickel wick and sixteenth inch diameter transfer lines and a battery condenser and a condenser on the external radiator. A picture of this LHP is shown in Figure 2. The LHP transferred the heat from a set of Radioisotope Heater Unit (RHU) heat source to the two condensers. The gas regulated thermal control valve was adjusted to a set temperature corresponding to the maximum battery temperature. The valve opened the flow to the radiator condenser whenever the evaporator temperature exceeded this set temperature. A detailed description of this design and some of the preliminary results was presented earlier [3]. A schematic of the battery thermal control is shown in Figure 3.

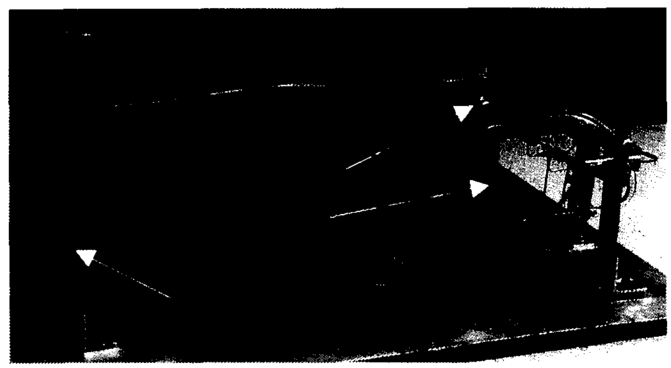

Figure 2. Loop Heat Pipe for Rover Battery Thermal Control

The key findings from the preliminary tests with nickel wick were that at low powers, below 10 Watts, the LHP performance was not consistent. In some cases the LHP started quickly and reached steady state temperatures whereas in other cases, it either did not start or start for several hours and the evaporator steady state temperatures were higher. This LHP was refitted with a titanium wick evaporator and the tests were continued to verify the valve operation. The evaporator power was set 6.5 Watts and the backpressure in the valve was set to correspond to certain valve open temperature value. The LHP started consistently at low powers of 6.5 Watts. The valve opens when the evaporator temperature reached was close to set temperature but valve closed about 15 C below the valve open temperature. At certain valve backpressures, the valve did not close. It was decided that the current valve design was not suitable for small power operations of 10 Watts. However, at higher power levels valve operation was more consistent.

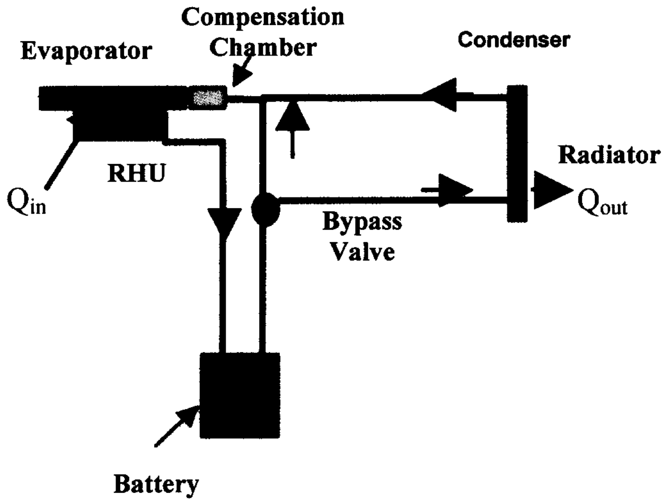

Figure 3. Rover Battery Thermal Control

A second configuration for the battery thermal control included a start up and a CC heater instead of the bypass valve (see Figure 4). This was investigated for the battery thermal control function.. This arrangement worked very well with a start up power of 3.5 watts and a CC heater power of 1 Watt. The length of time it takes to stop the LHP depends on the CC heater power and also the sink temperature. At higher CC heater power the LHP stopped quicker (10 minutes at 1 W to less than 2 minutes at 3.2 watts).

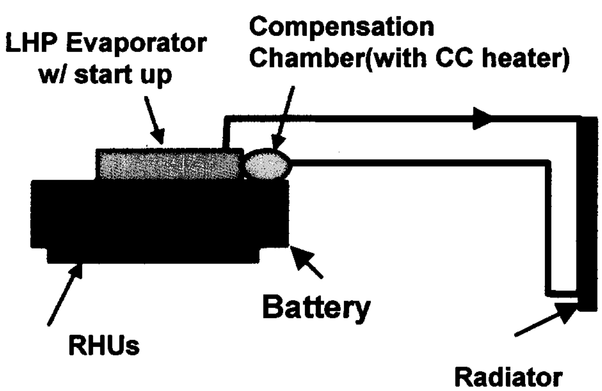

Figure 4 LHP Battery Thermal Control with Start Up and CC heater

A third LHP arrangement for rover thermal control consisted of removing heat from the solid state power amplifier (SSPA) during the day when its temperature went above upper limit. This is similar to the second configuration with the SSPA replacing the battery and RHU and the power level was at 45 Watts. Several tests were done to see how the LHP performs with a start up heater and a CC heater which is on continuously. The results are shown in Table 2. A start up heater of 4.9 watts was used and the CC heater was continuously when on.

A separate engineering unit of the SSPA LHP was designed and built and tests were conducted during the summer and fall of 2001 to verify its performance for the thermal control of rover SSPA. The LHP is shown in Figure 5 and its arrangement in the rover is shown in Figure 6. This LHP has a ½ inch diameter nickel wick and 1/16 inch diameter stainless steel liquid lines and 3/32 inch diameter vapor line. A heater was mounted on a fin attached at one end of the evaporator to provide a heat concentrator source for start up and a CC heater for stopping the LHP. The performance of the LHP was evaluated for various orientations of the compensation chamber and the evaporator, start up heater power and shut-off heater powers. The LHP performance met the requirements of the MER rover [4].

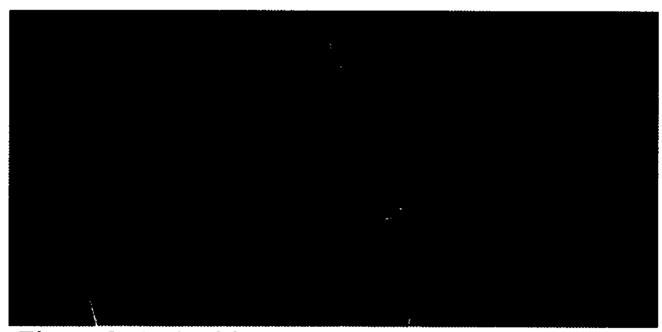

Figure 5. MER SSPA Loop Heat Pipe

Table 2. SSPA LHP Performance

Power, Watts	Sink, C	CC heater, W	Cond., W/C	Comments
45	-20	0.9	2.3	Horiz. CC-Evap
45	0	None	5.7	Horiz. CC-evap
45	10	0.9	2.1	Horiz
45	20	0.9	3.9	Vertical
45	35	0.9	8.8	Vertical
45	35	None	10	Vertical

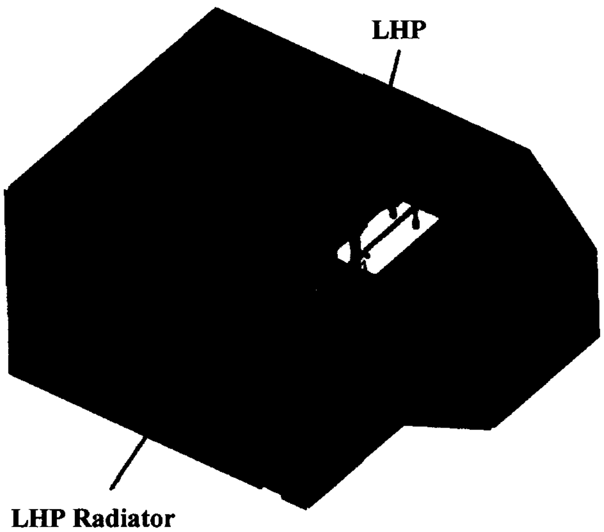

Figure 6. Rover LHP Inside the WEB

4. LHP FOR FUTURE MISSIONS

Future Mars missions are expected to include rovers and landers of all sizes. A key thermal control issue for these is to keep the night time heater power as low as possible while able to reject heat during the peak hours of the day. Miniature loop heat pipes will play an important role in the thermal control of Martian surface vehicles. They will be used both for removing excess heat from rover equipment and reject it to space and for transferring heat from hot to colder equipment inside the rover. MiniatureLHP when used in combination with other thermal control technologies such as phase change material thermal energy storage devices can provide an efficient thermal energy management architecture for rover which will reduce the need for night time heater power.

One of the new concepts that is currently being investigated is a miniature LHP with two evaporators and two condensers shown in Figure 7. In this case, a single LHP can remove heat from two heat sources and also move the heat from hot source to a colder sink inside the rover and thus conserve the heat for use at night. Preliminary test are currently conducted to characterize the performance of this LHP (Ku and Birur 2002).

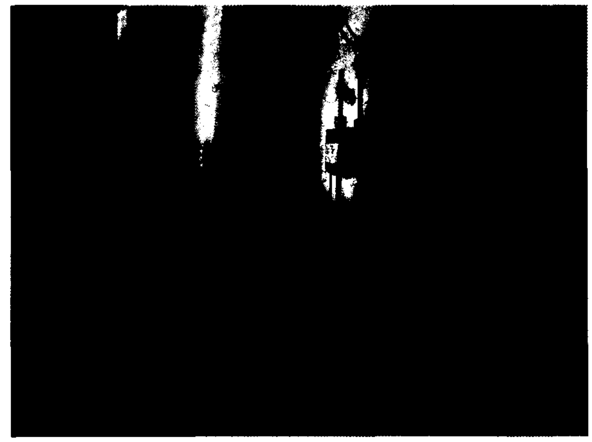

Figure 7. Miniature LHP with dual Evaporators

5. CONCLUSIONS

Miniature LHP provide an effective tool for the thermal control of Mars rovers and landers. Because of their light-weight, flexibility, and simplicity, they can be easily incorporated in the light weight rovers and landers. Their ability to function as an efficient heat switch and also as a heat transport device make them quite desirable compared to the existing thermal technologies. The three types of miniature LHPs investigated at JPL have demonstrated that they are suitable for thermal control of future Mars rovers and landers.

6. Acknowledgments

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Table 1. Comparison of Various Thermal Switch Concepts for Mars Rovers

Technology / Attributes	Mechanical Heat switch	Loop Heat Pipe	Mechanically pumped Coolant Loop
Practical heat transfer capacity range, W	1 to 20	10 to over 100	25 to over 500 W
Active/Passive System	Passive	Passive	Active
Configuration flexibility	Not flexible, needs to be located close to the heat sink and source	Very flexible, can easily transfer heat over large distance, over a meter	Very flexible, can transfer heat over an order of magnitude longer distance
Heat collection flexibility (at source)	Constrained to small foot print	Constrained to small foot print	No constraint of foot print
Heat rejection flexibility (at sink)	Constrained to small footprint, low radiator fin efficiency	No constraint on foot print	No constraints on foot print
Typical mass, kg	0.10 to 0.12	0.3 to 0.5	4 to 20
Conduction, W/K			
On	0.4 to 05	2 to 5	5 to 10
Off	0.02 to 0.025	0.02 to 0.03	0.03 to 0.05
Electric Power, W	None	1 for 'off' condition 5 for start up (a few min)	3 to 10 for "on" condition (including electronics)
Heritage	Good	Good	medium
Application	Component level thermal control	Component and spacecraft th. Control	Component and spacecraft level