Miniature Loop Heat Pipe with Multiple Evaporators for Thermal Control of Small Spacecraft

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Abstract: *This paper presents an advanced miniature heat transport system for thermal control of small spacecraft. The MLHP Thermal Management System consists of a miniature LHP with multiple evaporators and multiple deployable radiators with variable emittance coatings (VECs) on the radiator surfaces. Thermoelectric coolers are used to control the loop operating temperature. The thermal system combines the functions of variable conductance heat pipes, thermal switches, thermal diodes, and the state-of-the-art LHPs into a single integrated thermal system. It retains all the performance characteristics of state-of-the-art LHPs and offers additional advantages to enhance the functionality, performance, versatility, and reliability of the system. Steady state and transient analytical models have been developed, and scaling criteria have also been established. A breadboard unit has been built for functional testing in laboratory and thermal vacuum environments. Experimental results show excellent performance of the thermal system and correlate very well with theoretical predictions.*

Keywords: two-phase thermal control; miniature loop heat pipe; variable emittance coating.

Introduction

Loop Heat Pipes (LHPs) are very versatile heat transfer devices that have been used for thermal control of many commercial communications satellites and NASA's spacecraft, including ICESAT, AURA, SWIFT, and GOES. All LHPs currently servicing orbiting spacecraft have a single evaporator with a diameter of about 25mm. When the heat source has a large thermal footprint, or several heat sources need to be controlled at similar temperatures, an LHP with multiple evaporators is highly desirable. For small spacecraft, miniaturization of the LHP is also necessary in meeting the stringent requirements of low mass, low power and compactness. Also important in the thermal subsystem development are the minimization of the need for supplemental electrical heaters and design flexibility which allows for optimum placement of components.

Under the NASA Space Technology 8 (ST 8) project, a miniature loop heat pipe (MLHP) Thermal Management System with multiple evaporators and multiple condensers has been successfully developed to meet the requirements of small spacecraft. The MLHP Thermal Management System consists of a miniature LHP with multiple evaporators and multiple deployable radiators with variable emittance coatings (VECs) on the radiator surfaces. A breadboard unit has been built for functional testing in laboratory and thermal vacuum environments, and demonstrated excellent performance. Steady state and transient analytical models have also been developed and correlated well with experimental data. In addition, scaling criteria have been established to provide a means of comparison and generalization of data between different LHPs. The MLHP Thermal Management System has reached a technology readiness level (TRL) of 4.

This paper will give detailed descriptions of the MLHP Thermal Management System, including design, operating principles, performance characteristics, technology advances and advantages. Experimental tests and model correlation will also be discussed.

Description of MLHP Thermal Management System

Overview of the System Design: The MLHP Thermal Management System consists of an MLHP with multiple evaporators and multiple condensers, and deployable radiators coated with VECs. Other key elements include thermoelectric coolers (TECs) on the LHP compensation chambers (CCs), a capillary flow regulator, and an aluminum coupling block between the vapor line and liquid line. For the ST8 flight validation, an MLHP consisting of two evaporators, two condensers, a body mounted radiator and a deployable radiator will be used, as shown schematically in Figure 1.

The two most important features of the MLHP Thermal Management System are the integration of multiple evaporators into a single LHP, and the use of miniature evaporators with an outer diameter (O.D.) of 13mm. As will be elaborated on later, the MLHP combines the functions of variable conductance heat pipes (VCHPs), thermal switches, thermal diodes, and state-of-the-art LHPs into a single integrated thermal system. It retains all the performance characteristics of state-of-the-art LHPs and offers additional advantages to enhance the functionality, performance, versatility, and reliability of the system. More details are given below.

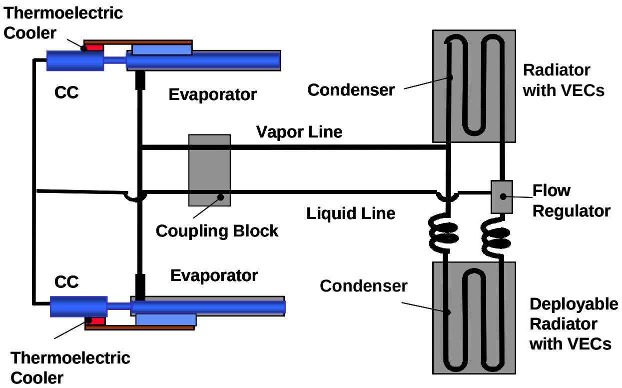

Figure 1. Schematic of the MLHP Thermal System for ST8 Flight Validation.

Multiple Miniature Evaporators: An LHP utilizes boiling and condensation of the working fluid to transfer heat, and surface tension forces developed by the evaporator wick to circulate the fluid [1-2]. It can transport large heat loads over long distances with small temperature differences. This process is passive and self-regulating in that the evaporator will draw as much liquid as necessary to be completely converted to vapor according to the applied heat load. When multiple evaporators are placed in parallel in a single loop, each evaporator will still work passively. No control valves are needed to distribute the fluid flows. All evaporators will yield the same vapor temperature as liquid vaporizes inside individual evaporators regardless of their heat loads. The loop provides a single interface temperature for all instruments. Furthermore, when an evaporator is exposed to a heat sink, such as when the attached instrument is turned off, the evaporator will receive heat from other evaporators servicing the operating instruments [3]. This will eliminate the need for supplemental electrical heaters while maintaining all instruments close to the saturation temperature. The evaporators can automatically switch between evaporating and condensing modes based on the surrounding thermal conditions. Therefore, each instrument can operate independently without affecting other instruments.

All evaporators have an outer diameter of 13mm. The evaporator mass is reduced by 70 percent when compared to 25mm evaporator used in state-of-the-art LHPs. Small evaporators also reduce the required fluid inventory in the LHP, and the mass and volume of the thermal system.

Multiple Condensers/Deployable Radiators: The fluid flow distribution among multiple, parallel condensers is also passive and self regulating [3, 4]. Each condenser will receive an appropriate mass flow rate so that the conservation laws of mass, momentum and energy are satisfied in the condenser section. If a condenser is fully utilized, such as when the attached radiator is exposed to a warm environment, vapor will be prevented from leaving that condenser by the capillary flow regulator located downstream of the condensers, and any excess vapor flow will be diverted to other condensers. Thus, no heat will be transmitted from a hot radiator back to the instruments, effecting a thermal diode action. Deployable radiators allow both sides of the radiators to dissipate heat, and hence reduce the required radiator area. The radiators can be folded in a stowed position prior to deployment.

TECs: The LHP operating temperature is governed by its CC temperature. The CC temperature as a function of the evaporator power for a given ambient temperature follows the well-known V-shaped curve as shown in Figure 2. The CC temperature can be controlled at a desired set point temperature of T_{set}. The state-of-the-art approach is to cold bias the CC and use electrical heaters to raise the CC temperature. As shown in Figure 2, the CC temperature can be controlled at T_{set} between heat loads of Q_{Low} and Q_{High}. However, this technique does not work for $Q < Q_{Low}$ when cooling of the CC is required.

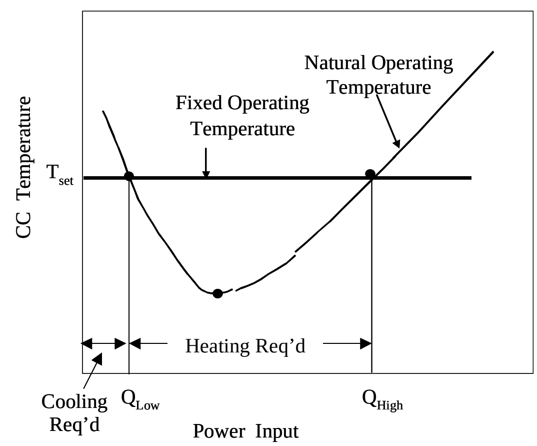

Figure 2. LHP Operating Temperature.

A TEC attached to the CC can provide heating as well as cooling to control the CC temperature. One side of a TEC can be attached to the CC, while the other side is connected to the evaporator through a flexible copper strap. When the CC is being cooled, the total heat output from the hot side is transmitted to the evaporator and ultimately dissipated to the condenser. This is particularly useful during the start-up of the LHP, when a higher heat load to the evaporator is always desirable. When the CC requires heating to maintain its set point temperature in the range of $Q_{Low} < Q < Q_{High}$, the TEC will draw heat from the evaporator. Depending on the efficiency of the TEC, savings on the control heater power can be substantial, especially under the cold sink and high/medium heat load condition.

The operating temperature of the MLHP Thermal Management System can be maintained by controlling any

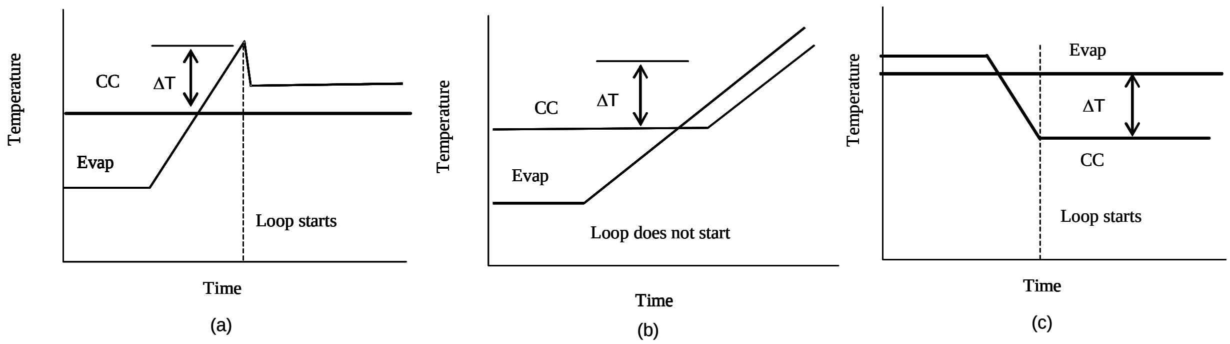

Figure 3. LHP Start-up.

number of CC's at the desired set point temperature [3]. For energy savings, only one CC temperature need be controlled at a time. Control can also be switched from one CC to another at any time. Furthermore, the CC set point temperature can be changed upon command. The ability of the CC to control the loop operating temperature at a constant value makes the MLHP Thermal Management System function as a variable conductance device.

In addition to maintaining the CC temperature, the TECs can be used to enhance the LHP start-up success. A typical LHP start-up involves raising the CC temperature above the evaporator temperature and then applying power to the evaporator. As the evaporator temperature rises above the CC temperature by a certain amount (the superheat), vapor bubbles will be generated in the evaporator and the loop will start, as shown in Figure 3(a). Unfortunately, the required superheat for boiling is stochastic and can range from less than 1K to more than 10K. A high superheat can lead to start-up difficulty because, while the evaporator temperature is rising to reach the required superheat, the CC temperature also rises due to the heat leak from the evaporator. Thus, the required superheat for bubble generation may never be attained, as shown in Figure 3(b). This is especially true when a low heat load is applied to the evaporator and a high superheat is required. The net heat load to the evaporator will be small during the start-up transient when the evaporator is attached to an instrument. To overcome the start-up difficulty, the state-of-the-art LHPs use a small-sized starter heater to provide a highly concentrated heat flux to generate first vapor bubbles locally. The required starter heater power is on the order of 30W to 60W for standard LHPs with a 25mm O.D. evaporator. For LHPs with small evaporators, the required starter heater power is estimated to be between 20W and 40W.

The TEC attached to the CC can maintain a constant CC temperature, and ensure that the evaporator will eventually overcome the required superheat no matter how high the required superheat and how low the heat load are, i.e. the condition shown in Figure 3(a) will occur. Alternatively, the TEC can be used to lower the CC temperature during the start-up transient to achieve the required superheat as shown in Figure 3 (c). Regardless of which method is implemented, the required starter heater power can be reduced or eliminated.

VECs: The VECs can be commanded to change their emittance to modulate heat rejection by individual radiators and regulate the temperature of the liquid leaving the condenser. The temperature of the liquid returning to the evaporator/CC will affect the control heater power required to maintain a constant operating temperature. Typically, the VEC should be at a high emittance state when the heat load is large and/or the radiator sink temperature is high, and at a low emittance state when the heat load is small and/or the radiator sink temperature is low. In the survival mode, setting the VECs at their minimum emittance can eliminate or reduce the supplemental heater power required in order to prevent the liquid from freezing. Hence, changing the VEC emittance for each radiator according to its thermal environment and the total system heat load leads to optimal performance of the MLHP.

The VEC technology used in the MLHP Thermal Management System, developed by Sensortex and shown in Figure 4, uses electrostatic forces to control the contact between a high emittance thin film and the substrate beneath to change the effective emittance [5]. It has control sections of about 10 cm^2. The VECs have yielded in effective emittance values ranging from 0.2 to 0.8.

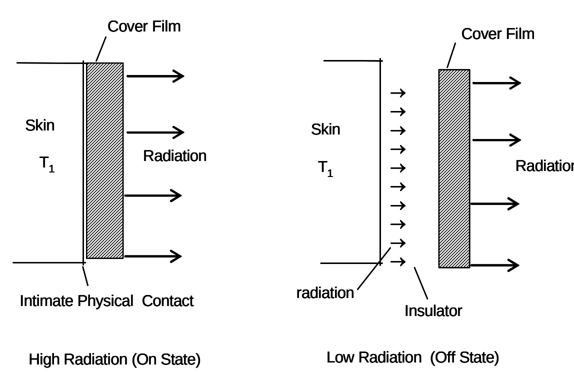

Figure 4. Electrostatic VECs.

Coupling Block: The coupling block allows the liquid returning to the evaporator/CC to absorb heat from the vapor line, which further reduces the TEC control heater power. Using feedback control, the combination of the TECs, VECs, and the coupling block can minimize the TEC control heater power.

Analytical Models and Scaling Criteria: An analytical model which simulates the steady state and transient behaviors of LHPs has been developed under a NASA SBIR 2 program [4]. It is used to correlate the MLHP experimental data in laboratory and thermal vacuum tests. Differential equations that govern the operation of LHPs with multiple evaporators and multiple condensers are developed, and a numerical scheme based on the Lagrangian method is employed to solve the equations. This method offers numerical stability and run time efficiency. Most importantly, it yields accurate solutions. The computer code is also very user-friendly.

The LHP operation involves some very complicated fluid and thermal processes, which are strongly influenced by gravitational, inertial, viscous, and capillary forces. To obtain better understanding of fluid flow and heat transfer phenomena in an LHP and to provide a means of comparison and generalization of data between different LHPs, some scaling criteria are needed. Using dimensional analysis, in combination with known heat pipe phenomena, a set of dimensional and dimensionless groups has been developed to relate geometry and configuration of the LHP components, properties of the wick and the working fluid, and the environmental conditions surrounding the LHP [6].

Technical Advances: Table 1 summarizes the technology advances and advantages of the MLHP Thermal Management System. Most comparisons are made in reference to state-of-the-art single-evaporator LHPs. Major technology advances are: 1) Miniaturization of the evaporator, i.e. reducing the evaporator diameter from 25mm to 13mm, 2) Multiple evaporators and multiple condensers in a single LHP, 3) TECs for temperature control and start-up success; 4) VECs on radiator surfaces to regulate the heat rejection, and 5) A transient LHP model and scaling rules.

Performance Characteristics: The LHP must be successfully started before the thermal system can begin operation. Using TECs to maintain a constant CC temperature, the MLHP can be started without auxiliary starter heaters. In fact, the loop can achieve a "turn-key" start-up by simply using instrument heat outputs. The evaporators can take even or uneven heat loads from the instruments. Likewise, the radiators can be exposed to different thermal environments. The loop will provide a

Table 1. Technology Advances of MLHP Thermal Management System.

Technology Item	**State-of-the-Art**	**MLHP Technology Advances**
Integral Thermal Subsystem – MLHP with TECs on CCs and VECs on radiators	Louvers, Heat Pipes, LHPs, Heaters, Thermostats	Flexible Locations of Heat Dissipating Components, Heat Load Sharing, TEC for Temperature Control and Start-up Enhancement, VECs for Power Savings
LHP Configuration	Single Evaporator	Multiple Evaporators
LHP Evaporator Diameter	25 mm O.D.	13 mm O.D.
Analytical Modeling of LHPs	Top-level Transient Models for Single Evaporator LHPs. No Scaling Rules	Detailed Transient Models for Multi-Evaporator LHPs Scaling Rules Established
LHP Start-up Method	Starter Heaters on Evaporator (20W to 40 W)	TEC on CC (<5W)
LHP Temperature Control	Control Heater on CC; Cold Biased, Heating Only, No Cooling Heater Power: 5 W to 10 W	TEC on CC plus Coupling Blocks on Transport Lines; Both Heating and Cooling Heater Power: 0.5 W to 2 W
Prevention of Fluid Freezing	Heaters on Radiators	VECs on Radiators Heaters on Radiators, if necessary

single operating temperature for all instruments. When an instrument is turned off, heat sharing among evaporators allows all instruments to be kept close to the saturation temperature. When the "off" instruments are turned on again, the attached evaporators will automatically switch back to normal operation.

Each of the multiple condensers will receive an appropriate mass flow rate based on its thermal environment and the total system heat load. Any changes in the system heat load and/or radiator environments will result in an automatic redistribution of flow rates among condensers. Multiple deployable radiators can be placed at different locations. As long as the radiators as a whole can dissipate the total heat load, some of the radiators can be exposed to warm environments. By adjusting the emittance, VECs can regulate the heat rejection by each radiator and prevent fluid from freezing during the survival mode. The flow regulators prevent vapor from going back to the evaporators, and regulate mass flow rate through each condenser/radiator. All these are accomplished passively, allowing the system to achieve optimal performance in accordance with instrument operational scenarios.

When the total heat load exceeds the LHP heat transport capability, vapor will penetrate the wick and flow to the CC. The loop operating temperature will rise. Tests results indicate that, in most cases, the LHP will reach a new steady state at a higher saturation temperature [7]. Thus, the LHP will undergo a graceful degradation in performance rather than a catastrophic failure. When the heat load is reduced, the loop will recover and operate at the original set point temperature.

In the survival mode when all instruments are turned off, the LHP will be automatically shut down as the temperature of the instrument/evaporator drops below the CC set point temperature. This will prevent heat from being transmitted from the instrument to the radiators. In other words, the LHP works as a thermal switch. When the instruments are turned on again, the LHP will resume its normal operation.

Operating Scenarios: There are several operating scenarios for the MLHP Thermal Management System. Figure 5 illustrates the three basic operating modes using an LHP with two evaporators and two condensers as an example.

- Both instruments are turned on and a high heat rate is flowing to the radiators. The VECs are commanded to a high or medium emittance state depending on the radiator sink temperatures.
- One instrument is turned on and the other is turned off. Part of the vapor generated in the evaporator attached to the 'on" instrument will flow to the evaporator attached to the 'off' instrument, i.e. the "off" instrument becomes a heat sink. The remaining vapor will flow to the condensers, and the VECs are commanded to a medium or low emittance state depending on the radiator sink temperatures.
- Both instruments are turned off. The spacecraft or the instruments are in a survival mode. The MLHP is shut down and becomes a thermal switch automatically. No heat is transmitted from the instruments to the radiators through the MLHP. The VECs are commanded to the lowest emittance to help prevent the liquid from freezing.

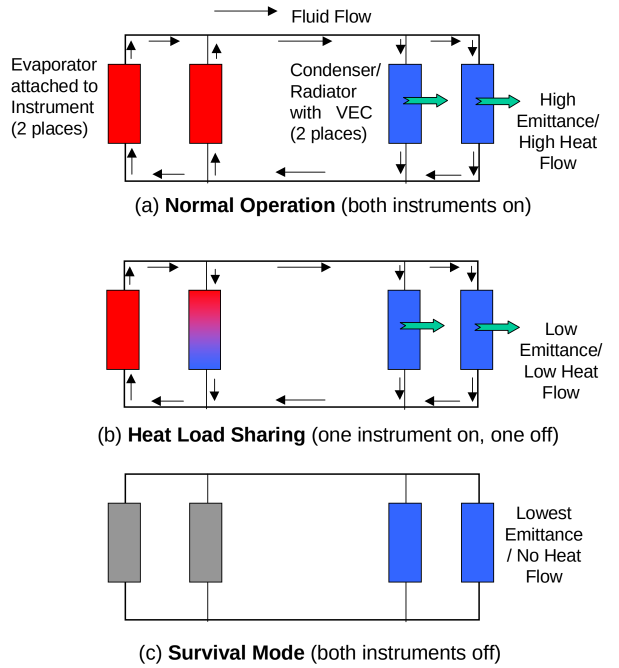

Figure 5. Operating Modes of the MLHP Thermal Management System.

Advantages Offered by the MLHP Thermal Management System: The MLHP Thermal Management system offers many advantages over conventional thermal control systems. It can also enhance functionality, performance, versatility, and reliability over a start-of-the-art LHP. These benefits can be rather significant for the end user.

- Using TECs, the MLHP can be started quickly with no or little starter heater power. The MLHP is thus close to a "turn-key" thermal control system.
- Multiple deployable radiators allow the radiators to be placed at optimal locations. With correct designs, the radiators will appropriately dissipate the heat load regardless of changes in instrument heat outputs or orbital environments. No heat will be pumped back to instruments, even if some radiators face the sun. By adjusting the emittance of VECs, the radiators can achieve optimal performance while saving control heater powers for CCs.

- During the survival mode, little or no supplemental heater power is is required to maintain the instrument temperature because the MLHP can be shut down. Also, little or no supplemental heater power is required to prevent liquid from freezing.
- The MLHP can be fully tested in spacecraft-level ground tests regardless of the orientations and elevations of the instruments and radiators.
- The LHP analytical model provides a useful tool for feasibility studies, trade studies, and preliminary design. It can also be used to predict the LHP transient performance once the final design is completed. The scaling criteria can be employed for a quick assessment of whether the design of a previously flown LHP can be modified for different geometries, configuration, sizes, and/or working fluids.
- The analytical model and scaling rules can be very valuable tools in guiding ground testing. With knowledge of the scalability and applicability of the ground tests results, and flight predictions by the analytical model, one can implement a test program that ensures no critical tests are overlooked and only relevant tests are to be performed. This will reduce the technical risk while realizing cost and schedule savings.

In summary, the MLHP Thermal Management System offers many benefits in all phases of a spacecraft mission. Successful flight validation will bring the benefits of MLHP technology to the small satellite arena and will greatly reduce uncertainties and abate risk for first users.

Breadboard MLHP Thermal Management System

A breadboard of the MLHP Thermal Management System was built and tested in laboratory and thermal vacuum environments to demonstrate a TRL of 4. The MLHP Breadboard, shown in Figures 6 and 7, consists of two evaporators, two condensers, a common vapor transport line and a common liquid return line. Each evaporator has an integral CC. Both evaporators are made of aluminum tubing with 15 mm O.D. by 76.2 mm length. One evaporator has a titanium wick with a pore radius of about 3 µm, while the other has a nickel wick with a pore radius of about 0.5 µm. Each CC is made of stainless steel tube of 14.8mm O.D. x 81.8 mm L. The vapor line and liquid line, each 1168mm long, are made of stainless steel tube with an O.D. of 3.3mm and 2.2mm, respectively. Each condenser is made of stainless steel tube of 2.2mm O.D. x 762mm L. A flow regulator consisting of capillary wicks is installed at the downstream of the condensers. The loop is charged with 15.5 grams of anhydrous ammonia.

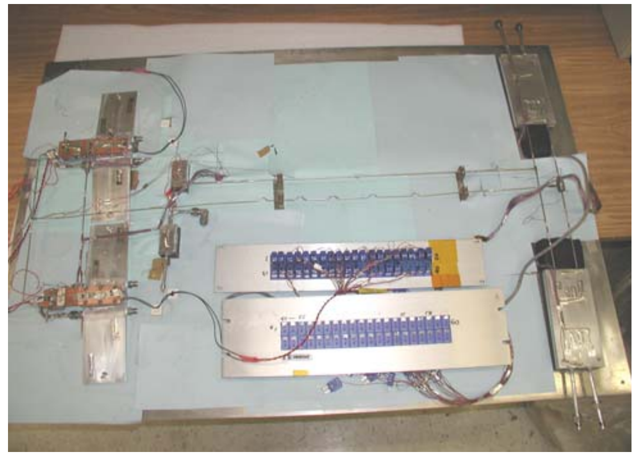

Figure 6. Photo of the MLHP Breadboard.

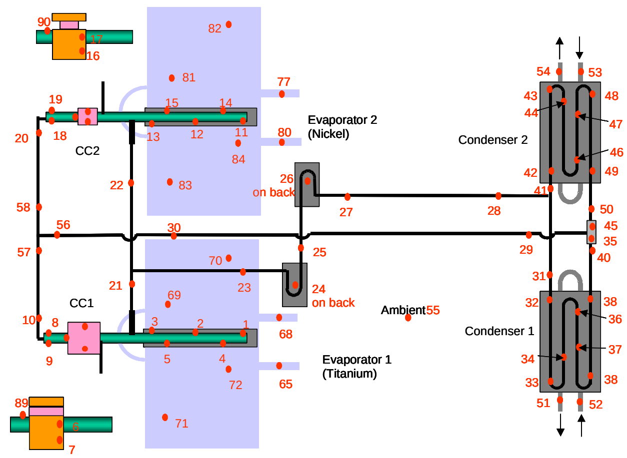

Figure 7. Schematic of the MLHP Breadboard with Thermocouples.

Laboratory Test: In laboratory tests, no VEC was attached to the MLHP Breadboard. Each condenser was attached to a cold plate, and each cold plate was cooled by a separate chiller. A thermal mass of 500 grams was attached to each evaporator to simulate the instrument mass. Two cartridge heaters attached to each thermal mass provided heat loads between 5W and 200W per evaporator. To demonstrate heat load sharing, each thermal mass had two channels to accommodate a coolant flow. In addition, each thermal mass was designed to provide a flat surface with an area of 76 mm by 300 mm so it could be cooled by radiation during heat sharing mode in the TV test.

A TEC was installed on each CC with a copper saddle, as shown in the inserts on the left corners in Figure 7. One side of the TEC was connected to the evaporator through a copper strap. Each TEC was controlled by a bi-polar power supply. Changing the polarity on the power supply changed the TEC operation between heating and cooling modes. Thermocouples 6, 7, 16, and 17 are located on the TEC mounting brackets, while 89 and 90 are on the CCs.

More than 300 hours of test data were collected in laboratory testing. The MLHP Breadboard demonstrated excellent performance. Main results are summarized below:

- Successful start-up with 5W or less to each evaporator
- Even heat loads to the two evaporators ranging from 5W/5W to 70W/70W
- Uneven heat loads to the two evaporators: 5W/0W, 0W/5W, 130W/0W, 0W/140W, 100W/5W, 5W/100W
- Even and uneven sink temperatures: 253K/253K, 293K/293K, 253K/293K, 293K/253K
- Either or both TECs could control the loop operating temperature within ± 0.3K under all conditions.
- The required control heater power for either TEC was less than 2W.
- Ability of the two evaporators to share heat loads.
- Low power operation with 5W to each evaporator.
- The loop automatically shut down when neither evaporator received a heat load.
- One of the sinks could be at a temperature higher than the saturation temperature.
- The flow regulator could stop the vapor flow when a condenser was fully utilized.

More detailed descriptions of the MLHP start-up, operating temperature control and heat sharing are given in the following sections

Figure 8 shows that the loop operating temperature could be maintained at 303K using either or both of the TECs under various combinations of heat loads and condenser sink temperatures. The Condenser 1 sink temperature was varied between 253K and 293K while the Condenser 2 sink was kept at 273K. Superimposed upon this condition was a power change between two highly uneven heat loads of 100W/5W and 5W/100W. The TEC control heater power was less than 2W under all conditions.

The ability of the TEC to control the loop operating temperature at low powers is illustrated in Figure 9. Without using TECs, the LHP's natural operating temperatures were 302.5K and 298.5K at heat loads of 10W/10W and 20W/20W, respectively. With TECs providing cooling, the loop operating temperature could be controlled very precisely at 295K. This represents a major improvement over state-of-the-art LHPs.

The ability of the TEC to cool the CC can also be used to enhance the loop start-up success as previously explained in conjunction with Figure 3(c). Test results verified that the loop could start successfully by cooling the CCs without applying any heat load to the evaporators. By maintaining the temperature of both CCs below the ambient temperature, the loop could continue to operate with only parasitic heat loads.

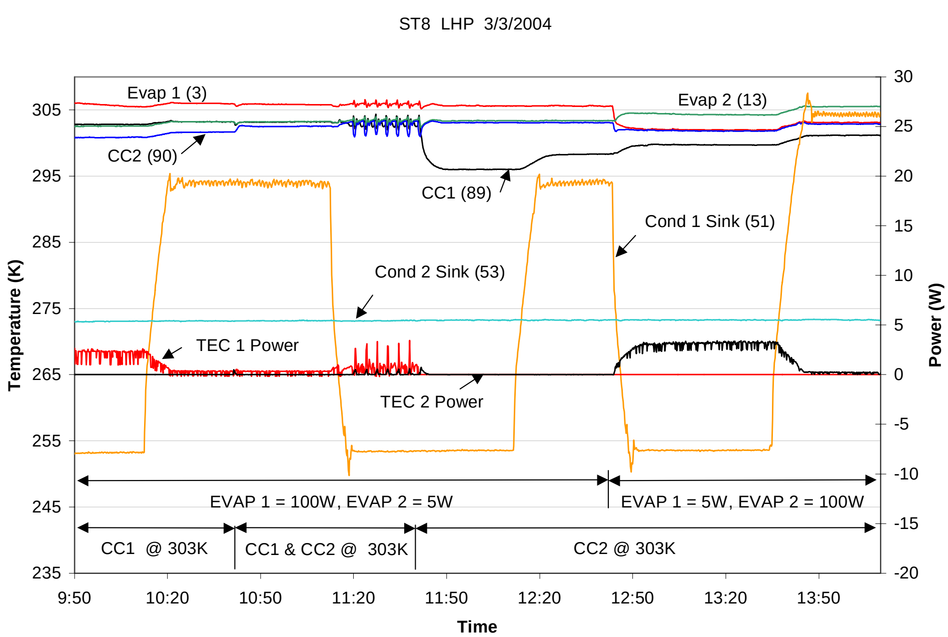

Figure 8. MLHP Breadboard Test with Varying Heat Loads and Sink Temperatures.

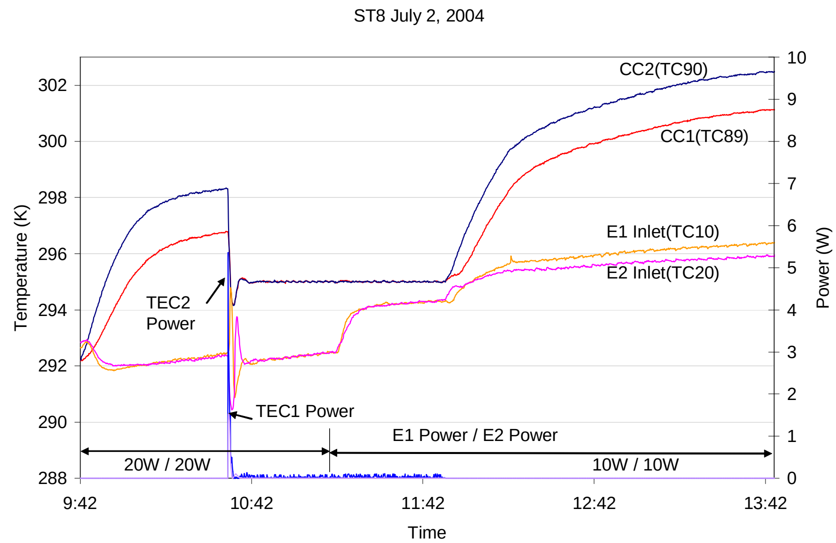

Figure 9. MLHP Operating Temperatures with and without using TECs.

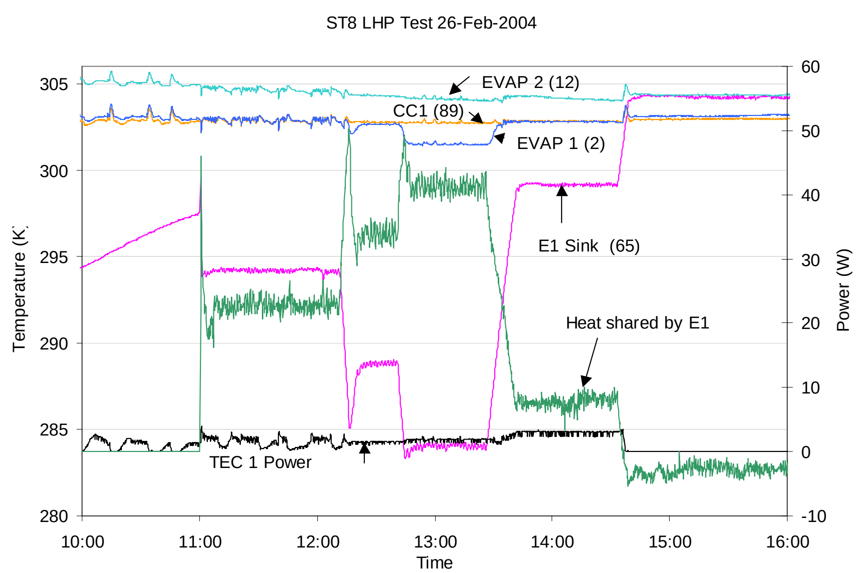

Figure 10. MLHP Breadboard Heat Load Sharing Test.

Figure 10 shows the heat load sharing operation. CC1 was controlled at 303K by TEC1. The heat load to Evaporator 2 was kept constant at 100W and no heat was applied to Evaporator 1. At 11:00, coolant was circulated to the Evaporator 1 thermal mass, and Evaporator 1 immediately shared heat from Evaporator 2. As the coolant temperature decreased, more heat was dissipated to the coolant flow and shared by Evaporator 1. Evaporator 1 was maintained close to the saturation temperature of 303K except at very low Evaporator 1 sink temperature where heat flowing to Evaporator 1 was insufficient to keep it at the saturation temperature. The control heater power for the TEC was less than 2W throughout the test.

Thermal Vacuum Test: In the thermal vacuum test, four VEC substrates, each with a dimension of 82.6mm x 177.8mm, were attached to the Condenser 1 cold plate, two at the top and two at the bottom. These VEC substrates were relatively small and could dissipate only 20W at the maximum emittance. Budget and schedule constraints in the Study Phase prevented the production and testing of more VEC substrates. A heater was attached to the underside of one VEC substrate. During the survival mode test, the radiator was exposed to different sink temperatures and the VECs were set to their maximum and minimum emittances. The heater power required to maintain the condenser above the freezing point of the working fluid was measured for each case.

An aluminum plate of 533mm x 438mm by 3.18mm thick was attached to the Condenser 2 cold plate to serve as the radiator. This radiator was painted black on both sides and was the main heat dissipating element during the TV test. The flat surface of each thermal mass attached to the evaporator was covered with kapton tape. Six copper cryopanels were used as radiator sinks, two for each condenser/radiator and one for each thermal mass. The cryopanels could be set at different temperatures independently to accommodate various tests.

Selected tests from the Laboratory Test were repeated to verify the MLHP operation in a TV environment. These tests included even and uneven heat loads, even and uneven sink temperatures, TEC temperature control, and heat load sharing. All tests were successful and the MLHP demonstrated the same performance characteristics as in the Laboratory Test. The main objective of this TV Test was to demonstrate that the VECs could regulate the temperature of the liquid exiting the condenser and minimize the radiator heat dissipation during the survival mode.

Table 2 shows the temperature of liquid leaving Condenser 1 as a function of the VEC emittance at two different heat loads. All cryopanels for Condenser 1 and Condenser 2 were kept at 120K. It is clearly seen that the liquid was leaving at a much lower temperature at maximum VEC emittance than at the minimum VEC emittance. Because the liquid temperature at the condenser exit is directly related to the subccoling to be overcome by the CC supplemental heaters, the feasibility of using VECs to reduce the TEC control heater power was demonstrated. Because only a small VEC-coated radiator was used and the other radiator had a fixed emittance, the heater power savings could not be precisely determined. This is a subject for further investigation.

Tests were also performed to demonstrate the effectiveness of the VECs in reducing the supplemental heater power for the radiator in a simulated survival mode. No heat loads were applied to the evaporators and the loop was shut down by keeping the CC1 temperature at 303K. The Condenser 1 cryopanel was kept at 180 K. The bonding material for the

Table 2. VEC Effect on Condenser Exit Temperature.

System Heat Load	VEC Emittance	Temperature of Liquid Leaving Condenser 1
30 W	Max	275 K
30 W	Min	300 K
20 W	Max	254 K
20 W	Min	273 K

VEC substrates had a minimum temperature of 223 K. When the Condenser 1 temperature reached 230 K, the heater on the VEC substrate was turned on and the required heater power to keep the Condenser 1 temperature at 230K was recorded. Tests were conducted with the VECs at their maximum and minimum emittances. The same tests were repeated for a cryopanel temperature of 120K. Test results are summarized in Table 3. It can be seen that the required heater power was reduced by more than one half as the emittance was changed from the maximum to the minimum. Note that neither the VEC design nor the substrate geometries were optimized.

Table 3. Required Heater Power to Maintain Condenser 1 Radiator at 230 K.

Cryopanel Temperature	VEC Emittance	Heater Power to Radiator
180 K	Max	7.6 W
180 K	Min	3.2 W
120 K	Max	11.8 W
120 K	Min	5.6 W

Analytical Model Correlation: Figure 11 shows the model predictions and the experimental data for two ambient tests where even heat load was applied to both evaporators and the two condenser sinks were kept at 283K and 263K, respectively. Note that the model predicts that the MLHP Evaporator 1 will dry out when the heat loads are greater than 50W/50W for 263K heat sinks, and 60W/60W for 283K heat sinks. Both predictions were within 20 percent of the test results, and were considered excellent. The model assumes the primary wick will dry out when vapor penetrates the largest pores (0.5 (m radius). In reality, the wick will not dry out until a sufficient number of smaller pores have also been penetrated.

Figure 12 shows the model predictions versus experimental data for an ambient test where both condenser sinks are kept at 273K and varying heat loads are applied to the evaporators. The CC temperatures are not actively controlled. The results show that the model predictions are within 2K of most temperatures, and are truly outstanding for two-phase flow modeling. For clarity, only temperatures of the two CCs are shown in the figure.

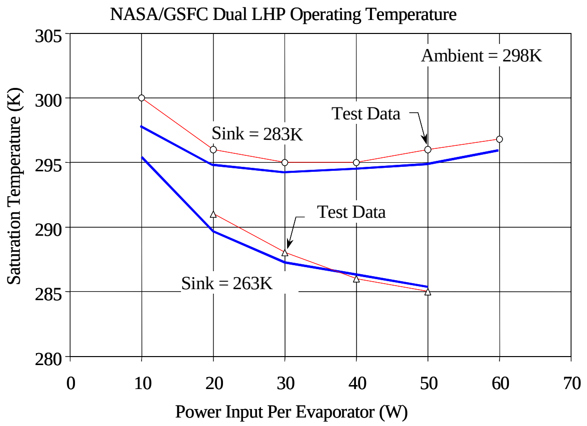

Figure 11. LHP Model Predictions versus Experimental Data.

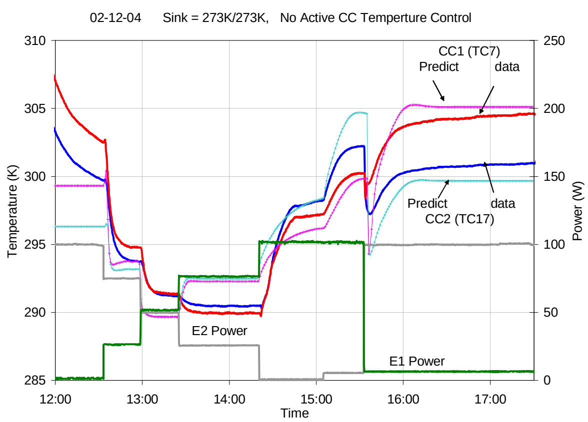

Figure 12. LHP Transient Model Predictions versus Experimental Data.

Summary and Conclusions

Under the New Millennium Program ST 8 Study Phase, an advanced MLHP Thermal Management System was developed. The thermal system consists of an LHP with multiple miniature evaporators and multiple condensers, variable emittance coatings, and thermoelectric coolers. It combines the functions of VCHPs, thermal switches, thermal diodes, and the state-of-the-art LHPs into a single integrated thermal system, and offer many advantages over the state-of-the-art LHPs. A breadboard unit has been tested in the laboratory and thermal vacuum environments, and demonstrated excellent performance. Steady state and transient analytical models have also been developed and the model predictions correlated well with experimental results. In addition, scaling criteria have been established. The MLHP Thermal Management System has therefore exceeded TRL 4.

The performance of capillary two-phase devices is known to be strongly influenced by gravity. The VEC has never been tested in the space environment for long term operation, either. The large time constant involved in heat transfer requires a long-duration space flight experiment to verify the zero-G performance of the MLHP Thermal Management System. Successful flight validation will bring the benefits of MLHP technology to science missions requiring small, low-power spacecraft.

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