Multi-Evaporator Miniature Loop Heat Pipe for Small Spacecraft Thermal Control – Part 1: New Technologies and Validation Approach

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Under NASA's New Millennium Program Space Technology 8 (ST 8) Project, four experiments – Thermal Loop, Dependable Microprocessor, SAILMAST, and UltraFlex - were conducted to advance the maturity of individual technologies from "proof of concept" to "prototype demonstration in a relevant environment", i.e. from a technology readiness level (TRL) of 3 to a level of 6. This paper presents the new technologies and validation approach of the Thermal Loop experiment. The Thermal Loop is an advanced thermal control system consisting of a miniature loop heat pipe (MLHP) with multiple evaporators and multiple condensers designed for future small system applications requiring low mass, low power, and compactness. The MLHP retains all features of state-of-the-art loop heat pipes (LHPs) and offers additional advantages to enhance the functionality, performance, versatility, and reliability of the system. Details of the thermal loop concept, technical advances, benefits, objectives, level 1 requirements, and performance characteristics are described. Also included in the paper are descriptions of the test articles and mathematical modeling used for the technology validation. An MLHP breadboard was built and tested in the laboratory and thermal vacuum environments for TRL 4 and TRL 5 validations, and an MLHP proto-flight unit was built and tested in a thermal vacuum chamber for the TRL 6 validation. In addition, an analytical model was developed to simulate the steady state and transient behaviors of the MHLP during various validation tests. Capabilities and limitations of the analytical model are also addressed.

Nomenclature

CC	=	compensation chamber
C_p	=	specific heat of the liquid
$D_c^{(i)}$	=	diameter of the ith condenser
$h_{c,2\phi}$	=	condensation heat transfer coefficient
$\Delta h_L^{(i)}$	=	end-to-end elevation of the ith condenser
$L_{c,2\phi}^{(i)}$	=	length of the ith condenser used to dissipate the latent heat
$m_c^{(i)}$	=	mass flow rate through the ith condenser

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$m_e^{(i)}$	=	mass flow rate through the i^{th} evaporator
m_t	=	total mass flow rate in the vapor line or liquid line
N_E	=	number of evaporators
N_C	=	number of condensers
$\Delta P_{c,1\phi}^{(i)}$	=	pressure drop across the subcooled section of the i^{th} condenser
$\Delta P_{c,2\phi}^{(i)}$	=	pressure drop across the two-phase section of the i^{th} condenser
$\Delta P_{cap}^{(i)}$	=	maximum pressure drop sustained by the i^{th} wick
ΔP_{EV}	=	pressure drop across the evaporator section
$\Delta P_{tot}^{(i)}$	=	total pressure drop imposed upon the i^{th} wick
ΔP_c	=	pressure drop across the condenser section
$\Delta P_c^{(i)}$	=	total pressure drop across the i^{th} condenser
$\Delta P_{FR}^{(k)}$	=	capillary pressure exerted by the flow regulator in the k^{th} condenser
$Q_E^{(i)}$	=	part of the heat load applied to i^{th} evaporator that is used for liquid evaporation
$Q_{IN}^{(i)}$	=	heat load applied to the i^{th} evaporator
$Q_L^{(i)}$	=	heat leak from the i^{th} evaporator to its compensation chamber
$Q_{sc}^{(i)}$	=	amount of liquid subcooling carried by the liquid returning to the i^{th} evaporator
$Q_{RA}^{(i)}$	=	heat exchange between the i^{th} CC and its surrounding
$r_p^{(i)}$	=	pore radius of the i^{th} wick
r_P	=	radius of curvature of the wick at the vapor/liquid interface
$T_{c,wall}^{(i)}$	=	condenser wall temperature in the i^{th} condenser
$T_{LL,IN}^{(i)}$	=	temperature of liquid at the inlet of the i^{th} CC
T_{sat}	=	loop saturation temperature
T_{set}	=	desired CC set point temperature
Δv	=	difference in specific volume between the liquid and vapor phases
θ	=	contact angle between the liquid and solid
λ	=	latent heat of vaporization of the working fluid
ρ_l	=	liquid density
σ	=	surface tension force

I. Introduction

A loop heat pipe (LHP) is a very versatile heat transfer device which can transport a large heat load over a long distance with a small temperature difference [1, 2]. LHPs have been used for thermal control of many commercial communications satellites and NASA's spacecraft, including ICESat, AURA, Swift, and GOES [3-5]. The LHPs currently servicing orbiting spacecraft have a single evaporator with a 25-mm outer diameter primary wick. An LHP with multiple evaporators is highly desirable because it can maintain several heat sources at similar temperatures and afford heat load sharing among several heat source components [6]. A multi-evaporator and multi-condenser LHP also offers design flexibility, allowing the thermal subsystem components to be placed at optimal locations. For small spacecraft applications, miniaturization of the LHP is necessary in order to meet the stringent requirements of low mass, low power and compactness. Under NASA's New Millennium Program Space Technology 8 (ST 8) Project, the Thermal Loop experiment would validate the performance of a miniature loop heat pipe (MLHP) with multiple evaporators and multiple condensers under a simulated space environment in a thermal vacuum chamber. Each evaporator has a primary wick with an outer diameter of 6.35 mm.

The ST 8 Project comprises four experiments: Thermal Loop, Dependable Microprocessor, SAILMAST, and UltraFlex. The purpose of the ST 8 project is to advance the maturity of the four technologies from "proof of concept" to "prototype demonstration in a relevant environment", i.e. from a technology readiness level (TRL) of 3 to a level of

6. For the Thermal Loop experiment, an LHP Breadboard was built and tested in the laboratory and thermal vacuum environments for the TRL 4 and 5 validations, respectively, and an MLHP proto-flight unit was built and tested in a thermal vacuum chamber for the TRL 6 validation. In addition, an analytical model has been developed to simulate the steady state and transient operation of LHPs.

A Thermal Loop experiment Technology Review Board (TRB), consisting of a group of independent outside LHP experts, has been assembled by the New Millennium Program Office to perform the following functions: 1) establish the criteria by which the Thermal Loop experiment will be judged to have achieved TRL 4, TRL 5, and TRL 6; 2) assess the achievement of TRL 4, TRL 5, and TRL 6 by the Thermal Loop experiment; and 3) evaluate the efficacy of the Thermal Loop experiment Technology Validation Plan.

This paper presents the Thermal Loop concept, technical advances and benefits, objectives, Level 1 requirements, and performance characteristics. Also described are the developments of hardware and software which were used to validate and advance the Thermal Loop technology. Validation results, both analytical and experimental, are described in a separate paper.

II. Thermal Loop Concept

Figure 1 shows the Thermal Loop experiment concept. At the heart of the Thermal Loop experiment is an MLHP which transports heat loads from heat sources to heat sinks while maintaining tight temperature control for all instruments under varying heat load and environmental conditions.

Key features of the Thermal Loop experiment include: 1) multiple evaporators in a single LHP where each evaporator has its own integral compensation chamber (CC); 2) a primary wick with an outer diameter (O.D.) of 6.35mm for each evaporator; 3) multiple condensers that are attached to different radiators; 4) a thermoelectric converter (TEC) that is attached to each CC and connected to the evaporator via a flexible thermal strap; 5) a flow regulator located downstream of the condensers; 6) coupling blocks connecting the vapor line and liquid line; and 7) ammonia working fluid.

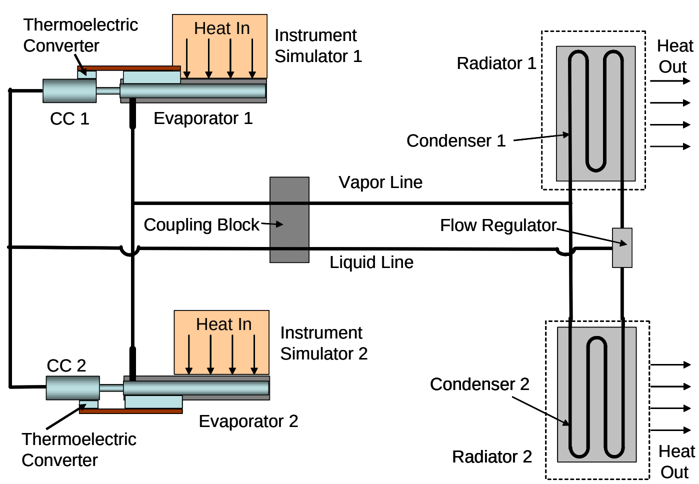

Figure 1. Thermal Loop Experiment Concept

III. Technical Advances and Benefits

Table 1 summarizes the technical advances and benefits of the Thermal Loop technology. Most comparisons are made in reference to state-of-the-art single-evaporator LHPs. Details are described below.

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 support the fluid circulation around the loop [1, 2]. 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 flow among the evaporators. All evaporators will produce vapor that has the same temperature as liquid vaporizes inside individual evaporators regardless of their heat loads. The loop works as a thermal bus that provides a single interface temperature for all instruments, and the instruments can be placed at their optimum locations. Furthermore, the instruments that are turned off can draw heat from the instruments that are operational because the evaporators will automatically share heat among themselves [2, 6]. This will eliminate the need for supplemental electrical heaters while maintaining all instruments close to the loop operating temperature. The heat load sharing function among evaporators is passive and automatic. Therefore, each instrument can operate independently without affecting other instruments. When all instruments are turned off, the loop can be shut down by keeping the CC at a temperature above the minimum allowable instrument temperature. No heat will flow to the condensers/radiators. Thus, the loop works as a thermal switch.

The primary wick in the evaporator has an outer diameter of 6.35mm. The evaporator mass is therefore reduced by more than 70 percent when compared to the evaporator having a 25mm O.D. primary wick 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.

Table 1. Technical Advances and Benefits of Thermal Loop Technology

State-of-the-Art	ST 8 Technical Advance
LHP has a single evaporator	LHP has multiple evaporators (Thermal Loop has two evaporators for demonstration)
Requires supplemental heaters to maintain temperatures of off-instruments	Heat load sharing among evaporators eliminates or reduces supplemental heater powers
LHP has 25mm wick	LHP has 6.35mm wick - reduced volume and mass
Top-level transient model for LHPs with a single evaporator No scaling rule has been established	Detailed transient model for LHPs with multiple evaporators Scaling rules were established
Relies on starter heater on evaporator for start-up Power required: 20W to 40W	Uses TECs on CCs to ensure successful start-up Power required: less than 5W
Control heater on CC for temperature control - cold biased, heating only, no cooling, Heater power: 5W to 20W	TECs on CCs and coupling block on transport lines for temperature control - heating and cooling Heater power: 0.5W to 5W

***Multiple Condensers/Flow Regulator**:* The fluid flow distribution among multiple, parallel condensers is also passive and self regulating [2, 6]. 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 has exhausted its dissipating capability, such as when the attached radiator is exposed to a warm environment, vapor will be prevented from entering the liquid return line 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.

***TECs**:* The LHP operating temperature is governed by its CC temperature. The CC temperature as a function of the evaporator power at a given condenser sink temperature follows the well-known V-shaped curve shown in Figure 2. The resulting temperature curve is the LHP natural operating temperature. 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 $Q < Q_{Low}$ where the natural operating temperature is higher than T_{set} and the CC requires external cooling instead of heating.

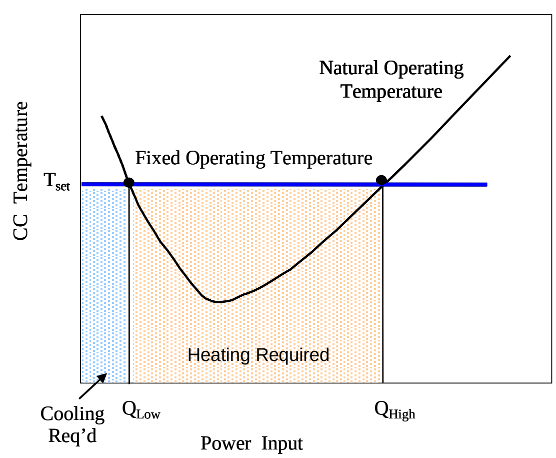

Figure 2. LHP Operating Temperature

A TEC can be attached to the CC to 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 can be connected to the evaporator via a flexible thermal strap. When the TEC is cooling the CC, the total heat output from the TEC hot side, i.e. the sum of the power applied to the TEC and the heat pumped out of the CC, is transmitted to the evaporator and ultimately dissipated to the condenser. When the TEC is heating the CC, some heat will be drawn from the evaporator through the thermal strap to the TEC cold side. The sum of the power applied to the TEC and the heat drawn from the evaporator is delivered to the CC. The heat drawn from the evaporator reduces the external power required to heat the CC. The power savings derived from using a TEC can be substantial when compared to conventional electric heaters, especially when the evaporator has a high/medium heat load and the condenser is exposed to a very cold environment.

The operating temperature of the MLHP can be maintained by controlling any number of the CCs at the desired set point temperature [7]. Control can also be switched from one CC to another at any time. Furthermore, the CC set point temperature can be changed upon command while the loop is operational. The ability of the CC to control the loop operating temperature at a constant value makes the MLHP function as a variable conductance thermal 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). However, 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 overcome 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 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.

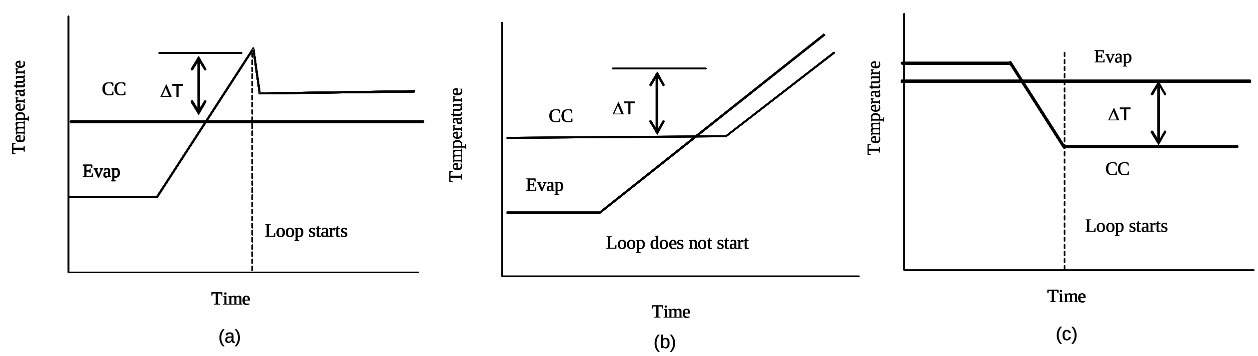

Figure 3. LHP Start-up

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 prevail. 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 substantially reduced or completely eliminated.

Coupling Block: The coupling block is made of a high thermal conductivity metal and serves as a heat exchanger between the vapor and liquid lines. It allows the liquid returning to the evaporator/CC to absorb heat from the vapor line, which further reduces the control heater power when the TEC is heating the CC.

Analytical Model: Part of the technology development for the Thermal Loop experiment is to develop an analytical model which simulates the steady state and transient behaviors of LHPs. The analytical model is based on conservation laws governing the operation of an LHP with multiple evaporators and multiple condensers. The model solves a set of differential equations using the Lagrangian method. Inputs to the model include detailed geometries of the LHP components, the evaporator power profiles, and environmental conditions. Outputs of the model are temperature and pressure distributions in the LHP. The model can be used as a stand-alone model for LHP design analysis, or as a subroutine for a general spacecraft thermal analyzer such as SINDA/FLUINT [8]. More details of the analytical model are described later.

Performance Characteristics: Figure 4 illustrates the performance of an MLHP having two evaporators and two condensers. The loop can be started by raising the CC temperature at a desired temperature that is above the ambient temperature using the TECs so as to flood the evaporators with liquid, and then turning on the instruments. Because the TECs can keep the CC temperature constant, the loop will eventually start. The heat loads to the evaporators can vary independently; both evaporators will yield 100 percent vapor at the same temperature. The two condensers will dissipate the total heat load coming from the evaporators. The load will be automatically distributed between two condensers according to the conservation laws. When an instrument is turned off, part of the heat load from the "on' instrument will flow to the "off" instrument. When both instruments are turned off, the loop can be shut down as long as the CC temperature is maintained above the minimum allowable instrument temperature, and no heat will be transmitted from the instruments to the radiators.

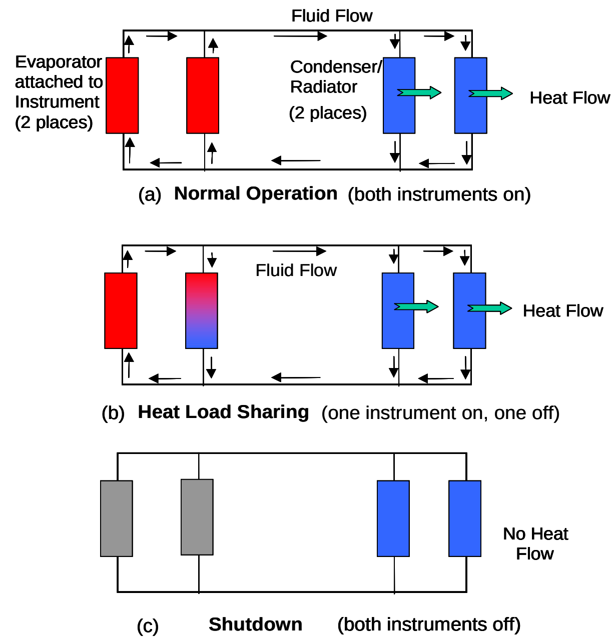

Figure 4. MLHP Operating Modes

IV. Level 1 Requirements And Technical Approach

The main objective of the Thermal Loop experiment was to advance the maturity of the technology from "proof of concept" to "prototype demonstration in a relevant environment." The MLHP was originally planned to fly on a ST 8 spacecraft. Unfortunately, NASA cancelled the space flight experiment part due to budget constraints. The current Thermal Loop experiment Level 1 requirements (non-flight) and full and minimum success criteria are summarized in Table 2.

Table 2. Level 1 Requirements and Success Criteria

Baseline Technology Validation/ Measurement Requirement	Full Project Success Criteria/Measurement Requirement	Minimum Project Success Criteria/Measurement Requirement
• Operate a flight configured, miniature, multi-evaporator loop heat pipe for small system applications capable of an 80% success rate on a minimum of 20 start-ups in a flight-like environment. • Develop an analytical model which can predict the loop's critical temperatures during steady state and transient operation.	• Heat load-share two loads in the range of 0 to 75 W while the loads either remove or add heat to the system	• Heat load-share two loads in the range of 0 to 50 W while the loads either remove or add heat to the system
	• Operating temperature of the Loop measured at the compensation chamber shall be within ±3°C of the desired set point temperature over 0°C to +35°C range	• Operating temperature of the Loop measured at the compensation chamber shall be within ±5°C of the desired set point temperature over 0°C to +35°C range

In order to bring the thermal loop technology from TRL 3 to TRL 6 and meet all the Level 1 requirements, the following technology validation approach was taken: (1) Fabricate an MLHP Breadboard; (2) Test the MLHP Breadboard in a laboratory environment to validate the attainment of TRL 4; (3) Test the MLHP Breadboard in a thermal vacuum chamber to validate the attainment of TRL 5; (4) Fabricate an MLHP proto-flight unit and test it in a thermal vacuum chamber to validate the attainment of TRL 6; and (5) Develop an analytical model to predict the behaviors of the MLHP Breadboard and proto-flight unit in laboratory and thermal vacuum environments at various TRLs.

V. MLHP Breadboard and Proto-flight Unit

MLHP Breadboard: Figure 5 shows a picture of the MLHP Breadboard, which consisted of two parallel evaporators with integral CCs, two parallel condensers, a common vapor transport line and a common liquid return line. Each evaporator was made of aluminum 6061 with an outer diameter (O.D.) of 9 mm and a length of 52 mm. The primary wick was made of titanium with a pore radius of about 1.5 µm. Each CC was made of stainless steel with an O.D. of 22.2 mm and a length of 72.4 mm. The vapor line, liquid line and condensers were all made of stainless steel. The vapor line had an O.D. of 2.38 mm and a length of 914 mm. The liquid line had an O.D. of 1.59 mm and a length of 914 mm. Both the vapor line and liquid line were coiled so as to reduce the space and to provide flexibility for testing. Each condenser had an O.D. of 2.38 mm and a length of 2540 mm, and was serpentined and sandwiched between two aluminum plates. Each set of aluminum plates were made into a semi-circular shape so that the entire MLHP Breadboard could fit into a thermal vacuum chamber for testing. A flow regulator consisting of capillary wicks was installed at the downstream of the two condensers. The MLHP was charged with 29.3 grams of anhydrous ammonia.

A thermal mass of 400 grams of aluminum was attached to each evaporator to simulate the instrument mass. The vapor line and liquid line were connected with several aluminum coupling blocks (20 mm by 20mm by 6mm each). A TEC was installed on each CC through an aluminum saddle. The other side of the TEC was connected to the evaporator via a copper thermal strap. A cartridge heater capable of delivering 1W to 200W was inserted into each thermal mass.

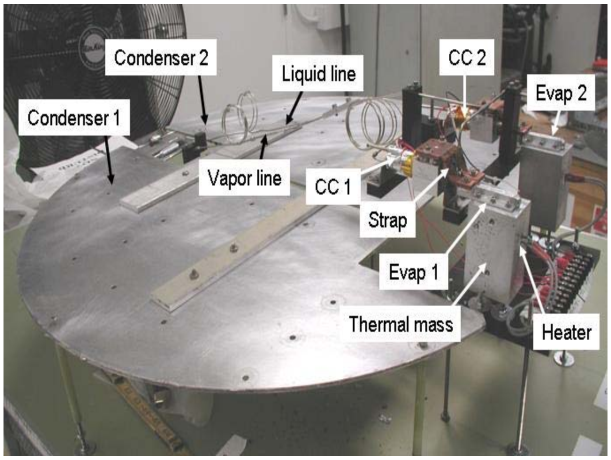

Figure 5. Picture of the MLHP

MLHP Proto-flight Unit: Figure 6 shows a picture of the MLHP proto-flight unit used for the TRL 6 valiation test. The proto-flight unit was intended to be mounted on the ST 8 spacecraft for a space flight experiment as shown in Figure 7. Unfortunately, NASA canceled the flight segment of the ST 8 project due to budget constraints. The designs of the evaporator, CC, condensers, vapor line, and liquid line were the same as those in the MLHP Breadbord except for the following: 1) The length of the vapor line, liquid line and condenser were 1580 mm, 1120 mm and 1676 mm, respectively; 2) The two radiators were rectangular, and each condenser was serpentined and embedded in the radiator; 3) The TEC was mounted on a saddle attached to the CC and a flexible thermal strap was used to connect the TEC to the evaporator; 4) Two TEC assemblies were used for each CC for redundancy; 5) To investigate the effect of thermal masses on the MLHP transient responses, a 540-gram aluminum thermal mass was

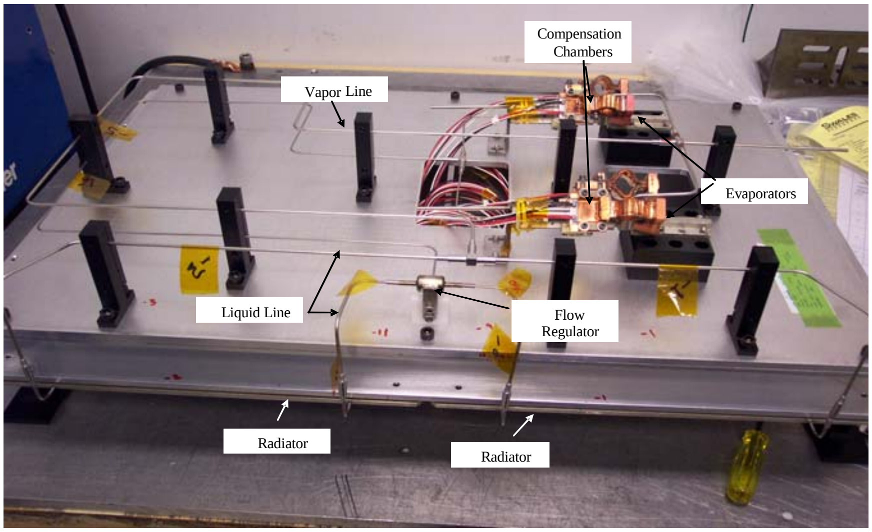

Figure 6. **MLHP Proto-flight Unit**

attached to Evaporator 1 and a 280-gram aluminum thermal mass was attached to Evaporator 2; and 6) the loop was charged with 31.3 grams of anhydrous ammonia.

Details of the MLHP Breadboard and proto-flight unit are described in a separate paper along with validation results.

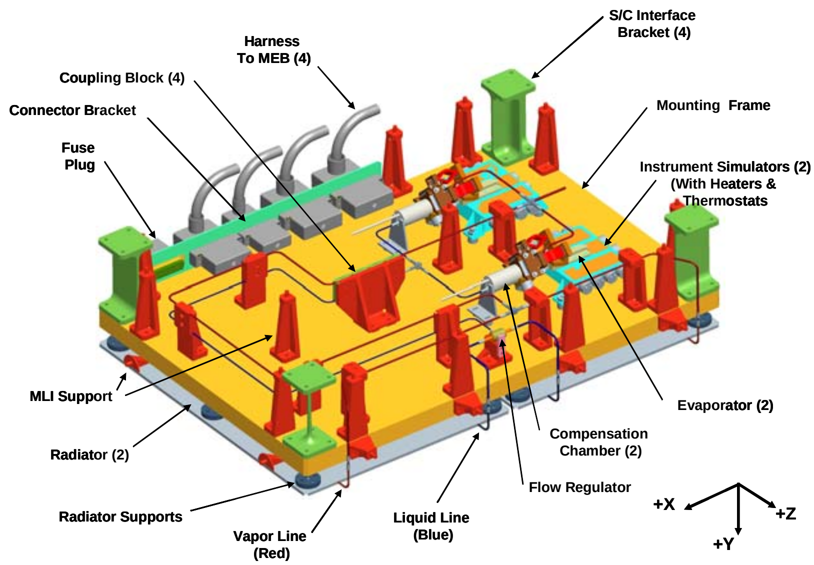

Figure 7. MLHP Flight Experiment Layout (View from Spacecraft)

VI. LHP Analytical Model

An LHP analytical model is a useful tool for trade studies, design analysis, and performance predictions. Development of LHP analytical models has not kept pace with the hardware advances. In the past, system level analytical models have been developed for LHPs with a single evaporator [9-12] using available general thermal and fluid flow computer codes which employ the lumped-parameter method to solve the basic conservation equations of mass, momentum, and energy for the thermodynamic state of the working fluid. However, these generalized thermal/fluid codes cannot model the “intricacies” of the LHP specific physical phenomena without a substantial programming effort from the user. In addition, when modeling a sudden change of the operating conditions, these codes have to reduce the time step to achieve numerical stability. In many cases, the required time step is so small that the computer run-time becomes impractical.

There have been no analytical models for LHPs with multiple evaporators, either steady state or transient. Recently, a highly capable LHP transient model has been developed under a NASA SBIR 2 program [13-15]. This LHP analytical model was further refined and updgraded under the ST 8 project. The governing equations, based on conservation laws of mass, momentum, and energy, have been derived specifically for the operation of LHPs with multiple evaporators and multiple condensers. The model then solves a set of ordinary differential equations using a numerical scheme based on the Lagrangian method. This method offers numerical stability and run time efficiency. More importantly, it yields accurate solutions. The computer code can be used as a stand-alone model for LHP design analysis, or as a subroutine for a general spacecraft thermal analyzer such as SINDA/FLUINT [8].

Theoretical Background: The following discussion applies to the general case of an LHP consisting of N_E evaporators and N_C condensers [6]. For illustration, an LHP having only two evaporators and two condensers is schematically shown in Figure 8. A flow regulator consisting of a capillary wick is usually installed at the exit of each condenser to prevent vapor from flowing out of the condenser. When an external heat load $Q_{IN}^{(i)}$ is applied to the ith evaporator, part of the heat, $Q_L^{(i)}$, is transmitted to the CC (the so-called heat leak), and the remaining heat,

$Q_E^{(i)}$, is used to evaporate liquid to generate a mass flow rate of $m_e^{(i)}$. The vapor flow from each evaporator then merges to form a total mass rate of m_t that flows to the condenser section. Thus,

$$Q_{IN}^{(i)} = Q_E^{(i)} + Q_L^{(i)} \qquad (i = 1 \ to \ N_E) \qquad (1)$$
$$Q_E^{(i)} = m_e^{(i)} \lambda \qquad (i = 1 \ to \ N_E) \qquad (2)$$
$$m_t = \sum_{i=1}^{N_e} m_e^{(i)} \qquad (3)$$

where λ is the latent heat of vaporization of the working fluid. Note that the evaporators are passive and self-regulating in that each evaporator, based on the applied heat load $Q_{IN}^{(i)}$, will draw a liquid flow of $m_e^{(i)}$ so that equations (1) and (2) are satisfied and the vapor will exit the evaporator with a quality of unity.

The total mass rate of m_t will be distributed among the N_C condensers. The ith condenser will receive a mass rate of $m_c^{(i)}$ with an associated heat load of $m_c^{(i)}\lambda$, and the vapor will be completely condensed over a length of $L_{c,2\phi}^{(i)}$. Thus,

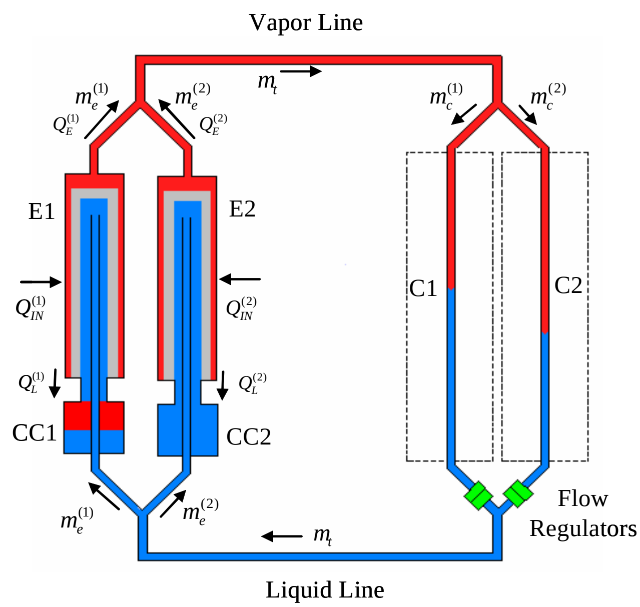

Figure 8. Schematic of an LHP with Multiple Evaporators and Multiple Condensers

$$m_t = \sum_{i=1}^{N_C} m_c^{(i)} \qquad (4)$$
$$m_c^{(i)} \lambda = \pi D_c^{(i)} L_{c,2\phi}^{(i)} h_{c,2\phi} (T_{sat} - T_{c,wall}^{(i)}) \qquad (i = 1 \ to \ Nc) \qquad (5)$$

where $D_c^{(i)}$ is the diameter of the ith condenser and $L_{c,2\phi}^{(i)}$ is the length required to dissipate the latent heat, $h_{c,2\phi}$ is the condensation heat transfer coefficient, T_{sat} is the loop saturation temperature, and $T_{c,wall}^{(i)}$ is the condenser wall temperature. The liquid will then be subcooled over the remaining length of the condenser. If a condenser has completely exhausted its heat dissipating capability, the vapor will be stopped by the flow regulator and the excess vapor will be diverted to other condensers, resulting in a flow re-distribution among all condensers. The liquid flow exiting each condenser then merges into a total liquid flow with a mass rate of m_t. The pressure drop in the ith condenser is the sum of the pressure drops in the two-phase region (over the length $L_{c,2\phi}^{(i)}$) and the subcooled (liquid phase) region, and the hydraulic pressure head due to gravity. Thus,

$$\Delta P_c^{(i)} = \Delta P_{c,2\phi}^{(i)} + \Delta P_{c,1\phi}^{(i)} + \rho_l g \Delta h_L^{(i)} = f(m_c^{(i)}, L_{c,2\phi}^{(i)}) \qquad (i = 1 \ to \ N_C) \qquad (6a)$$
$$\Delta P_c^{(k)} = \Delta P_{c,2\phi}^{(k)} + \Delta P_{FR}^{(k)} \qquad \text{(Condenser k is fully utilized)} \qquad (6b)$$

where $\Delta P_c^{(i)}$ is the pressure drop across the ith condenser, ρ_l is the liquid density, $\Delta h_L^{(i)}$ is the end-to-end elevation of the ith condenser, $\Delta P_{FR}^{(k)}$ is the capillary pressure exerted by the flow regulator in the kth condenser. However, there can be only one pressure drop over the condenser section. Hence,

$$\Delta P_c^{(i)} \equiv \Delta P_c \qquad (i = 1 \ to \ N_C) \qquad (7)$$

where ΔP_c is the pressure drop across the entire condenser section.

The liquid exchanges heat with the surroundings as it flows along the liquid return line. When it reaches the evaporator section, its temperature is at $T_{LL,IN}$, which is a function of the total mass flow rate m_t, diameter and length of the liquid transport line, temperature of the surroundings, and mode of heat transfer. The mass flow then splits among all evaporators, and each individual liquid flow further exchanges heat with its surroundings along the liquid inlet line. At the inlet of the ith evaporator/CC, the liquid flow has a temperature of $T_{LL,IN}^{(i)}$. The governing equations can be written as follows:

$$T_{LL,IN} = f\left(T_{c,out}, m_t, L_{LL}, D_{LL}, T_{amb}\right) \quad (8)$$

$$T_{LL,IN}^{(i)} = f\left(T_{LL,IN}, m_c^{(i)}, L_{LL}^{(i)}, D_{LL}^{(i)}, T_{amb}^{(i)}\right) \quad (i=1 \ to \ N_E) \quad (9)$$

$$Q_{SC}^{(i)} = m_e^{(i)} C_P \left(T_{sat} - T_{LL,IN}^{(i)}\right) \quad (i=1 \ to \ N_E) \quad (10)$$

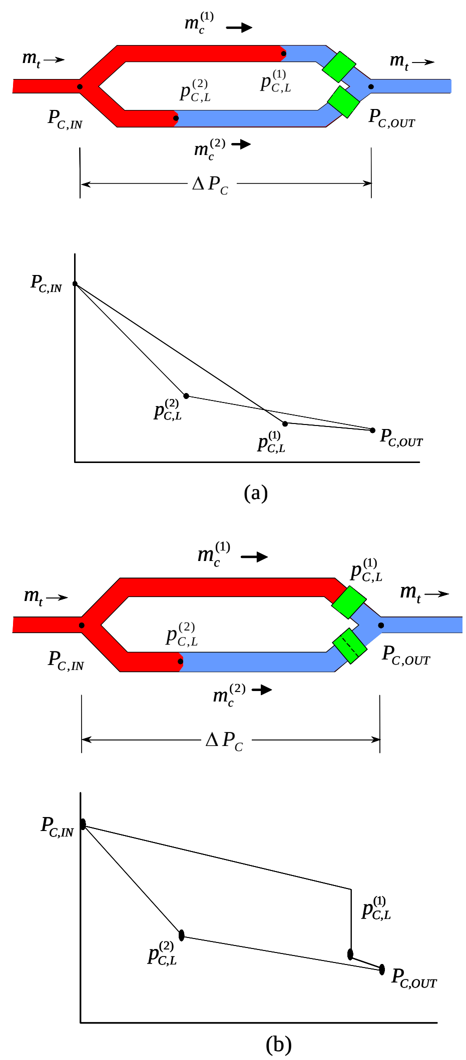

Figure 9. Flow Distribution and Pressure Drops in the Condenser Section

where C_p is the specific heat of the liquid. The temperature of the ith CC is determined by the energy balance between the liquid subcooling, $Q_{sc}^{(i)}$, the heat leak, $Q_L^{(i)}$, and the heat exchange between the CC and the surroundings, $Q_{RA}^{(i)}$. If there is no active measure to control the CC temperatures, the CC that reaches the highest temperature will contains two-phase fluid and control the loop operating temperature. All other CCs will be liquid filled [7]. If all CCs are controlled at the same set point temperature, the CC that has the lowest absolute pressure will control the loop operating temperature, and all other CCs will be liquid filled under most circumstances. The energy balance can be described as follows:

$$Q_L^{(k)} - Q_{sc}^{(k)} - Q_{RA}^{(k)} = 0 \qquad (T_{sat} \ determined \ by \ k^{th} \ CC) \quad (11)$$

$$Q_L^{(i)} - Q_{sc}^{(i)} - Q_{RA}^{(i)} \le 0 \qquad (i=1 \ \ to \ N_E, \quad i \ne k) \quad (12)$$

As each fluid flow completes its path, each evaporator is subjected to a total pressure drop which is the sum of pressure drops in the evaporator, vapor transport line, condenser section, liquid transport line, and individual wick. The total pressure drop must not exceed the maximum pressure drop that the capillary wick is able to sustain. Thus,

$$\Delta P_{cap}^{(i)} = \frac{2\sigma \cos\theta}{r_p^{(i)}} \qquad (\ i = 1 \ \ to \ N_E\ ) \quad (13)$$

$$\Delta P_{tot}^{(i)} \le \Delta P_{cap}^{(i)} \qquad (i = 1 \ \ to \ \ N_E\ ) \quad (14)$$

where $r_p^{(i)}$ is the pore radius of the ith wick, $\Delta P_{cap}^{(i)}$ is the maximum pressure drop that the ith wick can sustain, σ is the surface tension force, and θ is the contact angle. Equations (1) to (14) describe the operation of an LHP with multiple evaporators and multiple condensers.

Details of the solution procedures for the LHP analytical model are described in the literature [12-14]. The computer code was developed based on conservation laws of mass, momentum, and energy for the LHP. However, the governing equations were formulated so as to describe the interactions between the evaporators, condensers, and CCs using an approach analogous to the mass-spring-dashpot in a mechanical system.

The analytical model employs a nodal approach for the finite difference solution scheme. Various nodes are used to represent the evaporators, condensers, CCs, transport lines, and the working fluid at various locations. A nodal map is shown in Figure 10. Thermal conductors are used to connect the nodes for heat transfer calculations. The model assumes one-dimensional pipe flows, and a single saturation temperature for the vapor and liquid inside the CC. The model is capable of simulating LHPs with up to five parallel evaporators and five parallel condensers. As depicted in the figure, the node numbers and conductor numbers are assigned a priori by the computer code. The LHP model can be used as a sub-model to general thermal analyzers such as SINDA/FLUINT. Any node in the LHP sub-model can be connected to outside nodes in the global model to describe the thermal interactions between the LHP and its surrounding environments.

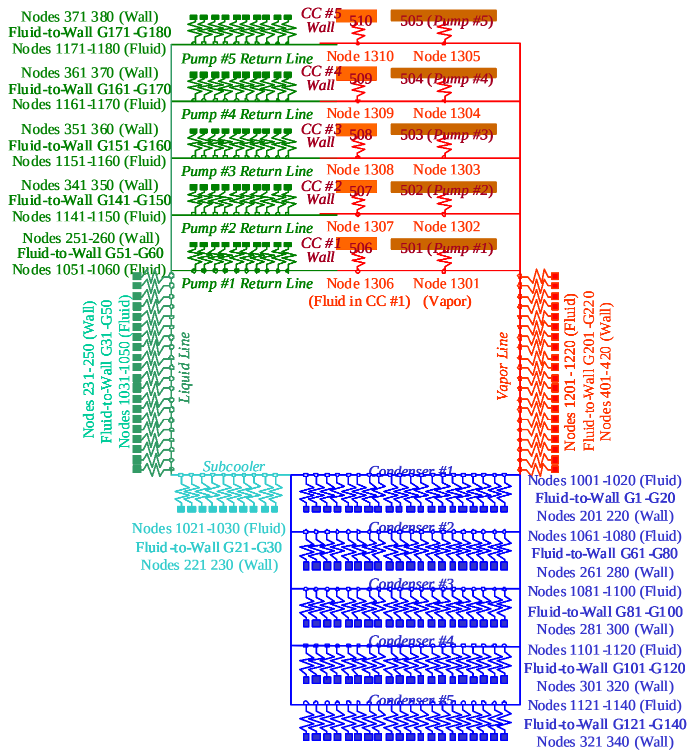

Figure 10. Nodal Map of the LHP Analytical Model

A numerical scheme based on the Lagrangian method is employed for the LHP model. This method offers numerical stability and run time efficiency. Most importantly, it yields accurate solutions. Figure 11 depicts the solution scheme when the LHP is used as a sub-model to a general thermal analyzer. The general thermal analyzer will read an LHP input file that contains geometric and property data and the initial boundary conditions pertinent to the LHP. The thermal analyzer then proceeds to its global thermal analysis. At some point, the LHP subroutine will be called to perform the LHP thermal calculations. After the LHP reaches a converging solutions for the given time step, the thermal analyzer continues to the next time step.

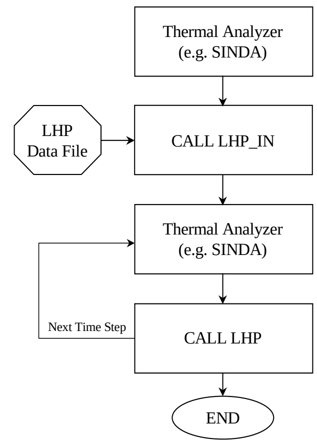

Figure 11. The Solution Scheme

When the LHP model detects that the LHP has reached its capillary limit (the maximum heat transport limit), it will send out a flag. The model will continue to perform the thermal analysis as if the LHP were still operating without the effect of vapor blowing through the evaporator wick. Thus, the model predictions will be inaccurate once the capillary limit has been exceeded. In other words, the LHP is incapable of simulating the loop performance past the capillary limit. The reason is that the pore size distribution of the wick is not known, thus the amount of vapor blowing through the wick is also unknown.

This LHP analytical model has been used to predict the performance of several LHPs with excellent agreement between the model predictions and the experimental results [15-16]. This model was used to predict the MLHP performance in the laboratory and thermal vacuum environments for the MLHP Breadboard and proto-flight unit. The validation results are presented in a separate paper [17].

VII. Conclusion

The Thermal Loop concept, technical advances and benefits, objectives, Level 1 requirements, and performance characteristics are described, along with the MLHP Breadboard and proto-flight unit for experimental investigations. Also described is the LHP analytical model which can predict the steady state and transient behaviors of the LHP operation, including the underlying governing equations, the nodal approach, the solution scheme, and capabilities and limitations.

The goal of the Thermal Loop experiment is to advance the technology from "proof of concept" to "prototype demonstration in a relevant environment", i.e. from a technology readiness level (TRL) of 3 to a level of 6. Results of the Thermal Loop technology validation, both experimental and analytical, are described in a separate paper.

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