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Loop Heat Pipe Startup Behaviors

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A loop heat pipe must start successfully before it can commence its service. The startup transient represents one of the most complex phenomena in the loop heat pipe operation. This paper discusses various aspects of loop heat pipe startup behaviors. Topics include the four startup scenarios, the initial fluid distribution between the evaporator and reservoir that determines the startup scenario, factors that affect the fluid distribution between the evaporator and reservoir, difficulties encountered during the low power startup, and methods to enhance the startup success. Also addressed are the pressure spike and pressure surge during the startup transient, and repeated cycles of loop startup and shutdown under certain conditions.

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 [1-3]. It utilizes boiling and condensation of the working fluid to transfer heat, and the surface tension forces of menisci formed at the liquid/vapor interfaces on the porous wick to sustain the pressure drop induced by the fluid flow. Over the past two decades, significant advances have been made in the LHP technology through extensive development efforts. As a result, LHPs have been used for instrument thermal control on many orbiting spacecraft [4-8]. Several future flight missions currently under development will also have LHPs onboard.

As shown in Figure 1, a typical LHP consists of an evaporator with an integral reservoir (also known as compensation chamber), a condenser, a vapor line and a liquid line. The evaporator contains a primary wick which sustains the pressure drop induced by the fluid flow around the loop, and a secondary wick which connects the evaporator to the reservoir. The rest of the loop is made of smooth tubes.

Detailed descriptions of the operating principles of an LHP can be found in the literature [2, 9]. An LHP must start successfully before it can commence its service. The startup of the LHP is a complex transient phenomenon, and is a function of the loop initial conditions prior to startup and the heat flux applied to the evaporator. Experimental tests also show that, in some cases, the way an LHP starts also affects its subsequent operations. This paper focuses on the issues related to the startup of a single-evaporator LHP servicing a heat source all by itself. The startup of multiple single-evaporator LHPs servicing the same heat source [7] are more complex and will not be covered here. Topics to be discussed include the four startup scenarios, initial fluid distribution between the evaporator and reservoir that determines the startup scenario, factors that affect the fluid distribution between the evaporator and reservoir, difficulties encountered during the low power startup, and methods to enhance the startup success. Also discussed are pressure spike and pressure surge, and repeated cycles of loop startup and shutdown. Note that the terms reservoir and compensation chamber (CC) will be used interchangeably in this paper.

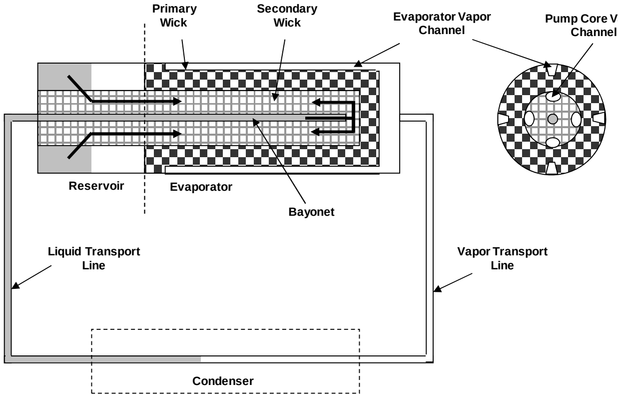

Figure1. Schematic of a Typical LHP

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II. LHP Startup Scenarios

The initial liquid/vapor distribution in the evaporator core (the space enclosed within the inner diameter of the primary wick) and in the vapor grooves on the outer surface of the primary wick has a great impact on the LHP startup transient behavior. If the evaporator core is filled with liquid, the heat leak from the evaporator to the reservoir is small. If the evaporator core contains vapor, the heat leak is large due to the heat pipe effect. If vapor is present in the vapor grooves, liquid will evaporate when a heat load is applied to the evaporator. If the grooves are completely filled with liquid, however, liquid will not evaporate immediately. Instead, nucleate boiling will take place and a certain amount of liquid superheat is required in order to initiate nucleate boiling.

2.1 Temperature Overshoot and Undershoot during Startup

During the loop startup, the reservoir temperature will change from its initial value to a final steady state value. The transition of the reservoir temperature during the startup transient can be smooth, i.e. the reservoir temperature gradually changes from its initial value to its final natural operating temperature. In many startups, however, an overshoot or undershoot of the reservoir temperature can occur. The temperature overshoot is defined as the difference between the maximum transient temperature and the initial or final temperature as shown in Figure 2. Likewise, the temperature undershoot is defined as the difference between the minimum transient temperature and the initial or final temperature. Even when the reservoir temperature is controlled during the startup transient, a temperature overshoot or undershoot can still occur because the reservoir is unable to adjust its temperature instantaneously due to limited control heater power.

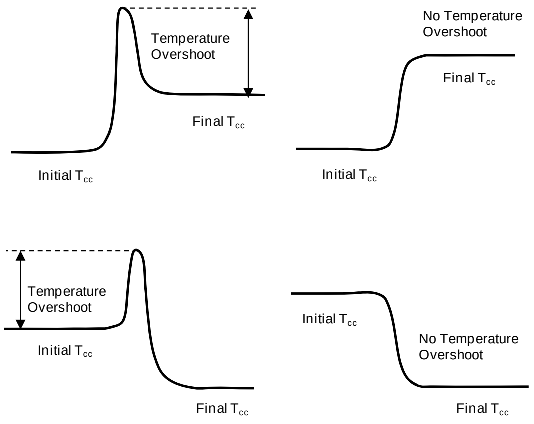
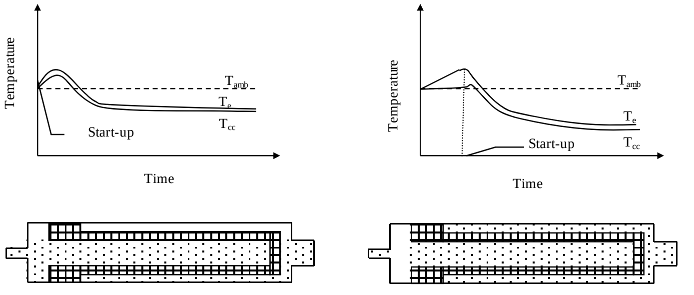


Figure 2. Temperature Overshoot during Startup

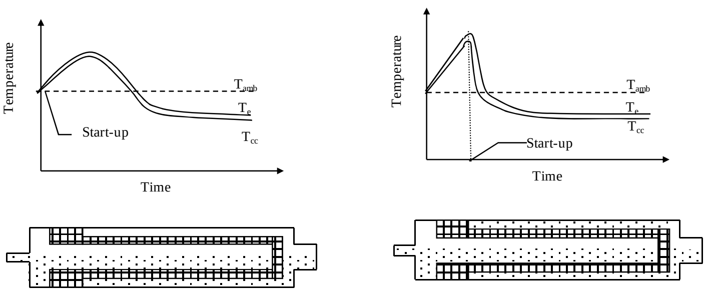
Many spacecraft require the heat source to be maintained within a narrow temperature range [10-11]. The issue with the temperature overshoot or undershoot is that it may cause the instrument temperature to be outside of its allowable temperature range. More details of the temperature overshoot during startup will be discussed in the next section while the temperature undershoot will be elaborated on later.

2.2 Four Startup Scenarios

There are four possible situations prior to loop startup [12] as shown in Figure 3, depending on the thermodynamic states of the fluid in the evaporator core and the fluid in vapor grooves. Also shown in Figure 3 are the temperature profiles of the reservoir and the evaporator from the moment power is applied to the evaporator [2]. It is assumed that, in all situations, the entire loop is initially at the ambient temperature except for the condenser, which is colder than the other parts.



(a) Situation 1 (c) Situation 3



(b) Situation 2 (d) Situation 4

Figure 3. LHP Startup Scenarios

In situation 1, the vapor grooves contain vapor and the evaporator core is completely filled with liquid. This leads to the most benign case where the loop will start immediately after the heat load is applied to the evaporator. Because of the heat leak from the evaporator to the reservoir is small, the temperature overshoot for the reservoir and evaporator will be very small, if any, during the startup transient. After the cold liquid from the condenser reaches the reservoir, the reservoir temperature will decrease and the loop will eventually reach a steady state.

In situation 2, both the evaporator core and vapor grooves contains vapor. The loop will also start as soon as the heat load is applied to the evaporator. However, because of the high heat leak, both the reservoir and the evaporator will experience a large temperature overshoot during the transient before cold liquid from the condenser returns to the reservoir. The transient period and the extent of the temperature overshoot depend on the heat load and the initial temperature of the liquid line and the heat exchange between the liquid line and its surroundings. A low heat load will have a long transient period and a large temperature overshoot because of the parasitic heat gain from the environment along the liquid line. The parasitic heat gains decreases as the evaporator heat load increases.

In situation 3, both the evaporator core and vapor grooves are flooded with liquid. The liquid in vapor grooves must be superheated in order to initiate nucleate boiling and generate first bubbles. Because the heat leak is small, the reservoir temperature will change little. The required superheat can eventually be achieved even with a low heat load. Once vapor is present in vapor grooves, the liquid will begin the evaporation process and no superheat is needed. Immediately after boiling, the evaporator temperature drops sharply and the reservoir temperature begins to control the loop operating temperature. The loop will eventually reach a steady state.

In situation 4, vapor grooves are filled with liquid and the evaporator core contains vapor. When a heat load is applied to the evaporator, the heat leak is large and the reservoir temperature will rise in tandem with the evaporator temperature as illustrated in Figure 4. If the evaporator temperature can rise faster than the reservoir temperature, the required superheat will be reached to initiate nucleate boiling. Otherwise, nucleate boiling will not occur and the loop will not start successfully.

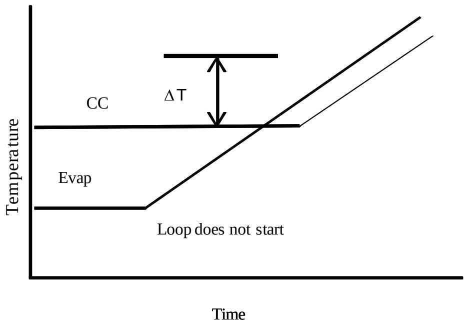


Figure 4. Unsuccessful Startup under Situation 4

2.3 Startup Success

The beginning of liquid evaporation or nucleate boiling in vapor grooves is characterized by a rise of the vapor line temperature to near the reservoir saturation temperature and a drop of the liquid line temperature. When temperatures of the reservoir, evaporator, vapor line and liquid line are plotted against time, it can be inferred from the test data what situation the startup is under. All four startup scenarios have been reported in the literature.

A successful startup is characterized by the following loop behaviors: 1) the vapor line temperature is the same as or close to the reservoir temperature; 2) the evaporator temperature is higher than the reservoir temperature by an amount determined by the heat load and the evaporator thermal conductance; 3) the liquid line temperature is lower than the reservoir temperature; and 4) temperatures of the reservoir, evaporator, vapor line and liquid line approach their respective steady state temperatures asymptotically.

Experimental results from ground testing of several LHPs are presented in the next section for illustration purposes. These LHPs are designated as LHP-A, LHP-B, and LHP-C, and are ordinary single-evaporator LHPs. Only schematics of these LHPs are presented. Details of their designs can be found in the referenced papers. Unless otherwise specified, all tests were conducted under ambient condition in a gravity netural environment using ammonia as the working fluid.

2.4 Effect of Heat Load on Startup Success

An LHP can start rather quickly and reliably as long as a large heat load (more precisely, a high heat flux) is applied even under the worst case scenario of situation 4. This can be attributed to the quick rise of the evaporator temperature above the reservoir temperature, and the circulation of a large flow of the working fluid. Under such a condition, there is ample liquid subcooling to balance the heat leak from the evaporator to the reservoir regardless of which startup scenario prevails. Some examples from tests conducted on LHP-A as shown in Figure 5 [14, 15] are presented below.

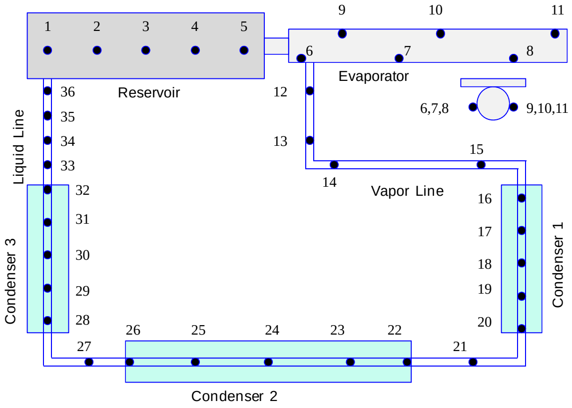


Figure 5. Schematic of LHP-A with Thermocouple Locations [14, 15]

Figure 6 depicts the temperature responses during the startup of LHP-A with 50W applied to the evaporator. As the power was applied, the evaporator temperature increased. Because the reservoir temperature rose with the evaporator, and a superheat was needed at the boiling incipience, it seemed to indicate a situation 4 startup. However, this was more likely a situation 3 startup. The slow rise of teh reservoir temperature was most likely due to a heat leak from the evaportor. A situation 4 startup would show a much sharper rise of the reservoir temperature in tandem with the evaporator temperature. Boiling started in less than 3 minutes after 50 W had been applied. All temperatures approach steady state values, and the loop started successfully with such a high power.

In most space applications, the evaporator is attached to a large thermal mass that is to be cooled. During the startup transient, the net heat load to the evaporator will likely be small. In other words, a low power startup prevails under most space applications. The startup with low powers under situations 1, 2, and 3 has not shown any problem. Many LHPs can start smoothly with very low powers under situation 1. For example, LHP-A demonstrated successful startups with powers ranging from 2W to 200W [14]. A large temperature overshoot may occur under situation 2, and it may take a long time for nucleate boiling to occur under situation 3. For low power startup under situation 4, there are several possible outcomes: 1) a smooth and successful startup; 2) a successful startup with a very large temperature overshoot; 3) an unsuccessful startup that yields an excursion of the evaporator and reservoir temperatures with no forward flow being established; 4) a reverse flow that is eventually overcome by a forward flow, leading to a successful startup; and 5) a sustaining reverse flow and thus an unsuccessful startup.

Figure 7 illustrates a successful startup of LHP-A with 5W. The heat load was applied at 9:33. This is clearly a situation 4 startup. Because of the high heat leak, the reservoir temperature followed the evaporator temperature closely, requiring the evaporator temperature to rise even higher. The high heat leak also left less power to heat the evaporator. Consequently, it took 45 minutes to initiate nucleate boiling, compared to 3 minutes when the heat load was 50W shown in Figure 6.

The evaporator temperature shown in Figure 7 reached a peak value of 301K with a temperature overshoot of less than 4K, which was not unusual. When the same LHP was tested in a thermal vacuum chamber and the evaporator/reservoir was raised 690 mm above the condenser, the evaporator temperature rose more than 35 degrees before nucleate boiling occurred with 10W heat load as shown in Figure 8. The loop finally reached a steady state with a temperature overshoot of 20 degrees. In real applications, the evaporator peak temperature during this startup was most likely higher than that

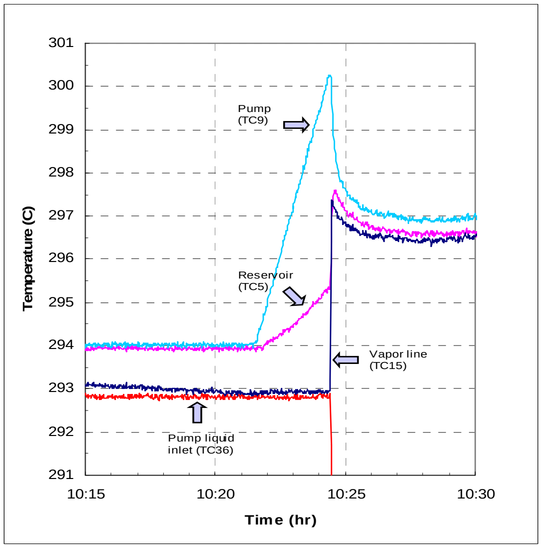


Figure 6. Startup of LHP-A with 50W

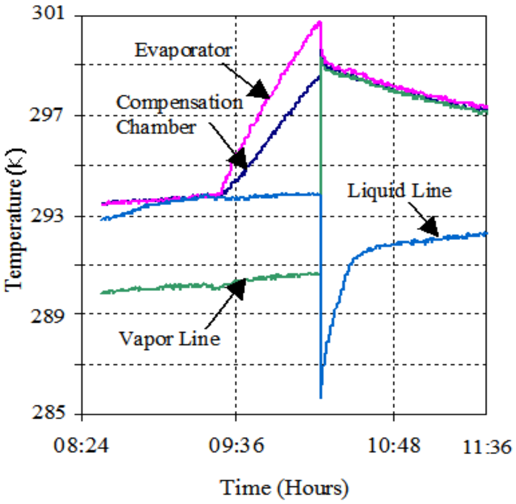


Figure 7. Startup of LHP-A with 5W

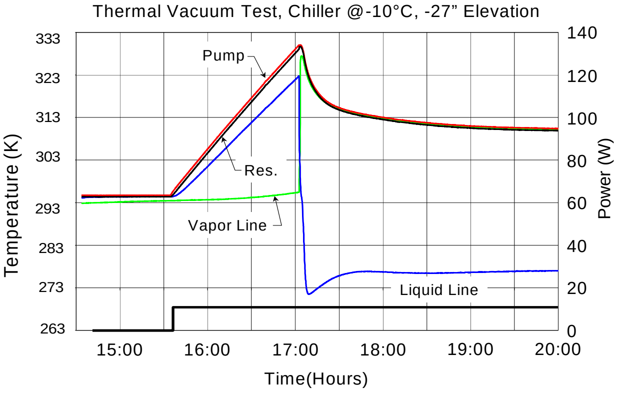


Figure 8. Startup of LHP-A with 10W in Thermal Vacuum Test

allowed by the source. Under such a circumstance, the startup process shown in Figure 8 would have been discontinued and an unsuccessful startup declared before nucleate boiling was initiated.

2.5 Flow Reversal

Another phenomenon associated with low power startup under situation 4 is a flow reversal. When the evaporator core contains vapor, liquid evaporation can occur inside the evaporator core with no superheat required while liquid in vapor grooves is being heated to achieve the required superheat for nucleate boiling. The heat source for liquid evaporation comes from the heat leak that is transmitted through the primary wick. The heat leak raises the reservoir temperature and pressure, which move the fluid to the condenser where the pressure is lower. The fluid will take the path of least resistance, which is via the liquid line because the menisci at the inner surface of the primary wick prevent vapor from penetrating the wick. The reverse flow will continue until nucleate boiling occurs in vapor grooves on the outer surface of the primary wick. Once a forward flow is established, it is easier for the vapor to be generated on the outer surface than the inner surface of the primary wick. Thus, the forward flow prevails from then on.

A reverse flow can happen at any heat load. With high heat loads, the forward flow is established so quickly that the reverse flow only lasts for seconds or less. At low heat loads, however, the reverse flow may last for an extended period. The low power startup shown in Figure 7 indicated a flow reversal as evidenced by the rise of the liquid line temperature with the reservoir temperature and a slight decrease of the vapor line temperature. The forward flow was established after nucleate boiling had occurred.

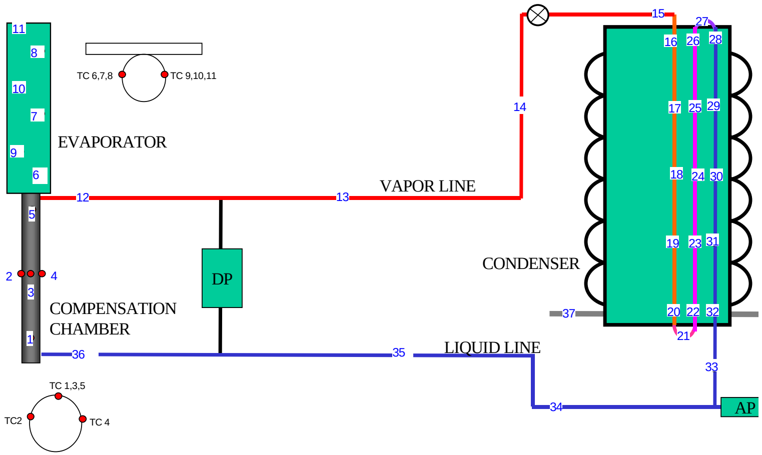


Figure 9. Schematic of LHP-B with Thermocouple Locations [15, 16]

Flow reversal was also observed during the low power tests of LHP-B shown in Figure 10 [15, 16], which was a situation 4 startup. The flow was reversed because the liquid line temperatures at TC 36 and TC 34 rose with the reservoir temperature and the vapor line temperature decreased and then remained subcooled. The reverse flow lasted for 4 hours without any sign of transition to a forward flow. Only when the power was increased to 100W was a forward flow established. The large mass flow rate at 100W brought ample subcooling to the reservoir, and helped collapse vapor bubbles inside the evaporator core. After a steady temperature of 299K was reached at 100W, the heat load was reduced to 5W. The forward flow continued and the loop reached a new steady temperature of 296K. Note that the loop operating temperature was lower at 5W than at 100W because the sink temperature was near the ambient temperature and the condenser was fully utilized under both heat loads.

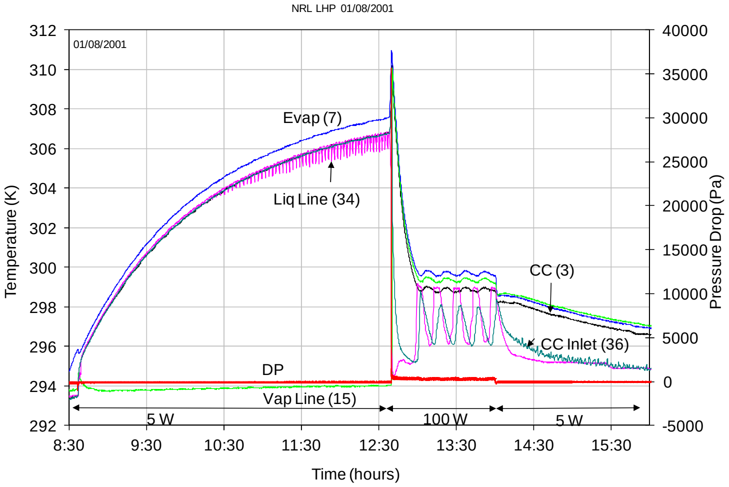


Figure 10. Flow Reversal during Startup of LHP-B with 5W

2.6 Temperature Control Methods and Startup Success

Several methods have been developed to control the reservoir temperature at its desired set point [10, 11]. The most common method to control the reservoir temperature is to cold bias the reservoir and use an electrical heater to compensate for subcooling. This method has been proven to be effective, but it also has its shortcomings. First, the electrical heater can only provide heating to the reservoir, i.e. the set point temperature can be maintained only for certain range of evaporator heat load. Second, the required CC control heater power can be very large when the condenser sink is very cold. Several methods have been used to reduce the control heater power requirement [17-22]. The method of using a coupling block between the vapor line and liquid line is effective in reducing the liquid subcooling and control heater power [6, 17]. On the other hand, this method is purely passive. At low powers, the liquid subcooling is small and the heat leak dominates.During the startup, the heat load is small, resulting in a high heat leak relative to the liquid subcooling. Thus, cooling instead of heating is needed for the reservoir during the startup, but the coupling block will heat the liquid line at all times. In essence, it raises the natural operating temperature of the loop at low powers. Since startup is basically a low power operation, using this method will increase the temperature overshoot during startup. When the temperature overshoot is too high, the loop may not start successfully before the maximum allowable temperature is reached [17]. When the LHP is tested at an adverse election, such an effect becomes even more pronounced as illustrated in Figure 8. Other active or semi-active enhancement methods for reservoir temperature control can avoid or mitigate such a problem [7, 10-11, 20-22].

III. Factors Affecting Fluid Distribution in Evaporator and Reservoir

The heat leak is strongly dependent upon the vapor void fraction inside the evaporator core. Furthermore, the higher the vapor void fraction, the higher the heat leak [13, 16]. It has been demonstrated over and over again in ground tests of many LHPs that the heat leak from the evaporator to reservoir is the single most important factor in determining the LHP behavior in all aspects of its low power operation. For a given LHP, the vapor void fraction inside the evaporator core is affected by combinations of several factors, including the evaporator/reservoir assembly design, fluid inventory, pre-conditioning of the loop, body forces, tilt between the evaporator and reservoir, and elevation between the evaporator/reservoir and condenser. The following examples illustrate the effect of various combinations of these variables on the LHP startup and its subsequent operations.

3.1 Evaporator Assembly Design and Gravity

There is a minimum volume requirement for the reservoir in order for the loop to operate properly [2]. In addition, the fluid inventory must be sufficient to accommodate the loop operation under all anticipated thermal conditions in space. Although in theory there is no upper limit on the reservoir volume, the reservoir size is optimized to accommodate the available real estate and to reduce the overall LHP volume and mass. The optimized reservoir design may have the same or a different diameter as the evaporator. Because the reservoir and evaporator form an integrated assembly, the assembly design and the amount of fluid inventory play an important role in the fluid distribution between these two components in ground testing.

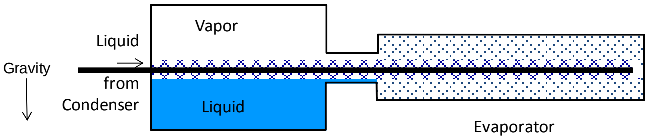


Figure 11. Liquid in the Reservoir in Concentric Evaporator Assembly in a Gravity Field

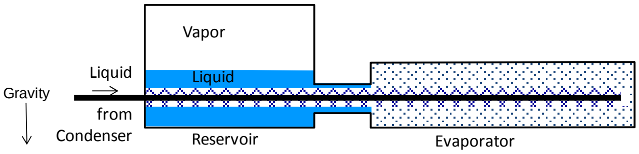


Figure 12. Liquid in the Reservoir in an Eccentric Evaporator Assembly in a Gravity Field

Figure 1 shows the fluid distribution in the evaporator and reservoir under the zero-G condition. A liquid puddle will stay on one end of the reservoir where the temperature is slightly lower due to the cold incoming subcooled liquid in the bayonet tube and the structure of vanes and wicks inside the reservoir. In ground tests, the liquid puddle will stay at the bottom of the reservoir instead. Unless the liquid in the reservoir rises to a level that covers the evaporator core, the evaporator core will contain vapor and the startup will be affected. The situation becomes worse when the reservoir has a larger diameter than the evaporator, as shown in Figure 11. The evaporator core could be mostly filled with vapor due to liquid drainage in the reservoir.

One method to mitigate the liquid drainage issue is to design an eccentric evaporator/reservoir assembly so that the reservoir and evaporator are on the same level in a gravity field as shown in Figure 12. In this design, the gravity will force liquid to fill the evaporator core. Such an eccentric design is especially useful for spacecraft level ground testing when the orientation of the LHP on the spacecraft is known in advance.

3.2 Fluid Inventory and Tilt in Ground Tests

Extensive experimental investigations of the start-up of LHP-B were conducted with various combinations of fluid inventory, tilt, condenser sink temperature, and heat load [12 - 16]. Figure 13 shows the cross sectional view of the reservoir and evaporator for three fluid inventories (83 grams, 100 grams, and 113 grams) and three tilts from evaporator end to the reservoir end (+6.35mm, 0 mm, and -6.35mm). The evaporator and reservoir have the same diameter. Test results show that the loop could start with 100W or 200W regardless of the fluid inventory, tilt, or condenser sink temperature. For heat loads less than 100W, start-up was highly dependent upon the fluid inventory and the tilt. With a fluid inventory of 83 grams, the loop could not start successfully below 25W in all three tilts. In contrast, the loop could start successfully with heat loads as low as 5W in all tilts with fluid inventories of 100 grams and 113 grams.

It can be seen from Figure 13 that even a slight tilt of the evaporator assembly has a big impact on the vapor void fraction in the evaporator core with 83 grams of inventory. In particular, when the evaporator end was raised +6.35 mm above the reservoir, one of the start-up tests led to a flow reversal with a heat load as high as 50W. Figure 14 shows the flow reversal lasted for about 15 minutes and the evaporator temperature rose by 20 degrees before nucleate boiling finally occurred and the forward flow was established. Such a long duration of flow reversal during the start-up with 50W was very unusual. Apparently, the heat leak was very large during the start-up transient under this test condition.

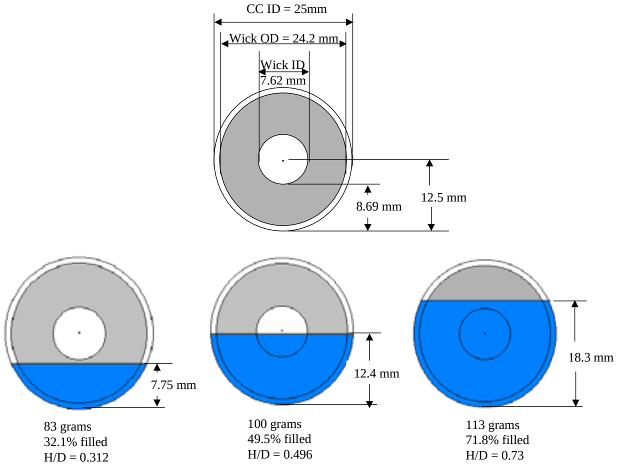


Figure 13. Cross-Sectional View of LHP-B Evaporator/Reservoir with Various Fluid Inventories

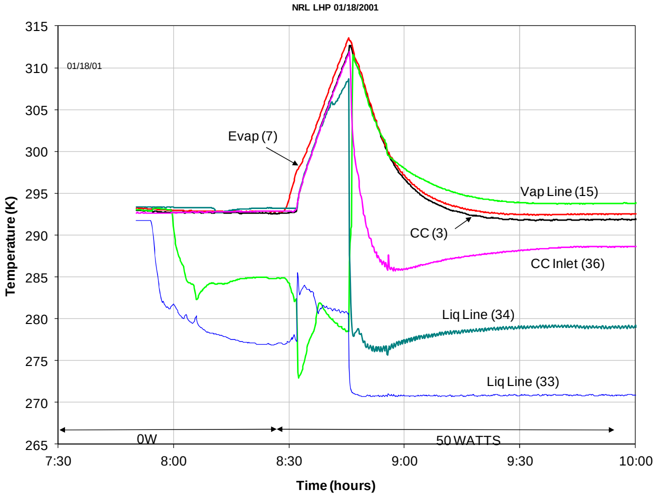


Figure 14. Flow Reversal during Startup Test of LHP-B with 50W

IV. Enhancing Startup Success

Under situation 3 and situation 4, liquid in vapor grooves must overcome the superheat required for nucleate boiling in order for the LHP to start successfully. For low power startups, the reservoir temperature may rise in tandem with the evaporator temperature under situation 4 as shown in Figure 4 and the required superheat may never be achieved. Because of the large thermal mass attached to the evaporator, most startups of LHPs for space applications will be low power startups. Although the loop should start successfully under situation 3 even with low powers, the time required to initiate nucleate boiling could be unacceptably long. Furthermore, some sensitive instruments require that the LHP be operational before they can be turned on, and still some instruments require the loop to start within a specified period of time. Two methods of enhancing the startup success are described below.

4.1 Startup Heater

When the first vapor bubble is generated in the vapor grooves, the bubble will quickly grow to occupy the entire length of the evaporator. Once vapor is present in the vapor grooves, liquid will go through the evaporation process which requires no superheat. Therefore, the key to starting the loop under situations 3 and 4 is to generate the first bubble or bubbles as soon as possible. A concentrated heat source over a localized area will achieve this goal. By attaching a small heater on the evaporator surface, a high heat flux will quickly raise the temperature of liquid in the vicinity of the heater while minimizing the heat leak to the reservoir. Thus, the reservoir temperature and the local evaporator temperature shown in Figure 4 will diverge rapidly to reach the required superheat. As soon the first bubble is generated, the loop will start. This is the essence of using a startup heater.

The startup heater has proven to be very effective in enhancing the startup success, and many LHPs in flight applications employ such a device because of its simplicity in design and ease in implementation [5-8].

4.2 Thermoelectric Converter

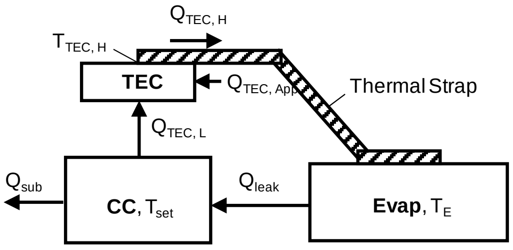


Figure 15. Heat Flow When TEC Is Cooling the Reservoir

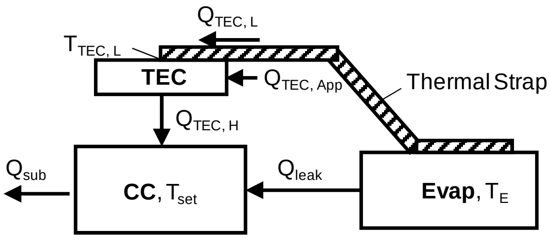


Figure 16. Heat Flow When TEC Is Heating the Reservoir

Another method to enhance startup success is to attach a thermoelectric converter (TEC) to the reservoir and connect the TEC to the evaporator through a thermal strap [22, 24-29]. The advantage of using a TEC is that it can provide both heating and cooling to the reservoir by changing the polarity of the voltage of the power supply. Figure 15 and Figure 16 show the heat flow when the TEC is cooling and heating the reservoir, respectively. During the startup, if the heat leak raises the reservoir temperature above its set point, the TEC will absorb the heat and maintain the reservoir set point. With a constant reservoir temperature, the evaporator can eventually achieve the required superheat to initiate nucleate boiling and ensure startup success. This is illustrated in Figure 17.

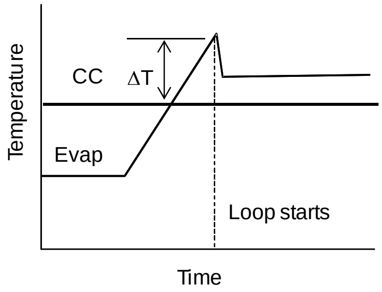


Figure 17. Evaporator and Reservoir Temperatures with TEC Control

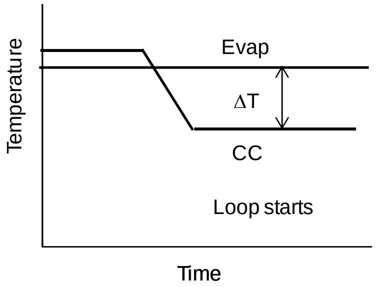


Figure 18. Startup by Lowering the Reservoir Temperature using TEC

The loop can also be started by simply lowering the reservoir temperature to achieve the required superheat as shown in Figure 18. When the TEC is cooling the reservoir, the absorbed heat along with the TEC power is delivered to the evaporator, which increases the power for startup. When the TEC is heating the reservoir for temperature control, part of the heat comes from the heat applied to the evaporator, and the required reservoir control heater power is substantially reduced.

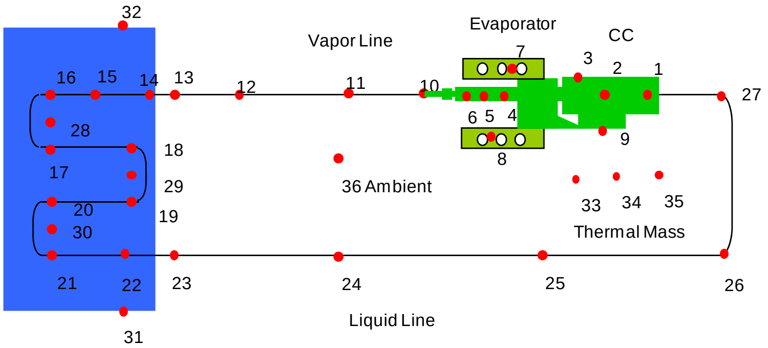


Figure 19. Schematic of LHP-C with Thermocouple Locations [22, 24-25]

Figure 19 shows the schematic of LHP-C, which is a miniature LHP [22, 24-25], and Figure 20 illustrates the TEC that was installed on the reservoir and connected to the evaporator via a copper strap. Extensive tests were performed in the laboratory, and the effectiveness of using a TEC for LHP temperature control and startup has been demonstrated. Startup tests were 100 percent successful, and the control heater power for reservoir temperature control was 40 to 60 percent less than that of using an electrical heater.

Figure 21 shows the startup of LHP-C using a TEC for reservoir set point temperature control. The evaporator and reservoir were at 299K initially. As a heat load of 10W was applied to the evaporator for startup, the reservoir was set to 303K using the TEC. The reservoir temperature rose to 303K and stayed nearly constant even when the evaporator temperature rose above the reservoir temperature because the heat leak was removed from the reservoir by the TEC. When the evaporator temperature overcame the required superheat, the loop started successfully. This is the startup mechanism illustrated in Figure 17. For comparison, a similar startup using an electrical heater to maintain the reservoir set point is shown in Figure 22. When the evaporator temperature exceeded the reservoir temperature, the reservoir also rose in temperature along with the evaporator because of the heat leak and because of the inability of the heater to cool the reservoir. Although the loop also started successfully, the temperature overshoot was much higher.

TECs were also installed on a breadboard and proto-flight units of an LHP with two evaporators and two condensers [26-29]. Again, all startup tests were 100 percent successful. In particular, the proto-flight unit demonstrated successful startup repeatedly by lowering the reservoir temperature below the evaporator temperature without applying power to the evaporators in thermal vacuum tests. Figure 23 shows the temperatures in one of the startup tests. For clarity, only temperatures of one set of the evaporator, reservoir, and thermal mass attached to the evaporator are shown. The loop was initially at 279K except for the condensers, which were at 173K. The TECs were turned on at 8:15 to cool the

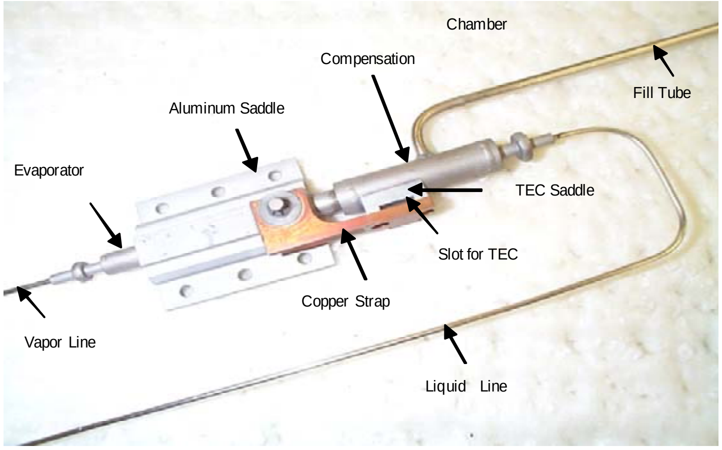


Figure 20. TEC and Copper Strap between Evaporator and Reservoir in LHP-C

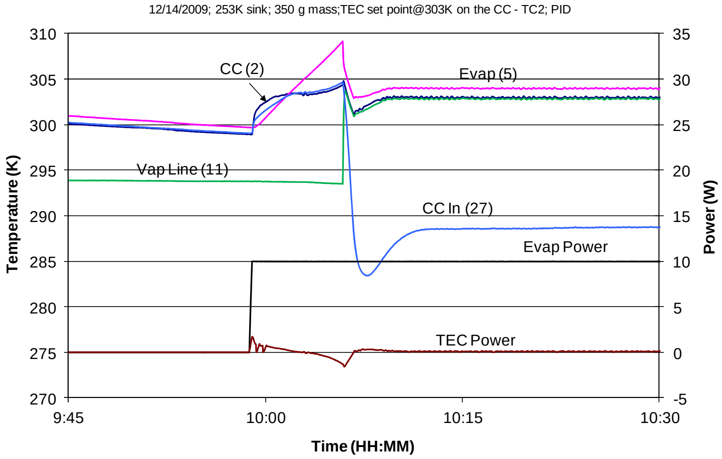


Figure 21. Startup of LHP-C Using TEC for Reservoir Set Point Temperature Control

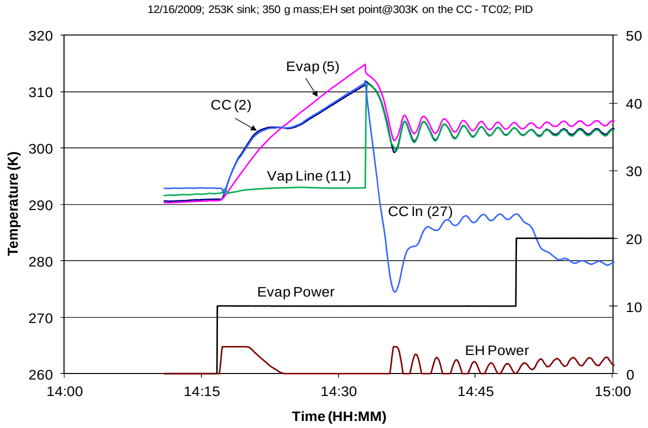


Figure 22. Startup of LHP-C Using Electrical Heater for Reservoir Set Point Temperature Control

reservoir toward the set point temperature of 258K. The loop was quiescent until the reservoir temperature dropped to 277K. The loop started at 8:17 with a superheat of 2K without applying any power to the evaporator. The startup and continued operation of the LHP were evidenced by the fact that temperatures of the evaporators, transport lines, and thermal masses all moved in tandem with the change of the CC temperatures. The heat input to the evaporators came from the power that was applied to the TECs, and the heat that was pumped out of the reservoirs. Once the loop was running, an additional heat source came from the release of the sensible heat by the thermal masses. This is the startup mechanism illustrated in Figure 18.

The TEC is very versatile and effective, but it also adds complexity in the design of the thermal subsystem. In order for the TEC to provide both heating and cooling to the reservoir, a bipolar power supply is needed, which adds weight to the system and requires control algorithms. In addition, TECs are susceptible to shear stress. Thus, for flight applications, special considerations must be given to the evaporator/reservoir assembly design and the installation of the TECs [30]. The use of the TEC on LHPs has not been validated in space flight for zero-G performance.

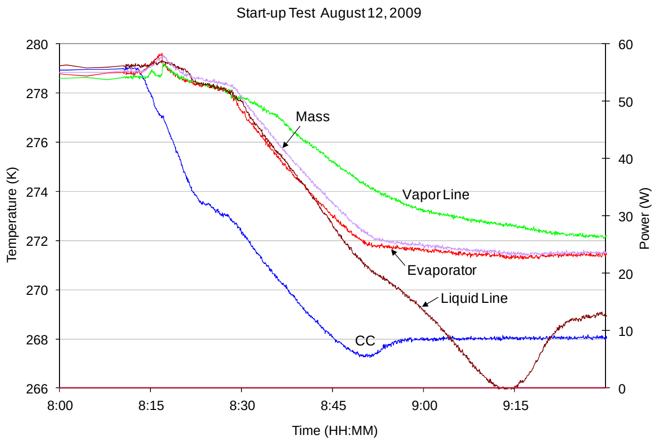


Figure 23. LHP Startup Using TEC to Lower Reservoir Temperature

V. OtherStartup Issues

5.1 Pressure Spike and Pressure Surge

Under situation 3 and situation 4, the liquid in the vapor grooves must overcome the superheat requirement for nucleate boiling. The required superheat can vary from a fraction of one degree to more than ten degrees. Immediately following the inception of nucleate boiling, the vapor bubble will absorb the sensible heat stored in the superheated liquid and grow rapidly. In fact, the growth of the vapor bubble is similar to an explosion. Tests have been conducted with a differential pressure transducer installed to measure the pressure drop across the evaporator. Experimental data shows that the pressure differential can be as high as 45 kPa. The actual pressure drop across the menisci at the outer surface of the primary wick could be even higher. Such a high pressure drop may exceed the capillary limit of the primary wick and cause the vapor to penetrate the wick to reach the evaporator core. However, the high pressure drop only lasted for less than one second. In fact, measuring the pressure spike was a hit or miss endeavor when the data was scanned once per second or less often. Such a pressure spike could be detected with certainty only if the data scan rate was set to 10 scans or 100 scans per second. Because of the short duration of the pressure spike and the ability of the LHP to tolerate a vapor bubble in the evaporator core, no LHP deprime due to the pressure spike has been observed.

Immediately following the boiling incipience, liquid in the vapor line will be swept into the condenser. An equal volume of the liquid will be moved toward the reservoir at the same volumetric flow rate as the vapor is being generated in the vapor grooves. In other words, the liquid is being swept out of the vapor line at the same speed as the vapor is flowing there. Depending on the ratio of the vapor specific volume to the liquid specific volume, the volumetric flow rate of the liquid along the condenser and liquid line can be two orders of magnitude higher than its steady state value at the same heat load during the normal operation of the LHP. Such a high flow rate will induce a surge of the pressure drop that is imposed on the primary wick until vapor reaches the condenser. The magnitude and duration of the pressure surge depend on the working fluid, the saturation temperature, the heat load, the volume of the vapor line and vapor grooves, and the initial vapor line temperature. For most fluids, the ratio of the vapor to liquid specific volumes increases rapidly with a decreasing temperature whereas the latent heat increase modestly with a decreasing temperature. Thus, the pressure surge will be more severe at a low reservoir temperature. Unlike a capillary pumped loop, an LHP has a much higher pumping capability and can usually sustain the pressure surge without any problem.

5.2 Reservoir Temperature Undershoot

When a slug of cold liquid is injected into the reservoir, the reservoir temperature will decrease if its temperature is not regulated by a heater. When a large amount of cold liquid enters the reservoir rapidly, the reservoir temperature will drop suddenly and sharply. Nevertheless, the evaporator can usually adjust its temperature swiftly to maintain its thermodynamic equilibrium with the reservoir regardless of whether a large thermal mass is attached or not. When the evaporator temperature drops along with the reservoir, the thermal mass simply releases its sensible heat to the evaporator. However, it is possible for the reservoir temperature to drop below the minimum allowable temperature set by the instrument or the spacecraft. Furthermore, in an unlikely scenario when the reservoir temperature drops more quickly than the evaporator can adapt, the pressure differential between the evaporator and the reservoir can exceed the wick capillary limit, leading to a loop deprime.

Even if an electrical heater or a TEC is used to regulate the reservoir temperature, a severe temperature undershoot can still occur when a large amount of cold liquid enters the reservoir suddenly because the heater power is not unlimited and the reservoir temperature cannot be raised so quickly. Thus, a violation of the minimum allowable temperature may still happen when the reservoir temperature is being regulated.

A large reservoir temperature undershoot can happen at any time during the LHP operation as a result of a sudden influx of a large amount of very cold liquid into the reservoir. This has been observed in ground testing of an LHP with a large condenser that was placed in a vertical position. However, a large reservoir temperature undershoot is most frequently seen during the startup of a fully flooded loop for reasons described in the previous section. Although the drop of the reservoir temperature itself is not an issue, its temperature rise when regulated by an electrical heater or a TEC could have an undesirable consequence. This is explained in the next section.

5.3 Repeated Cycles of Loop Startup and Shutdown

When the reservoir is heated, its temperature will rise and so will the corresponding saturation pressure. In order for the evaporator and reservoir to maintain a pressure balance, the evaporator temperature must rise fast enough to keep the corresponding temperature difference. If the rate of temperature increase in the reservoir is greater than that of the evaporator, the saturation pressure in the reservoir will eventually exceed the pressure in the evaporator. As a result, the evaporator will be flooded with liquid.

Following the inception of nucleate boiling during the startup, the vapor line is being cleared of liquid. During this period, a severe reservoir temperature undershoot could happen as explained in the previous section. In response, the reservoir control heater will be turned on. If the heater power is so large that it raises the reservoir temperature faster than the evaporator can follow, the loop will be flooded with liquid again by the time the reservoir reaches its set point temperature. The loop is shut down and has to re-start. However, the re-start will follow the same process as the previous startup. In some cases, this leads to perpetual startup and shutdown cycles unless some operating parameter is changed. The larger the rate of temperature increase of the reservoir compared to that of the evaporator, and the longer the reservoir is being heated, the higher the possibility of the loop being shut down temporarily.

Figure 24 shows the repeated startup and shutdown cycles in one of the LHP-C tests. The control temperature sensor was placed on the thermal mass with a set point of 313K, and the electrical heater installed on the reservoir was used to regulate the reservoir temperature so as to keep the thermal mass at its set point temperature of 313K. The loop was flooded with liquid prior to startup, and the reservoir had a very severe cold shock of 20 degrees after the boiling incipience. The reservoir control heater was turned on. With 4W to the reservoir and 10W to the evaporator/mass, the reservoir temperature rose much faster than the evaporator/mass could catch up. The entire loop was again flooded with liquid. This was evidenced by the rise of the reservoir temperature above the evaporator/mass temperature, the rise of the liquid line

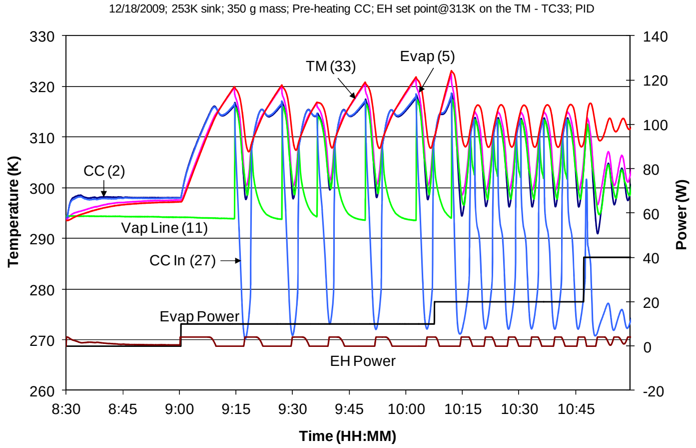


Figure 24. Repeated Startup and Shutdown Cycles of LHP-C

temperature to the reservoir temperature, and the drop of the vapor line temperature below the reservoir temperature. When the loop started again, it went through the same process over and over again.

The key to eliminating repeated startup and shutdown cycles is to prevent the reservoir temperature from rising above the evaporator temperature. There are several ways to accomplish this goal and all methods were successfully demonstrated in other LHP-C tests: 1) placing the temperature sensor on the reservoir - this shortened the delay of the reservoir response to the change of the control temperature sensor; 2) reducing the reservoir heater power – no repeated startup and shutdown cycles when the reservoir control heater power was 2W or less; 3) increasing the heat load to the evaporator/mass. Figure 24 shows successful startup when the heat load to the evaporator/mass was increased to 40W; 4) tightening the control band of the reservoir set point temperature to reduce the duration of reservoir heating; and 5) using a TEC instead of electrical heater for reservoir temperature control.

VI. Concluding Remarks

The startup of a loop heat pipe can be complex. Although most loop heat pipes aboard orbiting spacecraft have demonstrated successful startups uneventfully, difficulties in loop startup do arise from time to time. This paper presents an overview on various aspects of the loop heat pipe startup behaviors. Many examples are presented to show out-of-the-ordinary startup cases and some methods that can be used to alleviate such startup difficulties.

The fluid distribution between the evaporator and the reservoir dictates whether nucleate boiling will occur and whether liquid superheat is needed during the startup. In order for the LHP to operate properly, the fluid inventory must be sufficient to flood the entire loop with liquid and still has some liquid left in the reservoir. In space flight, the loop is usually preconditioned so that the entire loop is flooded with liquid. Thus, the loop startup degenerates to the Situation 3 startup. In ground testing, whether or not the loop can be completely flooded with liquid depends on the evaporator and reservoir assembly design, the fluid inventory, the tilt between the evaporator and reservoir, and the elevation between the evaporator and condenser. All four startup situations have been observed in ground testing, and some startup difficulties did occur, especially for low power startups.

Many spacecraft require the loop heat pipe to be operational prior to turning on their sensitive instruments. To overcome the superheat requirement for nucleate boiling and to enhance the startup success, a startup heater can be installed on the evaporator or a thermoelectric converter can be installed on the reservoir with a connection to the evaporator via a thermal strap. The startup heater proves to be very effective in improving the startup success. Because of its simplicity in design and ease in implementation, many loop heat pipes onboard spacecraft employ startup heaters. The thermoelectric converter almost guarantees a successful startup while providing both heating and cooling to the reservoir for set point temperature control. However, it also adds complexities in loop heat pipe assembly design, requires additional power supplies and adds weight. No loop heat pipes with thermoelectric converters have been flown in space so far.

The LHP startup represents a fast transient phenomenon that can result in pressure spike and pressure surge due to the rapid movement of the fluid. The rapid return of the cold liquid from the condenser to the reservoir can cause the reservoir temperature to drop suddenly, and may lead to perpetual cycles of startup and shutdown of the loop if the reservoir control heater power is too large. One must carefully evaluate the rate of temperature rise of the reservoir relative to that of the evaporator, and adjust the reservoir control heater power accordingly during startup.

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