Loop Heat Pipe Transient Behavior Using Heat Source Temperature for Set Point Control with Thermoelectric Converter on Reservoir

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The LHP operating temperature is governed by the saturation temperature of its reservoir. Controlling the reservoir saturation temperature is commonly accomplished by cold biasing the reservoir and using electrical heaters to provide the required control power. With this method, the loop operating temperature can be controlled within ±0.5K or better. However, because the thermal resistance that exists between the heat source and the LHP evaporator, the heat source temperature will vary with its heat output even if the LHP operating temperature is kept constant. Since maintaining a constant heat source temperature is of most interest, a question often raised is whether the heat source temperature can be used for LHP set point temperature control. A test program with a miniature LHP was carried out to investigate the effect on the LHP operation when the control temperature sensor was placed on the heat source instead of the reservoir. In these tests, the LHP reservoir was cold-biased and was heated by a control heater. Test results show that it was feasible to use the heat source temperature for feedback control of the LHP operation. In particular, when a thermoelectric converter was used as the reservoir control heater, the heat source temperature could be maintained within a tight range using a proportional-integral-derivative or on/off control algorithm. Moreover, because the TEC could provide both heating and cooling to the reservoir, temperature oscillations during fast transients such as loop startup could be eliminated or substantially reduced when compared to using an electrical heater as the control heater.

Nomenclature/Acronym/Symbol

CC	=	compensation chamber
EH	=	electrical heater
EVAP	=	evaporator
LHP	=	loop heat pipe
O.D.	=	outer diameter
PID	=	proportional-integral-derivative
SS	=	stainless steel
TC	=	thermocouple
TEC	=	thermoelectric converter
TM	=	thermal mass

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I. Introduction

A LOOP heat pipe (LHP) is a very robust and versatile heat transfer device which can transport large heat loads over long distances with small temperature differences[1, 2]. It utilizes boiling and condensation to transfer heat, and the surface tension force developed at the liquid/vapor interface on the evaporator wick to sustain the flow circulation. LHPs are being used on several commercial communications satellites and NASA's Swift, Aura, GOES-N and GOES-R spacecraft[3-11]. The LHP operating temperature is governed by the saturation temperature of its reservoir (also called the compensation chamber); the latter is a function of the heat load to the evaporator and the condenser sink temperature. For spacecraft applications requiring a narrow temperature range, regulating the LHP operating temperature becomes necessary. There are various ways to control the LHP operating temperature, depending upon the requirement on the tightness of the temperature control and the availability of the spacecraft power[12-13]. Nevertheless, all temperature control methods use the same underlying principal, i.e. to cold bias the LHP reservoir and use a control heater to maintain the reservoir temperature at the desired set point. In all of the LHPs onboard the above-mentioned orbiting spacecraft, the temperature sensor used for LHP operating temperature control has been placed on the reservoir. Using this method, the loop operating temperature can be controlled within ±0.5K or better. However, because of the thermal resistance that exists between the heat source and the LHP evaporator, the heat source temperature will vary with its heat output even if the LHP operating temperature is maintained constant. Since maintaining a constant heat source temperature is of most interest to the users, a question often raised is whether the heat source temperature can be used for LHP set point control.

A test program with an LHP was carried out to investigate the effect on the LHP operation when the control temperature sensor was placed on the heat source instead of the reservoir. The test article is a miniature LHP made by the Thermacore, Inc. in 2003. The loop was tested for its heat transport performance in 2003 under a laboratory condition and demonstrated a heat transport capability of 140W[14]. The loop was dormant between 2003 and 2009. Tests under the current program were conducted between December 2009 and February 2010, and between April and June 2011. In these tests, a thermal mass (TM) that simulated the heat source was attached to the LHP evaporator. The LHP reservoir was cold-biased, and a control heater was used to heat the reservoir. In addition to the location of the control temperature sensor, other test variables included: 1) thermal mass of 117 grams and 350 grams; 2) heat load to the thermal mass between 10W and 140W; 3) electrical heater (EH) versus thermoelectric converter (TEC) attached to the reservoir to serve as the control heater; and 4) proportional-integral-derivative (PID) versus on/off control scheme for the reservoir control heater.

This paper presents some of the test results when a TEC was attached to the reservoir as the control heater. Both the PID and the on/off control schemes were tested. In the following descriptions, the terms reservoir and compensation chamber (CC) are used interchangeably.

II. Test Article and Test Setup

The test article was a miniature LHP which consisted of an evaporator with an integral CC, a vapor line, a liquid line and a condenser[14]. Main features of this miniature LHP included: 1) a 7-mm outer diameter (O.D.) evaporator, 2) a stainless steel (SS) primary wick with 1.2 μm pore size, 3) SS vapor and liquid transport lines with a 1.59 mm O.D., 4) an aluminum condenser with a 2.39 mm O.D., and 5) a fluid inventory of 1.5 gram of ammonia. Main design parameters are summarized in Table 1. Figure 1 shows a picture of the test article when it was delivered in 2003 where, for clarity, a portion of the transport lines has been left out. Figure 2 shows a close-up view of the evaporator and CC. A TEC was attached to the CC and a copper strap connected the hot side of the TEC to the evaporator. The condenser was serpentined for four passes and was mounted to an aluminum cold plate as shown in Figure 3.

Table 1. Summary of Design Parameters

Item	Description
Evaporator	Aluminum Shell, 7 mm O.D. x 51 mm L
Primary Wick	SS, 5.6 mm O.D. x 2.4 mm I.D 1.2 μm pore size, 1.0 x 10^{-14} m^2 permeability
Secondary Wick	SS screen, 400 x 400 mesh
Compensation Chamber	SS, 9.52 mm O.D. x 25.5 mm L
Vapor Line	SS, 1.59 mm O.D. x 560 mm L
Liquid Line	SS, 1.59 mm O.D. x 635 mm L
Condenser	Aluminum, 2.39 mm O.D. x 200 mmL
Working Fluid	Ammonia, 1.5 grams
Total Mass	79 grams

In this test program, a Dale Ohm electrical heater was attached to the reservoir while keeping the original TEC. In addition, two aluminum thermal masses, 117 grams and 350 grams (the combination of 117-gram and 233-gram masses) shown in Figure 4, were attached to the aluminum saddle. Each of the two aluminum masses (117 grams and 233 grams) contained holes to accommodate cartridge heaters which provided up to 150W of power. The thermal mass served as the instrument simulator (the heat source) which dissipated heat to the LHP. The condenser plate was cooled by a refrigerator by flowing coolant to the copper tube soldered to the plate as shown in Figure 5).

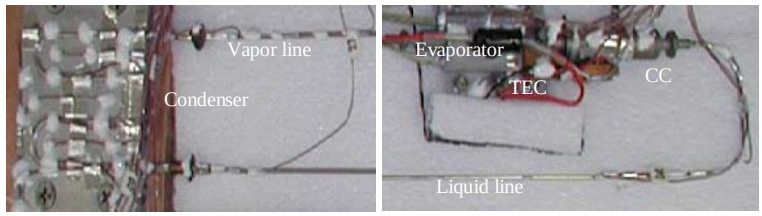

Figure 1. Picture of the Miniature LHP

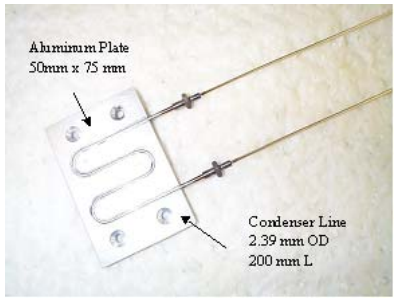

Figure 3. Picture of the Condenser Section

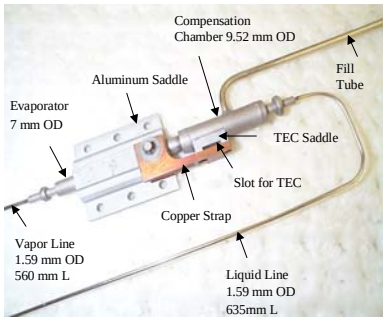

Figure 2. Picture of the Evaporator and CC Section

The reservoir was cold biased by the cold liquid returning from the condenser, and was heated either by the electrical heater or the TEC. A bipolar power supply was used for TEC operation. By changing the polarity of the power supply, the TEC could heat or cool the reservoir. The TEC power was calculated from the measured voltage and current, where positive and negative voltages indicated that the reservoir was being heated and cooled, respectively. Thermostats were used for all heaters for over temperature protection. A Labview program was used to regulate the reservoir temperature by using either the PID or on/off control scheme. The parameters for the PID control were fixed for all tests. A dead band of 0.1K was used when the on/off control scheme was employed.

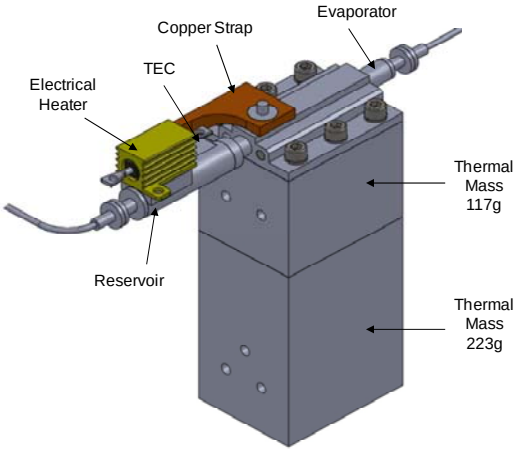

Figure 4. Evaporator/CC Section with Thermal Masses

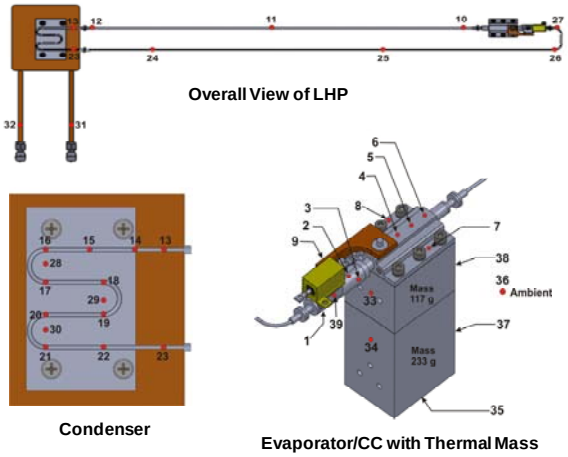

Figure 5. Thermocouple Locations

Forty type T thermocouples were used to monitor the temperatures of the LHP components and the test setup as shown in Figure 5. Tests were conducted by using thermocouples (TCs) #2, #5, and #33 for set point temperature control of the reservoir, evaporator and thermal mass, respectively. A data acquisition system consisting of a personal computer, a CRT monitor, a Hewlett-Packard data logger, and Labview software was used to display and store data every two seconds.

III. Test Program

The main objective of this test program was to investigate the feasibility of operating the LHP when the control temperature sensor was placed on the heat source. The LHP operating temperature was still governed by the temperature of its reservoir, and the latter was cold biased and heated by a control heater. In this test program the control temperature sensor was placed on the reservoir, evaporator, and thermal mass (simulating the heat source) to maintain the respective component at a constant temperature. Placing the control temperature sensor on the reservoir represents the traditional way of operating the LHP. The thermal mass was installed in such a way as to create a relatively large thermal resistance for heat conduction (0.23K/W) between the thermal mass and the LHP evaporator. In contrast, placing the control temperature sensor on the evaporator represents the condition of near-zero thermal resistance between the thermal mass and the LHP.

Other variables in this test program included: 1) thermal mass of 117 grams and 350 grams; 2) heat load to the thermal mass between 10W and 140W; 3) electrical heater versus TEC attached to the reservoir as the control heater; and 4) proportional-integral-derivative versus on/off control scheme for the reservoir control heater. The test variables are illustrated in Figure 6.

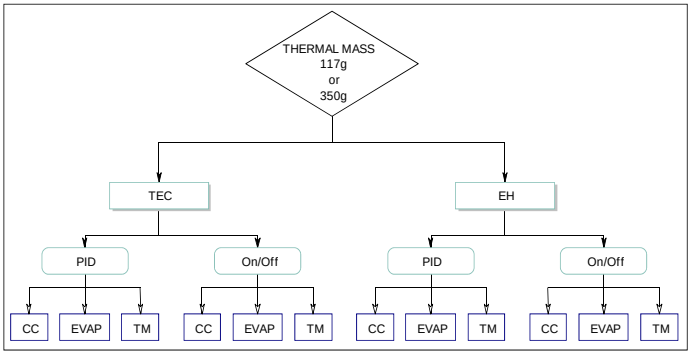

Figure 6. Diagram of Overall Test Program

Each test was conducted by selecting the thermal mass, the reservoir control heater, the temperature control scheme, and the location of the control temperature sensor. The set point temperature was fixed at 293K, 303K, and 313K when the control temperature sensor was placed on the reservoir, evaporator and thermal mass, respectively. Power was then applied to the thermal mass, and increased in steps after a steady state was reached at each step. Once the thermal mass temperature exceeded 343K or the condenser exhausted its convective heat dissipating capability, the power was lowered to 30W and 10W. Using different set point temperatures when the control temperature sensor was placed on different components allowed the LHP to operate over a similar power range for all tests.

IV. Test Results

Extensive power ramp-up tests have been conducted where the heat load was increased in steps. In addition, several power cycle tests were performed where the control temperature sensor was placed on the thermal mass with a set point of 313K and on the reservoir with a set point of 298K. The heat load to the thermal mass was cycled between 20W and 80W and between 40W and 80W for several hours. The following discussions focus on tests where the TEC was attached to the LHP reservoir although some tests with an electrical heater attached to the reservoir will also be presented for comparison. TECs have been used on several LHPs, including an LHP with two evaporators and two condensers, to control the CC temperature in ground tests and demonstrated excellent performance[14-17]. The TEC has an advantage over the traditional electrical heater in that a single device can provide both heating and cooling to the reservoir. Using a bipolar power supply, the TEC can automatically switch its operation between the heating and cooling modes as required. Tests were conducted with PID and on/off control schemes, and with 117-gram and 350-gram thermal masses. The presentations below are arranged in groups so as to illustrate the effects on the LHP operation due to: 1) the heat load to the thermal mass; 2) the location of the control temperature sensor; 3) the use of the PID and on/off control schemes, 4) the thermal mass, and 5) the power cycle.

Each test was performed as follows. Prior to the LHP startup, the condenser sink was cooled to 253K. As soon as the heat load was applied to the thermal mass, control of the set point temperature for the designated component (the reservoir, evaporator, or thermal mass) was activated. After the LHP successfully started and the designated component for temperature control reached a steady state, the heat load to the thermal mass was increased in steps until the thermal mass temperature exceeded 343K or the condenser exhausted its convective heat dissipating capability. Afterwards, the heat load was reduced to 30W and 10W to demonstrate that the LHP could resume its normal temperature control function. The power cycle test was conducted by cycling the heat load to the thermal mass between 20W and 80W and between 40W and 80W. In the following figures, selected thermocouples (TCs)

were used to illustrate temperatures of the various elements: TC #2 – CC, TC #5 – evaporator, TC #11 – vapor line, TC #24 – liquid line, TC #27 – liquid line at the CC inlet, and TC #33 – thermal mass.

117-gram Thermal Mass and PID Control Scheme - The first group of tests had the 117-gram thermal mass attached to the evaporator and the PID control scheme was employed. Figure 7 shows the temperature profiles for the test where the control temperature sensor (TC #2) was placed on the reservoir with a set point of 293K. Initially, the reservoir was pre-heated to 298K so as to flood the entire loop with ammonia. A heat load of 10W was then applied to the thermal mass for startup, and the PID control scheme was activated to maintain the reservoir at 293K. Details of the startup transient will be discussed in the next section. After the loop started, the TEC was able to maintain the reservoir temperature at the 293K set point for heat loads between 10W and 120W. At each power increase, the evaporator and thermal mass rose to higher temperatures due to the heat transfer requirement. At 140W, the condenser exceeded its heat dissipating capability at a vapor temperature of 293K. Warm liquid returned to the reservoir, raising the reservoir temperature to 297K, which was its natural operating temperature in thermal equilibrium. Because the reservoir temperature was above its set point of 293K, the TEC operated in the cooling mode, attempting to maintain the reservoir set point temperature. When the heat load was reduced to 30W and 10W, the TEC was able to maintain the reservoir at the 293K set point again, and the evaporator and thermal mass temperatures dropped accordingly.

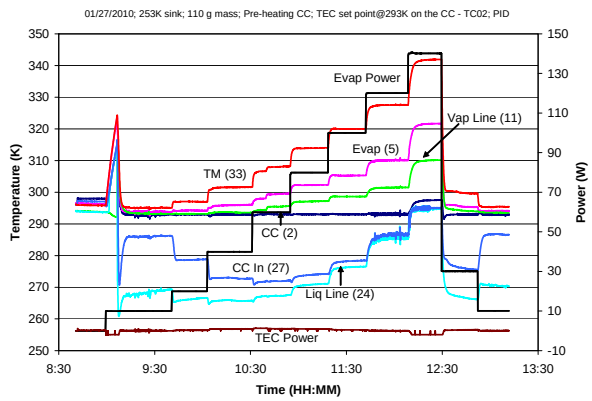

Figure 7. Temperature Profiles for Test with Reservoir Controlled at 293K (117g/TEC/PID)

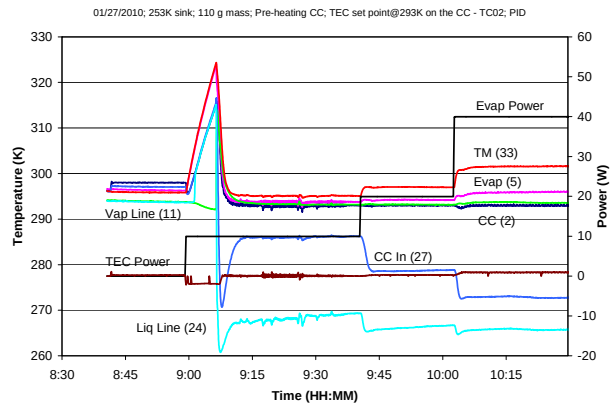

Figure 8. Temperature Profiles for Startup with Reservoir Controlled at 293K (117g/TEC/PID)

Figure 8 shows details of the startup transient. The reservoir was kept at 298K before the startup process began. When 10W was applied to the thermal mass for startup, the TEC was operating in the cooling mode to cool the reservoir to its set point of 293K as indicated by the negative TEC power. The thermal mass and evaporator were gradually heated by the 10W heat load to temperatures higher than that of the reservoir. Because of the heat leak from the evaporator to the reservoir, the TEC with 2W power was unable to cool the reservoir to 293K. During this period, a back flow of the working fluid occurred in the LHP as indicated by the rise of the liquid line temperature and the fall of the vapor line temperature. When the loop finally started, a forward flow was established, which was evidenced by the rise of the vapor line temperature and the fall of the liquid line temperature. The reservoir temperature dropped rapidly due to an injection of cold liquid from the condenser. Subsequently, the TEC heated the reservoir to maintain its set point temperature at 293K. Because of thermal resistances, the evaporator and the thermal mass were at higher temperatures than the reservoir. After the loop reached a steady state, the heat load was increased to 20W.

Figure 9 show the temperature profiles for a test similar to that of Figure 7, except that the control temperature sensor was placed on the evaporator (TC #5) with a set point temperature of 303K. In this case, the TEC was able to maintain the evaporator temperature at 303K for heat loads between 10W and 100W. As the heat load increased, the thermal mass temperature also increased because a higher temperature difference was needed to transfer the higher power. Likewise, the reservoir temperature decreased with an increasing heat load in order to keep the evaporator temperature constant. At 100W, the reservoir temperature was 291K. At 120W, the reservoir temperature rose to 293K in order to dissipate the higher power. Consequently, the evaporator temperature rose above its set point temperature. The TEC operated in the cooling mode and drew the maximum available control power of 2W, attempting to cool the reservoir so as to maintain the evaporator at its set point temperature. When the heat load was decreased to 30W and then 10W, the condenser resumed its heat dissipating capability at a lower reservoir temperature and the evaporator was again controlled at 303K.

Figure 10 shows the temperature profiles during the startup transient. Initially, the reservoir was heated to 298K for pre-conditioning. The evaporator and thermal mass were at 295K. As a heat load of 10W was applied, the command to control the evaporator at 303K was activated. Because the evaporator was below its set point of 303K, the TEC began to heat the reservoir. With 10W to the thermal mass, the evaporator was also heated and its temperature gradually rose. When the evaporator temperature exceeded 303K, the TEC switched to the cooling mode and the reservoir temperature began to drop. Soon after, the reservoir temperature dropped below the evaporator temperature by about 3K and the loop started. With cold liquid returning from the condenser to the reservoir, the TEC switched to the heating mode to maintain the evaporator set point temperature at 303K.

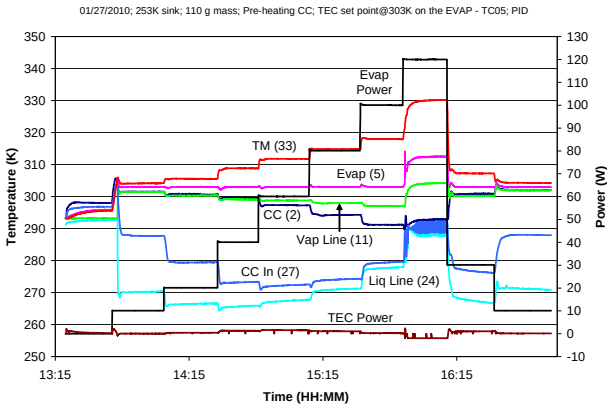

Figure 9. Temperature Profiles for Test with Evaporator Controlled at 303K (117g/TEC/PID)

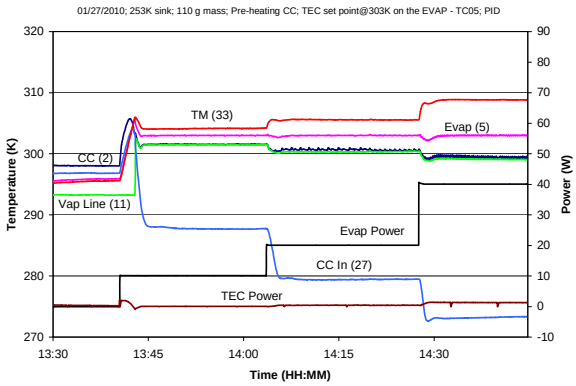

Figure 10. Temperature Profiles for Startup with Evaporator Controlled at 303K (117g/TEC/PID)

Figure 11 depicts the temperature profiles for the test where the control temperature sensor was placed on the thermal mass (TC #33). The goal was to maintain the thermal mass (the heat source) at a constant temperature of 313K under various heat loads. For the heat loads of 10W, large temperature oscillations were observed and the thermal mass temperature was at 312.5K ± 2K. During this period, the loop underwent repeated startup and shutdown cycles. Only when the heat load was increased to 20W and higher was the thermal mass temperature maintained at 313K without noticeable temperature oscillations. At each power increase, the reservoir temperature was automatically lowered in order to maintain the thermal mass at 313K. At 100W, the reservoir operated at its natural operating temperature of 288K, which was not low enough to keep the thermal mass at 313K. When the heat load was decreased to 30W, the reservoir temperature dropped and the thermal mass was kept at 313K again. As the heat load was lowered to 10W, large temperature oscillations reappeared. These temperature oscillations at low heat loads were a result of interactions among the reservoir, reservoir control heater power, thermal mass, and thermal mass power, as will be explained next.

The transient phenomena for loop startup with low powers are illustrated in Figure 12. Initially, the evaporator, and thermal mass were at 295K and the reservoir was heated to 298K. As a heat load of 10W was applied to the

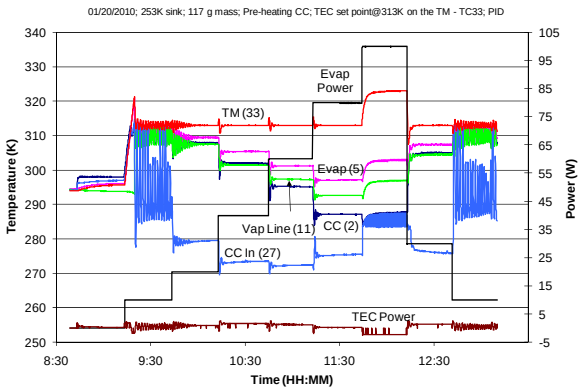

Figure 11. Temperature Profiles for Test with Thermal Mass Controlled at 313K (117g/TEC/PID)

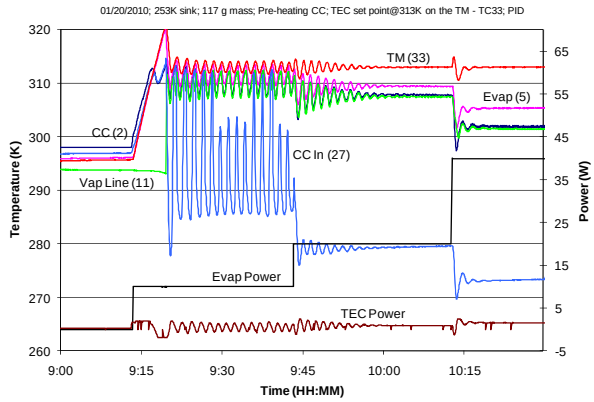

Figure 12. Temperature Profiles for Startup with Thermal Mass Controlled at 313K (117g/TEC/PID)

thermal mass, the reservoir heater control was activated and the TEC was turned on to maintain the thermal mass at 313K. With 2W to the reservoir and 10W to the 117-gram thermal mass, the reservoir temperature rose at a faster rate than the thermal mass and evaporator. When the thermal mass temperature exceeded 313K, the TEC switched to the cooling mode, resulting in a decrease of the reservoir temperature. The thermal mass temperature continued to rise while the reservoir temperature was decreasing. The loop started when the temperature differential between the evaporator and the reservoir reached about 2K (the wall superheat). With the injection of cold liquid from the condenser to the reservoir immediately following the startup, the reservoir temperature dropped sharply and so did the thermal mass. When the thermal mass temperature dropped below 313K, the TEC began to heat the reservoir. The reservoir temperature again rose at a faster rate than that of the thermal mass. The loop was subsequently shut down. What followed were repeated startup and shutdown cycles. When the heat load was increased to 20W, the rate of temperature increase in the reservoir no longer exceeded that of the thermal mass. Consequently, there were no repeated startup and shutdown cycles and the loop ran steadily with the thermal mass maintained at 313K.

117-gram Thermal Mass and on-off Control Scheme - The above-mentioned tests were repeated with the TEC controlled by an on/off scheme. Figure 13 shows the temperature profiles where the control temperature sensor was placed on the reservoir with a set point of 293K. These temperature profiles are similar to those shown in Figure 7 in that the reservoir temperature was kept constant for all the heat loads until the condenser ran out of its heat dissipating capability, that the evaporator and the thermal mass temperatures rose with each power increase, and that the reservoir resumed its temperature control function after the heat load was reduced to 30W and 10W near the end of the test. However, temperatures of the reservoir, evaporator, and thermal mass displayed larger oscillations than those shown in Figure 7. This difference was the result of using the on/off control scheme instead of the PID scheme. It was observed during the test that the rise and fall of the temperatures of the reservoir, evaporator, and thermal mass corresponded to the on and off cycles of the TEC power. The transient behavior illustrated by Figure 14 was somewhat different from that illustrated by Figure 8. The required superheat for startup was much smaller than that shown in Figure 8, and the loop started shortly after 10W was applied to the thermal mass. The superheat requirement for start-up is stochastic in nature and cannot be predicted in advance. The loop simply displayed two different superheats at the boiling inception in these tests.

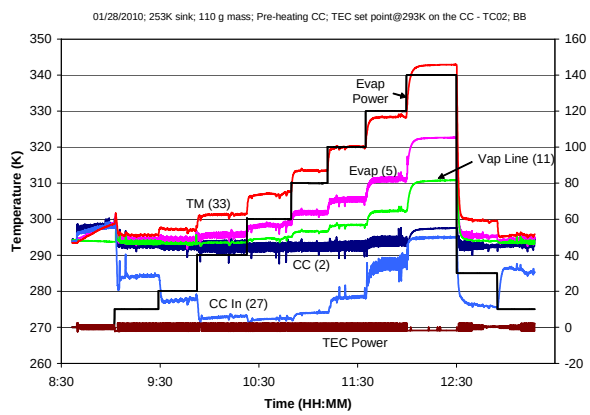

Figure 13. Temperature Profiles for Test with Reservoir Controlled at 293K (117g/TEC/on-off)

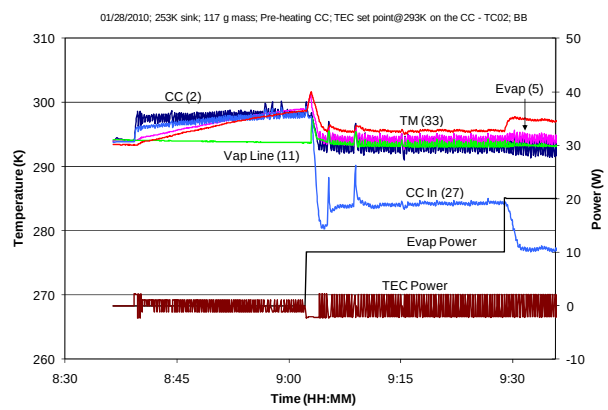

Figure 14. Temperature Profiles for Startup with Reservoir Controlled at 293K (117g/TEC/on-off)

Figure 15 shows the temperature profiles for the test with the control temperature sensor located on the evaporator and set at 303K. They are similar to those shown in Figure 9 except that amplitudes of temperature oscillations for the reservoir, evaporator and thermal mass were larger than those when the PID control scheme was employed. At 120W, the condenser reached its heat dissipating capability. The loop operated at the reservoir's natural operating temperature of 292K and the evaporator temperature rose to 310K, higher than its set point of 303K. The startup transient was illustrated in Figure 16. When a heat load of 10W was applied to the thermal mass, the TEC heated the reservoir until the evaporator reached 303K. The TEC was then switched to the cooling mode and the loop started with a small superheat. Again, the rise and fall of temperatures of the reservoir, evaporator, and thermal mass corresponded to the on and off cycles of the TEC power.

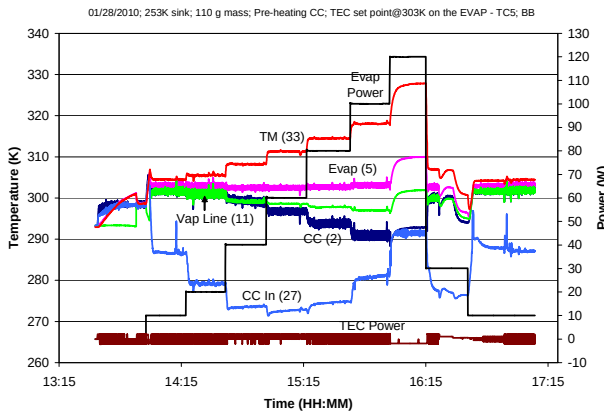

Figure 15. Temperature Profiles for Test with Evaporator Controlled at 303K (117g/TEC/on-off)

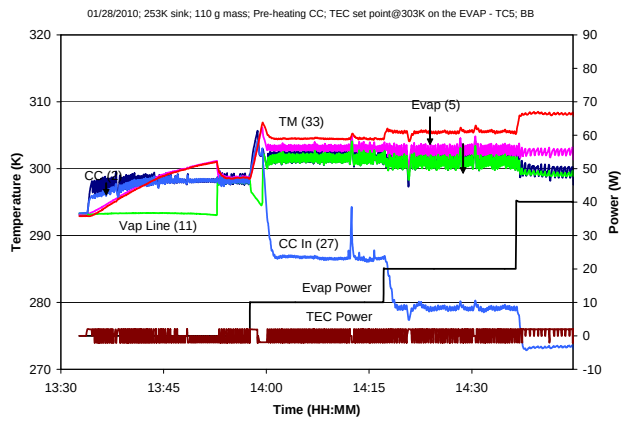

Figure 16. Temperature Profiles for Startup with Evaporator Controlled at 303K (117g/TEC/on-off)

Temperature profiles for the LHP operation with the control temperature sensor placed on the thermal mass and controlled at 313K are shown in Figure 17. With 10W to the thermal mass, the loop displayed repeated startup and shutdown cycles as shown in more detail in Figure 18. The loop started successfully at 20W without shutdown although small temperature oscillations persisted. Temperatures were stable and the thermal mass was maintained at 313K between 40W and 80W. In this power range, temperature fluctuations were mainly due to the on/off cycles of the TEC control power. At 100W and 120W, the reservoir was at its natural equilibrium temperatures, which were not low enough to maintain the thermal mass at its set point temperature of 313K.

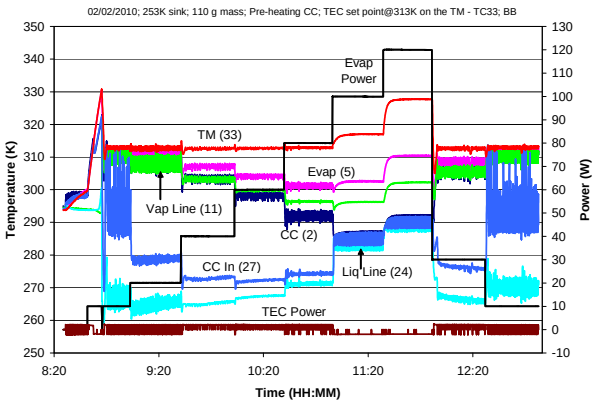

Figure 17. Temperature Profiles for Test with Thermal Mass Controlled at 313K (117g/TEC/on-off)

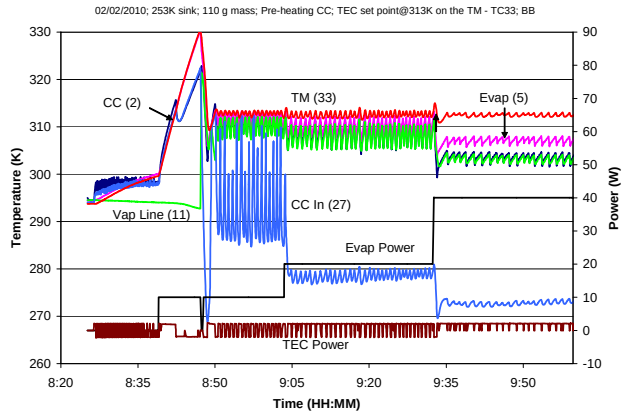

Figure 18. Temperature Profiles for Startup with Thermal Mass Controlled at 313K (117g/TEC/on-off)

350-gram Thermal Mass with PID and On-Off Control Schemes - The effect of the thermal mass on the loop operation is presented next. The power ramp-up tests were conducted with the 350-gram thermal mass attached to the evaporator. Figure 19 shows the temperature profiles for the test where the control temperature sensor was placed on the thermal mass (TC #33), and the TEC was controlled via a PID scheme. The thermal mass temperature could be controlled at its set point of 313K over a power range of 10W to 80W with no noticeable oscillations except at the very beginning of the startup. At 100W, the thermal mass temperature was higher than its set point temperature because the natural operating temperature of the reservoir was higher than that required to keep the thermal mass at 313K. When the heat load was decreased to 30W, the thermal mass was kept at 313K again. As the heat load was lowered to 10W, no temperature oscillations were seen. Thus, compared to the temperature profiles shown in Figure 11, the loop ran more stably with the 350-gram thermal mass than with the 117-gram thermal mass.

Figure 20 shows the temperature profiles during the startup transient. When 10W was applied to the thermal mass, the TEC was turned on. The reservoir temperature continued to rise until the thermal mass reached 313K, then the TEC began to cool the reservoir. While the thermal mass temperature continued to rise, the reservoir temperature

continued to decrease. The loop started when the thermal mass was at 318K and the reservoir at 313K (5K wall superheat). A slug of cold liquid was injected into the reservoir following the startup, causing the reservoir temperature to drop, which also brought the thermal mass temperature below 313K. The TEC switched to the heating mode. The fast rise of the reservoir temperature caused the loop to shut down. But the loop started again quickly. From then on, the loop operated stably without repeated startup and shutdown cycles.

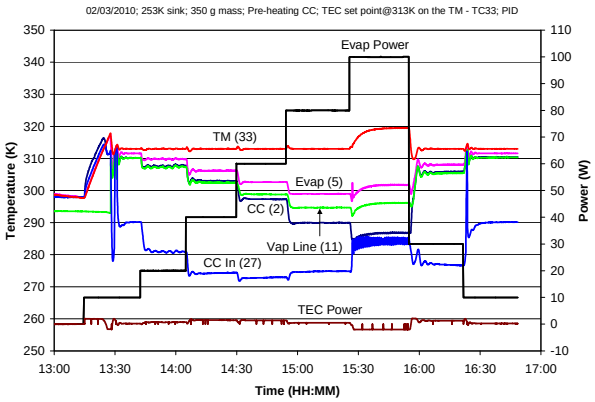

Figure 19. Temperature Profiles for Test with Thermal Mass Controlled at 313K (350g/TEC/PID))

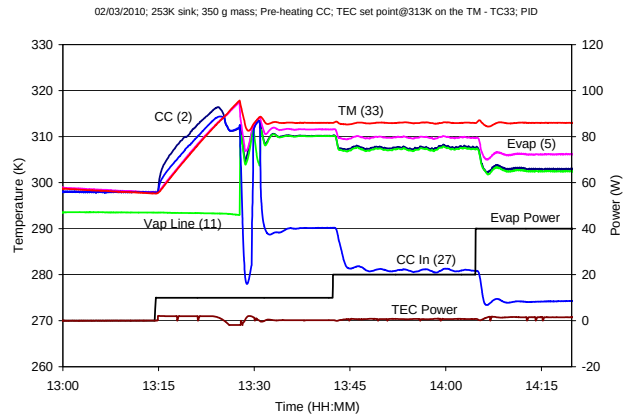

Figure 20. Temperature Profiles for Startup with Thermal Mass Controlled at 313K (350g/TEC/PID)

Figure 21 shows the temperature profiles for a test similar to that shown in Figure 19 except that the TEC was controlled via the on/off scheme. The thermal mass temperature was controlled at its set point of 313K between 10W and 80W. At 100W, the thermal mass temperature exceeded 313K because the reservoir was running at its natural operating temperature which was higher than that required to maintain the thermal mass at 313K. At 120W, the reservoir's natural operating temperature was even higher and the thermal mass temperature rose to 328K. When the heat load was decreased to 30W, the reservoir temperature dropped and the thermal mass was maintained at 313K again. During the startup with 10W, large temperature oscillations were seen on the reservoir, evaporator, vapor line, and especially on the liquid line as shown in Figure 22. The temperature oscillations appeared again at the end of the test with 10W heat load, and the loop was close to be shut down occasionally. The temperature oscillations were caused by the on and off cycles of the TEC power. When comparing Figure 21 to Figure 17, one can see that the loop displayed smaller temperature oscillations with the 350-gram thermal mass than with the 117-gram thermal mass. In addition, the loop showed repeated startup and shutdown cycles with 117-gram thermal mass (Figure 18), but not with 350-gram thermal mass (Figure 22).

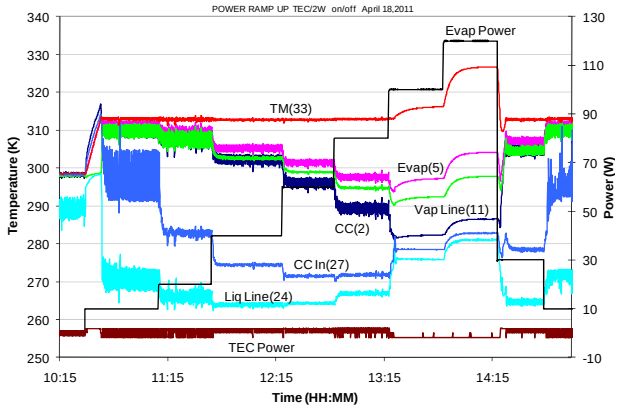

Figure 21. Temperature Profiles for Test with Thermal Mass Controlled at 313K (350g/TEC/on-off)

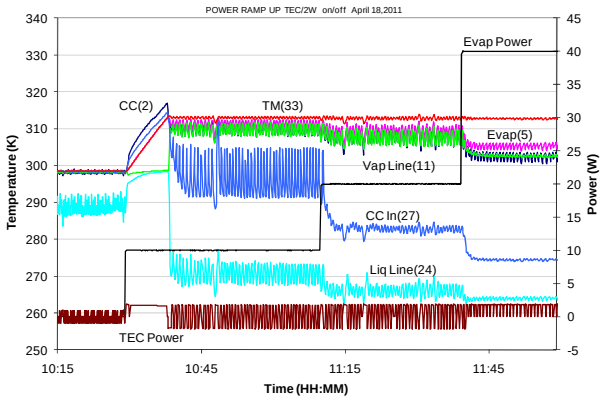

Figure 22. Temperature Profiles for Startup with Thermal Mass Controlled at 313K (350g/TEC/on-off)

The LHP operating temperature is governed by the saturation temperature of its reservoir. When the control temperature sensor is placed on the thermal mass, it is expected that the reservoir will respond to the change more slowly than when the control sensor is placed on the reservoir itself. This could result in larger temperature oscillations during fast transients. If the power profile is know in advance, however, it is possible to place the

control temperature sensor on the reservoir and still maintain the heat source at the desired set point. This can be accomplished by adjusting the reservoir set point temperature as a function of the heat load based on the known thermal resistance between the thermal mass and the reservoir. Such tests were performed under this test program.

Figure 23 shows the temperature profiles when the control temperature sensor was placed on the reservoir and the set point temperature was varied with the heat load applied to the 117- gram thermal mass. The reservoir set point as a function of the heat load was taken from the experimental data shown in Figure 11 and the TEC was controlled via the PID scheme. Using this method, the thermal mass temperature was maintained fairly constant at 313K for powers between 10W and 80W, and temperature oscillation seen in Figure 11 disappeared. A similar test was performed with the 350-gram thermal mass attached to the evaporator. The reservoir set point temperature as a function of the heat load was taken from experimental data shown in Figure 19. The temperature profiles are shown in Figure 24. Again, the thermal mass temperature was maintained fairly constant for powers between 10W and 80W, and temperature oscillation at 10W during the start-up transient disappeared.

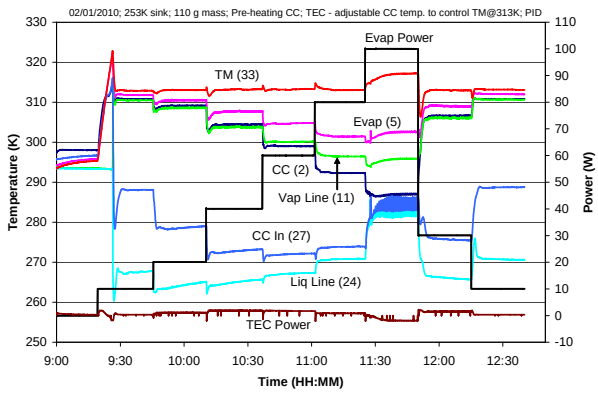

Figure 23. Varying CC Temperature to Maintain Thermal Mass at 313K (117g/TEC/PID)

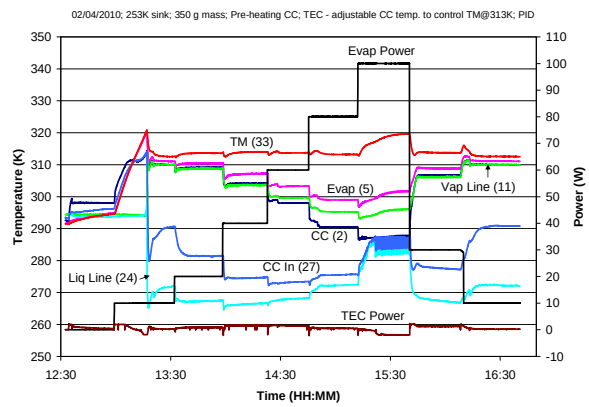

Figure 24. Varying CC Temperature to Maintain Thermal Mass at 313K (350g/TEC/PID)

Power Cycles - The power profile from the heat source is usually not known in advance. To compare the advantages and disadvantages of placing the control temperature sensor on the reservoir versus on the thermal mass, several power cycle tests were performed where the heat load to the thermal mass was changed between 40W and 80W, and between 20W and 80W. When the control temperature sensor was placed on the reservoir, the set point was fixed at 298K. Under this condition, the thermal mass temperature would vary with the heat load. When the temperature sensor was placed on the thermal mass, the set point was fixed at 313K. Under this condition, the reservoir temperature would change with the heat load in order to keep the thermal mass temperature at its set point. The purpose of these tests was to study the loop's response and the temperature variation of the thermal mass as the heat load changed.

Figure 25 shows the temperature profiles for the test with 350 gram thermal mass and the control temperature was placed on the thermal mass with a set point of 313K. The PID control scheme was employed. The thermal mass temperature could be maintained at 313K at all powers during steady state. Its temperature fell to 310K temporarily when the power decreased from 80W to 40W, and to 308K when the power decreased from 80W to 20W. When the power dropped from 80W to 40W or 20W, the reservoir temperature must be increased in order to maintain the thermal mass temperature at 313K. With a maximum heater power of 2W to the TEC, the reservoir temperature could not be raised quickly enough. A larger TEC power would alleviate the problem.

Figure 26 shows the temperature profiles for a similar power cycle tests where the control temperature sensor was placed on the reservoir with a set point of 298K. The same heater power of 2W was provided to the TEC, which was controlled via the PID scheme. The thermal mass temperature varied from 305K to 308K and to 320K when the heat load changed from 20W to 40W and to 80W, respectively. These temperature variations were due to the heat transfer requirement at different powers. The temperature increased and decreased smoothly during the power transients.

Results shown in Figure 25 and 26 indicate that, once the loop had started, placing the control temperature sensor on the thermal mass instead of the reservoir yielded smaller temperature variations for the thermal mass as long as the heat load was not too low to cause repeated startup and shutdown cycles.

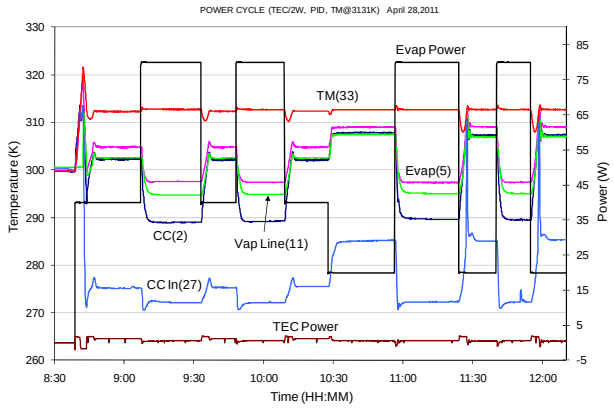

Figure 25. Temperature Profiles for Power Cycle Test with Thermal Mass Controlled at 313K (350g/TEC/PID)

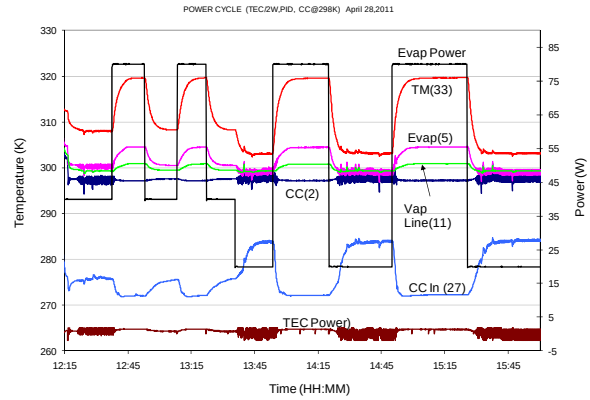

Figure 26. Temperature Profiles for Power Cycle Test with CC Controlled at 298K (350g/TEC/PID)

These power cycle tests were repeated with the same conditions except that the TEC was controlled via the on/off scheme. The results are shown in Figure 27 and 28. The thermal mass temperatures at 20W, 40W and 80W shown in Figure 27 were the same as those shown in Figure 25 except for larger temperature oscillations resulting from the on/off events of the TEC control. The same conclusion can be drawn for the power cycle test where the control temperature sensor was placed on the reservoir with a set point of 298K by comparing the temperature profiles shown in Figure 28 and Figure 26.

Results shown in Figure 27 and 28 again indicate that, once the loop had started, placing the control temperature sensor on the thermal mass instead of the reservoir yielded smaller temperature variations for the thermal mass provided the heat load was not too low to cause repeated startup and shutdown cycles.

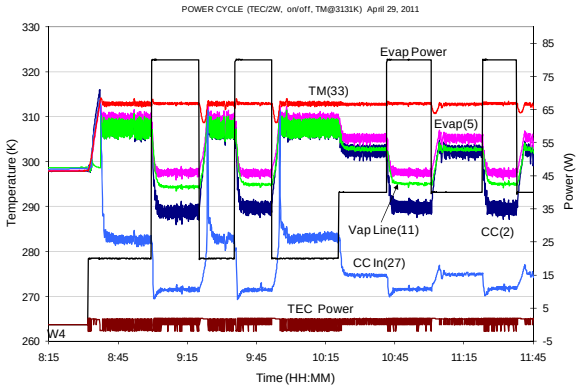

Figure 27. Temperature Profiles for Power Cycle Test with Thermal Mass Controlled at 313K (350g/TEC/On-Off)

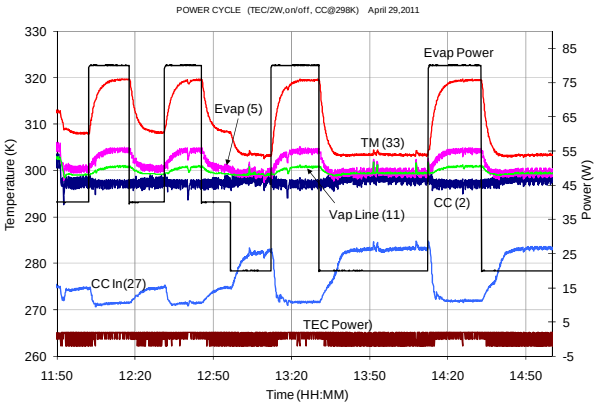

Figure 28. Temperature Profiles for Power Cycle Test with CC Controlled at 298K (350g/TEC/On-Off)

V. Summary and Discussions

This test program was carried out to investigate the feasibility of using the heat source temperature for feedback control of the LHP operation. In this method, the control temperature sensor was placed on the heat source and this temperature was used to alter the saturation temperature of the reservoir, which was cold biased and heated by a control heater. As the heat output from the heat source changed, the reservoir temperature must vary in order to maintain the heat source at the desired set point temperature. Test results show that this method is feasible and the heat source can be maintained at the desired set point over a large range of heat loads. The main issue with this method is the LHP operation at low powers where interactions between the reservoir and the heat source can result

in large temperature oscillations. This is particularly true for the loop startup, which is usually a low power operation.

Test results show that it is feasible and may be even advantageous to place the control temperature sensor on the heat source instead of the reservoir when a TEC is used as the control heater. Because a TEC is capable of providing both heating and cooling to the reservoir, any fast transient temperature change can be better mitigated. Unfortunately, the same cannot be said when an electrical heater is used as the reservoir control heater. Tests performed under this test program using an electrical heater showed that the fast temperature transients could persist and could even be amplified because the electrical heater had no cooling capability. As an example, Figure 29 shows the temperature profiles of a power ramp-up test where the control sensor was placed on the 350-gram thermal mass with a set point of 313K and an electrical heater was used to regulate the reservoir temperature using the PID scheme. This test was similar to that shown in Figure 19. In this test, the loop went through repeated startup and shutdown cycles at 10W and 20W, and large temperature oscillations were seen on the loop components and the thermal mass. Figure 30 shows more details of the temperature oscillations during the startup transient. The loop began it normal operation at 40W without being shut down but still went through some temperature oscillations. Temperature oscillations disappeared when the heat load was increased to 80W or greater. When the heat load was decreased to 30W, large temperature oscillations re-appeared. The loop resumed its startup and shutdown cycles when the power was further decreased to 10W. The same test with an electrical heater and the on/off control scheme yielded similar results. Thus, more sophisticated control schemes are needed in order to gain stable loop operation and good temperature control of the heat source. Results of the tests with an electrical heater for reservoir temperature regulation under this test program will be published in another paper.

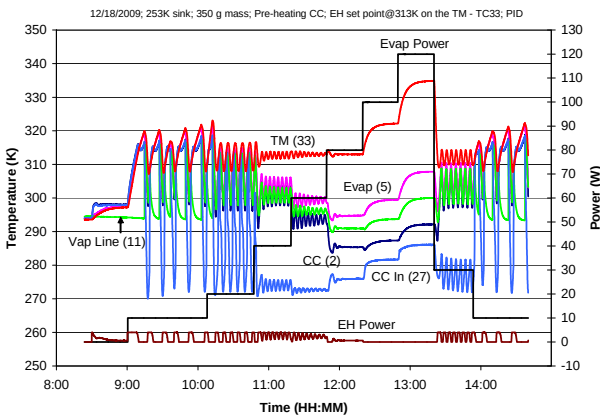

Figure 29. Temperature Profiles for Test with Thermal Mass Controlled at 313K (350g/EH/PID)

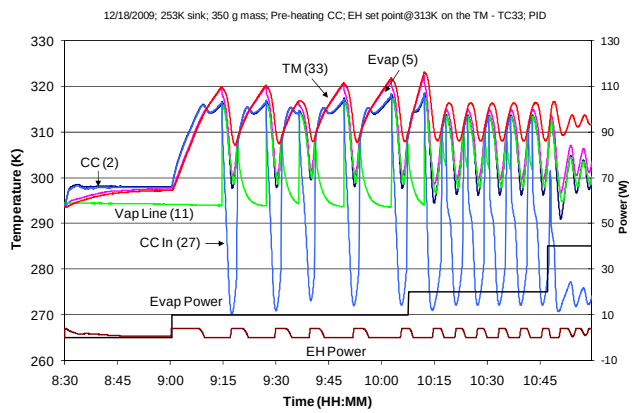

Figure 30. Temperature Profiles for Startup with Thermal Mass Controlled at 313K (350g/EH/PID)

VI. Conclusion

It is feasible to use the heat source temperature for feedback control of the loop heat pipe operation. By placing the control temperature sensor on the heat source, and attaching a control heater to the reservoir to regulate its saturation temperature in accordance with the heat load, the heat source can be maintained within a tight temperature range. A potential drawback of this method is that temperature oscillations can occur at low powers where the loop heat pipe may display repeated startup and shutdown cycles. Using a thermoelectric converter as the reservoir control heater, this problem can be avoided or alleviated. Results of the power cycle tests show that, using a thermoelectric converter as the reservoir control heater, it may be advantageous to place the control temperature sensor on the heat source itself once the loop has started. No sophisticated control algorithm is needed for the thermoelectric converter. However, a bipolar power supplied is required so that the thermoelectric converter can automatically change its operation between the heating and cooling modes as required. The use of a thermoelectric converter to control the reservoir temperature for loop heat pipe operation has been verified in ground tests and demonstrated excellent performance. However, such application has not been validated in space.

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