Loop Heat Pipe Operation Using Heat Source Temperature for Set Point Control

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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. Using this method, the loop operating temperature can be controlled within ±0.5K. 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 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 has been carried out to investigate the effects on the LHP operation when the control temperature sensor is placed on the heat source instead of the reservoir. In these tests, the LHP reservoir is cold-biased and is heated by a control heater. Tests results show that it is feasible to use the heat source temperature for feedback control of the LHP operation. Using this method, the heat source temperature can be maintained within a tight range for moderate and high powers. At low powers, however, temperature oscillations may occur due to interactions among the reservoir control heater power, the heat source mass, and the heat output from the heat source. In addition, the heat source temperature could temporarily deviate from its set point during fast thermal transients. The implication is that more sophisticated feedback control algorithms need to be implemented for LHP transient operation when the heat source temperature is used for feedback control.

Nomenclature/Acronym/Symbol

CC   =   compensation chamber
EH   =   electrical heater
EVAP   =   evaporator
LHP   =   loop heat pipe
PID   =   proportional-integral-derivative
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 effects 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, and the LHP reservoir was cold-biased and heated by a control heater. 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 using an electrical heater and a TEC attached to the reservoir with a PID control scheme. In the following descriptions, the terms reservoir and compensation chamber (CC) will be 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 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, $1.0 \times 10^{-14}\,m^2$ 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 mm L
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 (Figure 5).
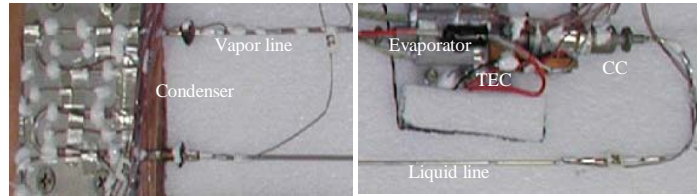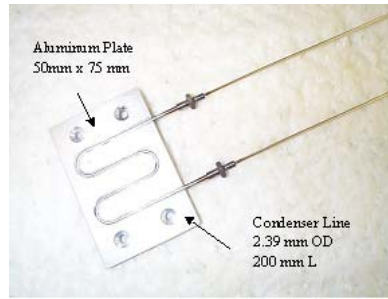

Figure 1. Picture of the Miniature LHP

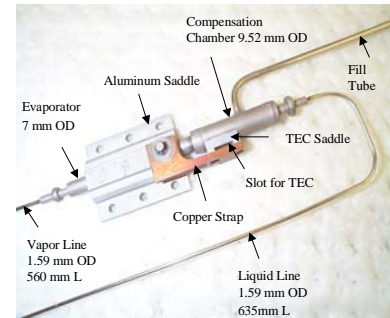**Figure 3. Picture of the Condenser Section**

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.
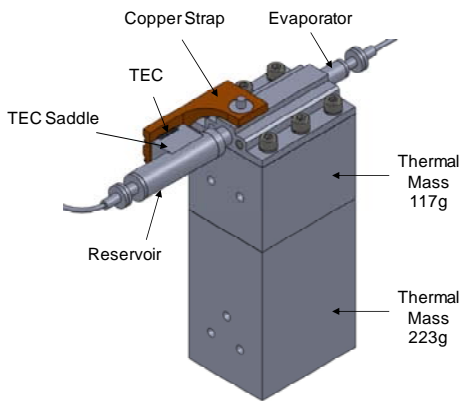

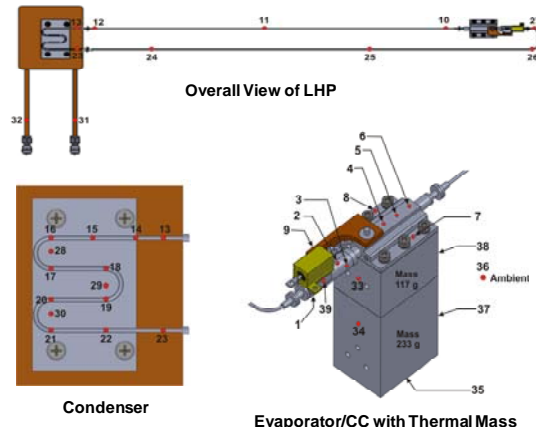**Figure 4. Evaporator/CC Section with Thermal Masses**

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, an HP 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.

Each test was conducted by selecting the thermal mass to be attached, 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 reser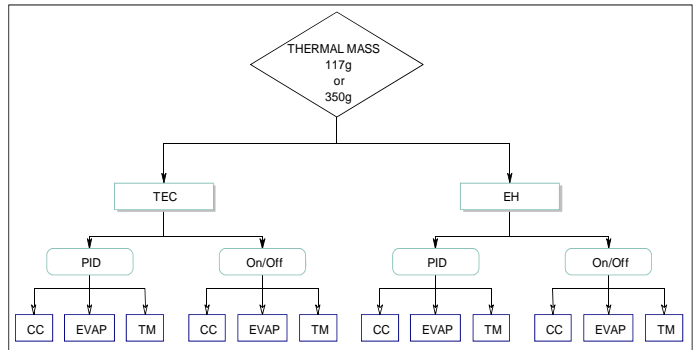voir, evaporator and thermal mass, respectively. Power was then applied to the thermal mass, and increased in steps after a steady state was reached at each step. Once the thermal mass temperature exceeded 343K or the condenser exhausted its convective heat dissipating capability, the power was lowered 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.

Figure 6. Diagram of Overall Test Program

IV. Test Results

Extensive power ramp-up tests shown in Figure 6 have been conducted. 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. Since the main purpose of this test program was to investigate the feasibility of using the heat source temperature for feedback control of the LHP operation, the following discussions focus on the test results with the 350-gram thermal mass and with the PID control scheme for the reservoir control heater although results with the 117-gram thermal mass will also be presented. The presentations 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 electrical heater or TEC as the reservoir control heater; 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 for a few cycles.

350-gram Thermal Mass and Electrical Heater - The first group of tests had the 350-gram thermal mass attached to the evaporator and the electrical heater was used as the reservoir control heater. Figure 7 shows the temperature profiles for the test where the control temperature sensor was placed on the reservoir (TC #2) with a set point of 293K. As 10W was applied to the thermal mass, the loop started almost immediately. The reservoir was maintained at 293K for heat loads up to 120W. As the heat load increased, temperatures of the evaporator and the
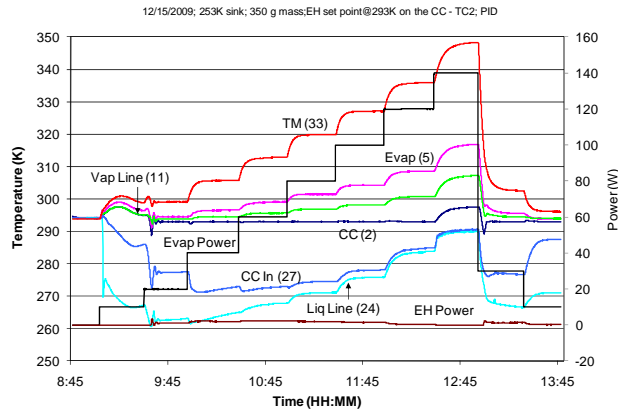
12/15/2009; 253K sink; 350 g mass;EH set point@293K on the CC - TC2; PID

12/15/2009; 253K sink; 350 g mass;EH set point@293K on the CC - TC2; PID

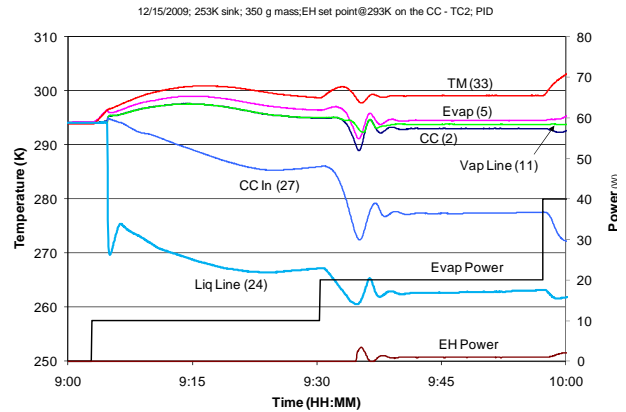**Figure 7. Temperature Profiles for Test with Reservoir Controlled at 293K (350g/EH/PID)**

Figure 8. Temperature Profiles for Startup with Reservoir Controlled at 293K(350g/EH/PID)

thermal mass also increased due to the heat transfer requirement. At 120W, the reservoir was still at 293K, and the evaporator and the thermal mass were at 307K and 335K, respectively. At 140W, the condenser could not dissipate all the heat with the vapor at 293K. As a result, warm liquid returned to the reservoir, raising the reservoir temperature to 297K, which was its natural operating temperature. Because the reservoir temperature was above its set point of 293K, the electrical heater was turned off. The heat load was then reduced to 30W and 10W, and the reservoir was again controlled at 293K and both the evaporator and thermal mass temperatures dropped.

Figure 8 shows more details of the startup operation. Prior to the startup, the reservoir, reservoir inlet, evaporator and thermal mass were all at the room temperature of 294K. As soon as 10W was applied to the thermal mass, the loop started as evidenced by the rise of the vapor line temperature and the fall of the liquid line temperature. Because the liquid returning to the reservoir was not cold enough to lower the reservoir temperature below the set point of 293K, the reservoir heater was not turned on. When the heat load was raised to 20W, a slug of cold liquid was injected into the reservoir, causing the reservoir temperature to drop to 289K. The reservoir heater was turned on automatically, and the reservoir temperature was maintained at 293K from this point on.

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 evaporator temperature was maintained at 303K for heat loads between 10W and 100W. As the heat load increased, the thermal mass temperature increased due to the heat transfer requirement. For the same reason, the reservoir temperature decreased with an increasing heat load in order to keep the evaporator temperature constant. At 100W, the reservoir was at 292K. At 120W, the reservoir temperature reached its natural operating temperature of 291.5K, not low enough to maintain the evaporator at 303K. Consequently, the evaporator temperature rose above its set point
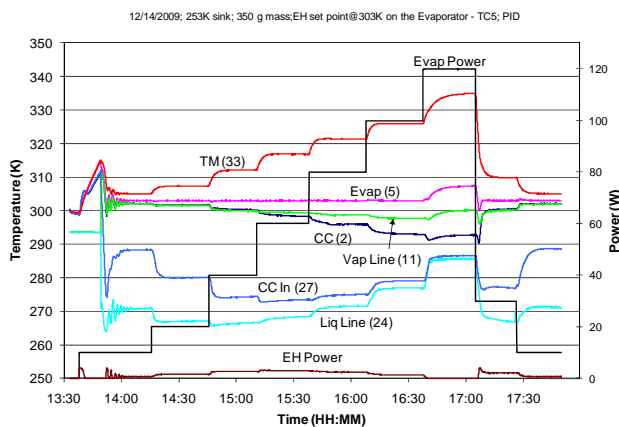

12/14/2009; 253K sink; 350 g mass;EH set point@303K on the Evaporator - TC5; PID

12/14/2009; 253K sink; 350 g mass;EH set point@303K on the Evaporator - TC5; PID

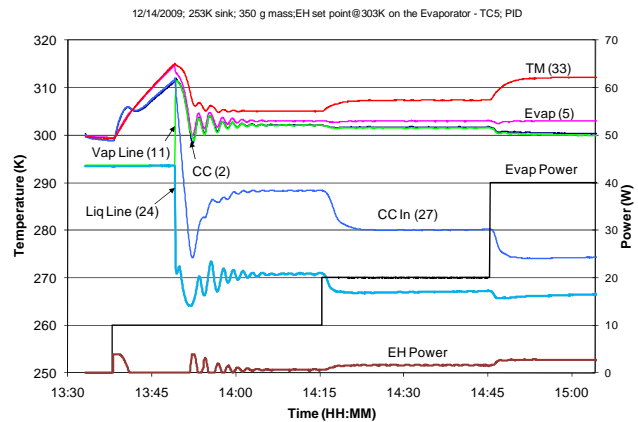**Figure 9. Temperature Profiles for Test with Evaporator Controlled at 303K (350g/EH/PID)**

Figure 10. Temperature Profiles for Startup with Evaporator Controlled at 303K (350g/EH/PID)

5

temperature, and the control heater was automatically turned off. When the heat load was decreased to 30W and then 10W, the reservoir regained sufficient subcooling and was able to maintain the evaporator at 303K.

Figure 10 shows the temperature profiles during the startup transient. Initially, the reservoir, reservoir inlet, evaporator and thermal mass were all at 299K. As a heat load of 10W was applied, the command to control the evaporator at 303K was activated. Because the evaporator was below its desired set point, the reservoir control heater was turned on and 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 reached 303K, the reservoir heater was turned off and the reservoir temperature began to drop. The LHP did not start and the evaporator temperature continued to rise. Soon after, the reservoir temperature started to rise again because the reservoir also received heat from the evaporator due to a heat leak. When the loop finally started, a slug of cold liquid was pushed into the reservoir, causing the reservoir temperature to drop. This was followed by the heating of the reservoir. After a few cycles of temperature oscillations with diminishing amplitudes, mainly due to the on and off cycles of the reservoir control heater, the reservoir and evaporator temperatures eventually stabilized.

The temperature profiles for the test with the control temperature sensor placed on the thermal mass (TC#33) are shown in Figure 11. The goal was to maintain the thermal mass at a constant temperature for variable heat loads. For heat loads of 10W and 20W, large temperature oscillations were observed and the thermal mass could not be kept at a constant temperature of 313K. Only when the heat load was increased to 40W and higher was the thermal mass temperature maintained within a smaller range of the set point temperature. For heat loads of 80W and above, temperature oscillations disappeared. At each power increase, the reservoir temperature was lowered in order to maintain the thermal mass at 313K. For heat loads of 100W and 120W, the thermal mass temperature was higher than the set point of 313K because the reservoir reached its natural operating temperatures, which were not low enough to maintain the thermal mass at 313K. When the heat load was decreased to 30W and 10W, large temperature oscillations reappeared. These temperature oscillations at low heat loads were caused by the interactions among the control heater, the reservoir and the thermal mass, as will be explained next.
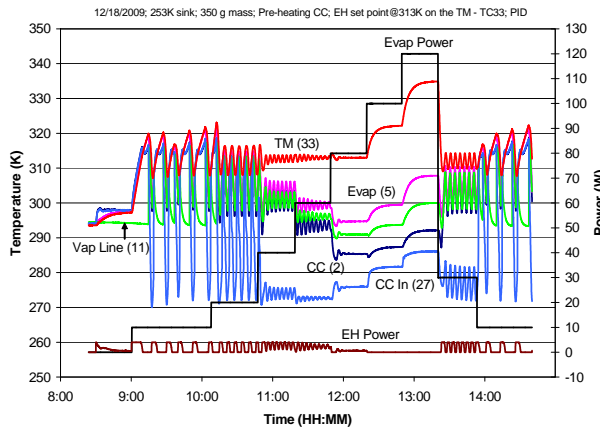

Figure 11. **Temperature Profiles for Test with Thermal Mass Controlled at 313K (350g/EH/PID)**
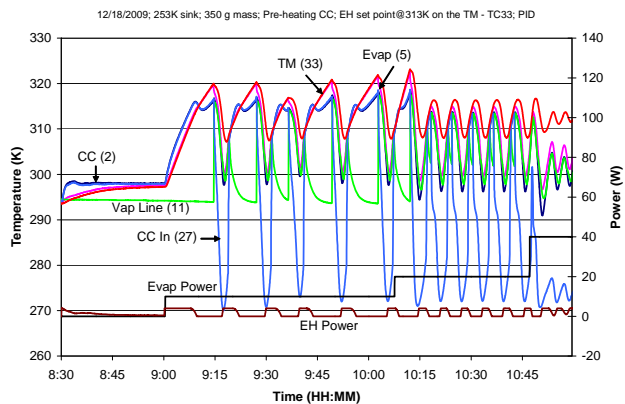
Figure 12. **Temperature Profiles for Startup with Thermal Mass Controlled at 313K (350g/EH/PID)**

The transient phenomena for loop startup with low powers are illustrated in Figure 12. Initially, the reservoir, evaporator, and thermal mass were at 295K, and the condenser sink was at 253K. When 10W was applied to the thermal mass, the reservoir control heater was turned on because the thermal mass temperature was below its set point of 313K. With 4W to the reservoir and 10W to the 350-gram thermal mass, the reservoir temperature rose at a much faster rate than that of the thermal mass. When the thermal mass reached 313K, the reservoir heater was turned off. The reservoir temperature decreased for a short period then rose again due to the heat leak from the evaporator. When the loop started, cold liquid was injected from the condenser to the reservoir. The reservoir temperature dropped sharply, and so did the thermal mass temperature. When the thermal mass temperature dropped below 313K, the reservoir control heater was turned on. The loop was subsequently shut down because the reservoir temperature rose at a faster rate than that of the thermal mass. What followed were repeated startup and shutdown cycles. When the heat load was increased to 20W, temperature oscillations persisted but the amplitudes decreased. The 20W heat load prevented the loop from being shut down during the upswing of the reservoir temperature. In other words, the rise of the thermal mass temperature was no longer overcome by the rise of the reservoir temperature. This is evidenced by the rise and fall of the vapor temperature in tandem with the reservoir

temperature. The fluid in the LHP was in a normal forward motion when the reservoir temperature was decreasing, and was in the reversed direction when the reservoir temperature was increasing. The 20W heat load also made the thermal mass to respond more quickly and experienced less of the temperature overshoot above 313K when the reservoir temperature was rising. This effect became more evident when the heat load was increased to 40W, resulting in much smaller temperature oscillations.

The reduction of the amplitude of the temperature oscillation with an increasing heat load to the thermal mass shows the importance of the rate of the reservoir temperature increase relative to that of the thermal mass. Decreasing this ratio will reduce the possibility of shutting down the loop when the reservoir heater is turned on, and this can be accomplished by reducing the reservoir control heater power, and/or increasing the thermal mass heat load. Figures 13 and 14 show the temperature profiles for a test similar to that shown in Figures 11 and 12, except that the maximum power for the reservoir control heater was limited to 2W. With 2W to the reservoir and 10W to the thermal mass, the rate of the reservoir temperature increase did not exceed that of the thermal mass, and no repeated startup and shutdown cycles were seen. The loop was shut down once after the initial startup. It restarted successfully and operated stably thereafter.
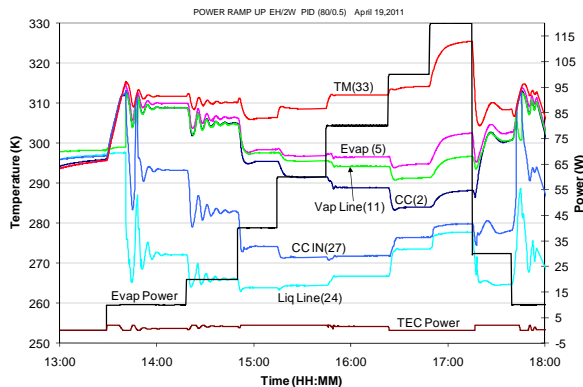

Figure 13.   Temperature Profiles for Test with Thermal Mass Controlled at 313K (350g/EH/PID)
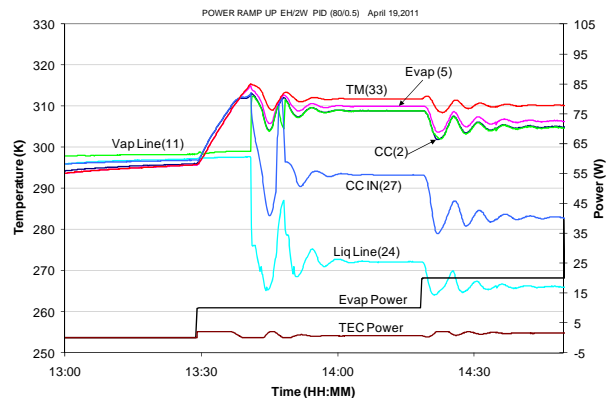

Figure 14.   Temperature Profiles for Startup with Thermal Mass Controlled at 313K (350g/EH/PID)

On the other hand, Figure 13 shows that the thermal mass could not be maintained at 313K for heat loads between 20W and 60W because the 2W control heater power was insufficient to overcome the liquid subcooling, i.e. the reservoir could not be heated to high enough temperatures required to keep the thermal mass at 313K. For example, Figure 11 shows that at 40W, the average reservoir temperature was about 300K in order to keep the thermal mass at 313K. Figure 13 shows that the reservoir could only be heated to 296K with a 2W heater power, and the thermal mass was at 308K. It is possible to use different reservoir control heater powers for startup and normal operation. However, this will require more sophisticated control algorithm for autonomous LHP operation.

350-gram Thermal Mass and TEC - Results of the tests using the TEC as the reservoir control heater are presented next. The maximum control heater power was limited to 2W. Figure 15 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 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. The transient behavior illustrated by Figure 16 was somewhat different from that illustrated by Figure 8. The loop did not start right away when 10W was applied to the thermal mass. Instead, some superheat between the evaporator and the reservoir was required for the loop startup, and the reservoir temperature rose with the evaporator temperature due to a heat leak during the period when the required superheat was being built up. The superheat requirement is stochastic in nature and cannot be predicted in advance. The loop simply displayed two superheat requirements for these two tests.

Figure 17 shows the temperature profiles for the test where the control temperature sensor was placed on the evaporator with a set point of 303K. They are similar to those shown in Figure 9. At 120W, the condenser reached its convective heat dissipating capability. Unlike the electrical heater which could only provide heating to the reservoir, the TEC worked in the cooling mode to try to lower the reservoir temperature. The evaporator temperature eventually rose to 310K, higher than the set point of 303K. The startup transient was illustrated in Figure 18. Because of an operator error, control of the evaporator temperature was activated and the reservoir control heater was turned on for about 10 minutes before 10W was applied to the thermal mass. The reservoir was heated to a

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temperature higher than the evaporator until the evaporator temperature reached 303K. The TEC power then dropped to zero. After the reservoir temperature deceased below the evaporator temperature, the loop started successfully.
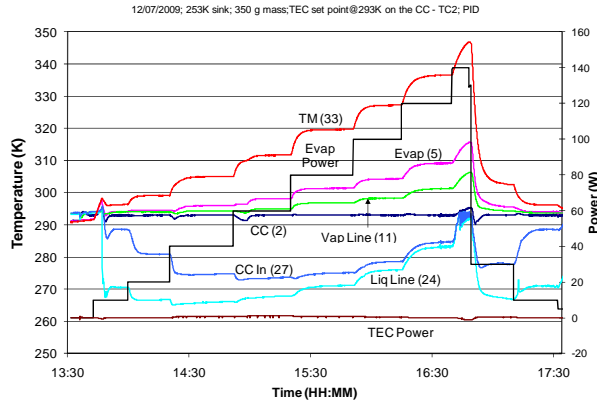

Figure 15. Temperature Profiles for Test with Reservoir Controlled at 293K (350g/TEC/PID)
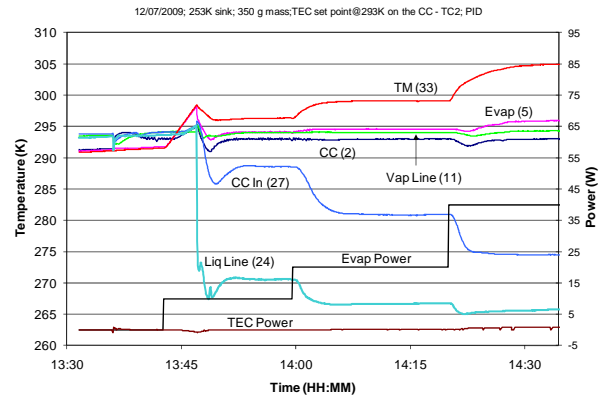

Figure 16. Temperature Profiles for Startup with Reservoir Controlled at 293K(350g/TEC/PID)
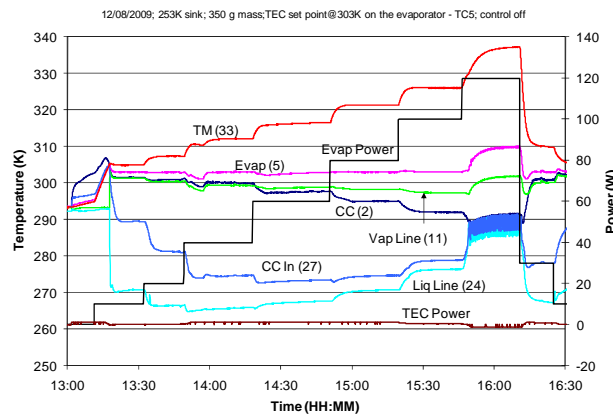

Figure 17. Temperature Profiles for Test with Evaporator Controlled at 303K (350g/TEC/PID)
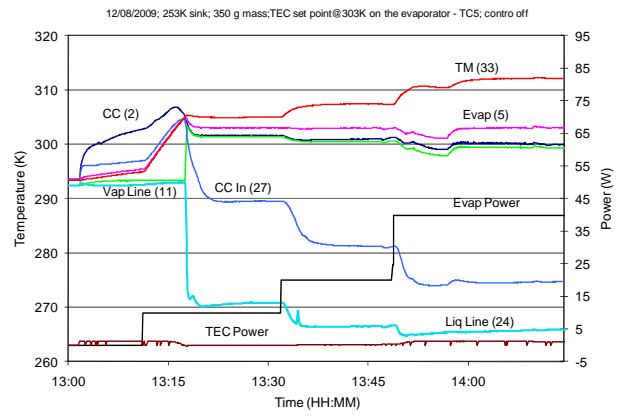

Figure 18. Temperature Profiles for Startup with Evaporator Controlled at 303K (350g/TEC/PID)

Temperature profiles for the LHP operation with the control temperature sensor placed on the thermal mass and controlled at 313K are shown in Figure 19. With 10W to the thermal mass, the loop started and then was shut down once. After the second startup, the loop went into stable operation and the thermal mass was maintained at 313K for heat loads up to 80W. At 100W, the reservoir was at its natural operating temperature of 288K, which was not low enough to maintain the thermal mass at its set point temperature of 313K. The maximum TEC power was set at 2W in this test. Thus, the startup transient shown in Figure 20 was similar to that shown in Figure 14 where the maximum electric heater power was also set at 2W. This represented a major improvement for startup transient when compared to Figure 12 where the maximum electrical heater power was set at 4W, which caused the repeated startup and shutdown cycles. Furthermore, Figure 13 shows that with 2W to the electrical heater, the control heater power was not sufficient to heat the reservoir to high enough temperature to maintain the thermal mass at 313K for heat loads between 20W and 60W, but Figure 19 shows that with 2W of TEC power, the thermal mass could be kept at 313K over the power range of 10W to 80W. When working in the heating mode, the TEC can take additional heat from the evaporator through the thermal strap, thus saving the heater power[13-14]. In other words, in Figure 19 the actual heat input to the reservoir was higher than the power applied to the TEC.
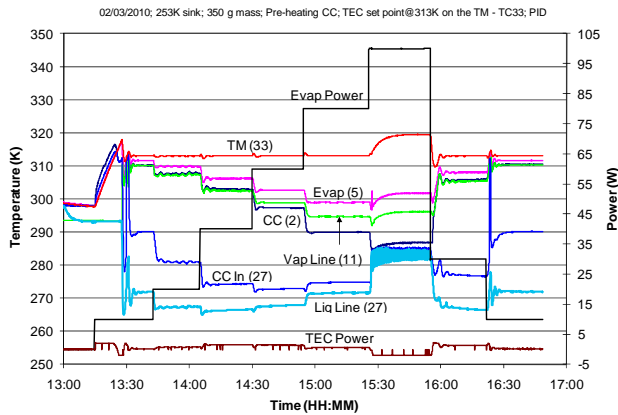
Figure 19. Temperature Profiles for Test with Thermal Mass Controlled at 313K (350g/TEC/PID)
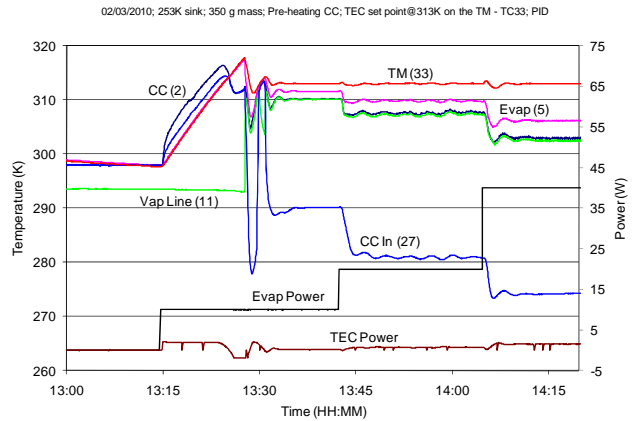

Figure 20. Temperature Profiles for Startup with Thermal Mass Controlled at 313K (350g/TEC/PID)

117-gram Thermal Mass and Electrical Heater - The effect of the thermal mass on the loop operation is presented next. Figure 21 shows the temperature profiles for the test with 117-gram thermal mass attached to the evaporator. The control temperature sensor was placed on the thermal mass (TC#33), and the electrical heater was used as the reservoir control heater. The loop temperatures were similar to those shown in Figure 11 where the 350-gram thermal mass was attached to the evaporator. One noticeable difference is that the amplitude of the temperature oscillations was smaller for the 117-gram thermal mass than for the 350-gram thermal mass at 10W and 20W (and at 30W near the end of the test). This is more clearly seen when comparing Figure 22 to Figure 12. A smaller thermal mass was able to respond to the reservoir temperature change more quickly and hence could mitigate the overshoot and undershoot of the thermal mass temperature variations at low powers.
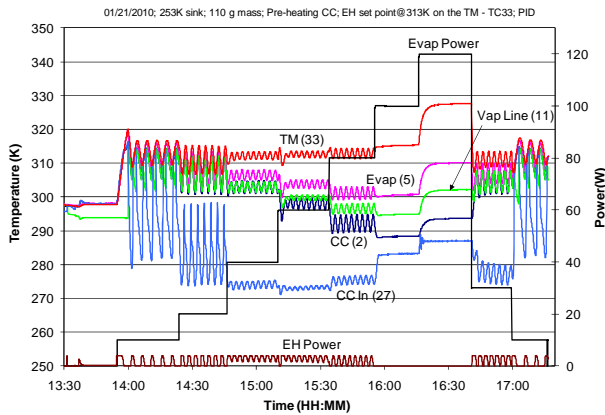

Figure 21. Temperature Profiles for Test with Thermal Mass Controlled at 313K (117g/EH/PID)
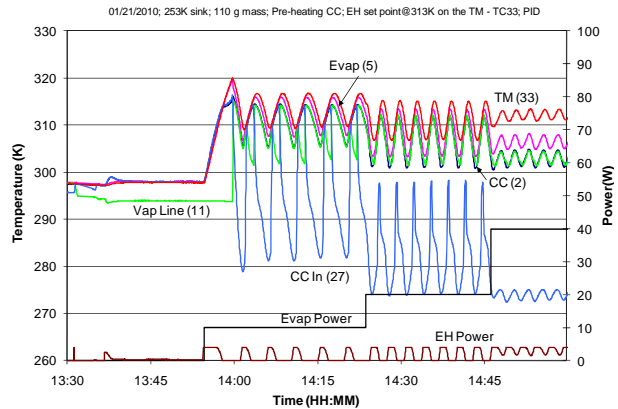

Figure 22. Temperature Profiles for Startup with Thermal Mass Controlled at 313K (117g/EH/PID)

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 temperature change more slowly than when the control sensor is placed on the reservoir itself. This could result in larger temperature oscillations during fast thermal transients because of the time delay. If the power profile is know in advance, 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 reservoir set point was varied with the heat load applied to the 350- gram thermal mass. The reservoir set point as a function of the heat load was actually taken from the experimental data

shown in Figure 11 and the electrical heater was used as the reservoir control heater. Using this method, the thermal mass temperature was maintained fairly constant at 313K for powers between 10W and 80W, and temperature oscillations seen in Figure 11 were substantially reduced.

A similar test was performed with the 117-gram thermal mass attached to the evaporator and the electrical heater as the reservoir control heater. The temperature profiles are shown in Figure 24. The reservoir set point temperature as a function of the heat load was taken from experimental data shown in Figure 21. Again, the thermal mass temperature was maintained fairly constant for powers between 10W and 80W. The amplitudes of the temperature oscillations shown in Figure 24 were smaller than those shown in Figure 21. Furthermore, Figures 23 and 24 illustrate that the LHP could respond to the thermal transient more quickly with the 117-gram thermal mass than with 350-gram thermal mass.
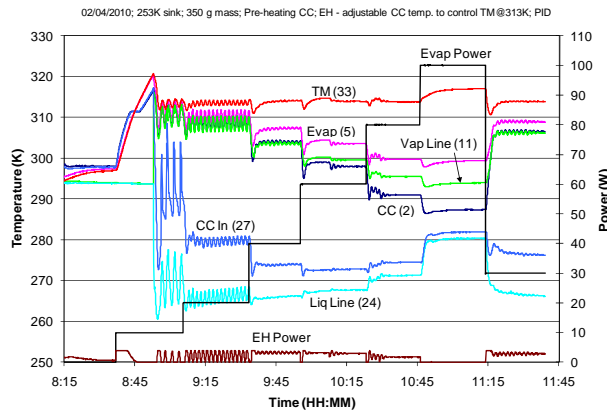

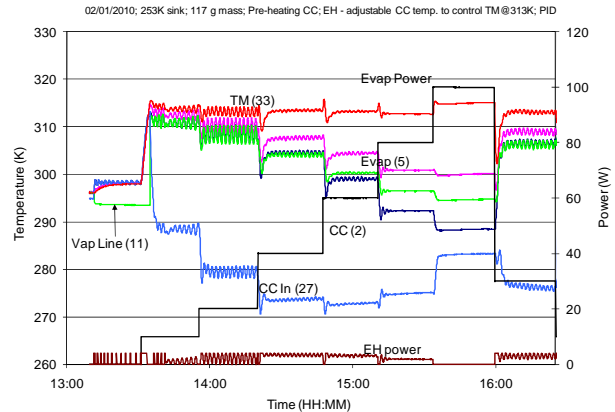**Figure 23.   Varying CC Temperature to Maintain Thermal Mass at 313K (350g/EH/PID)**

Figure 24.   Varying CC Temperature to Maintain Thermal Mass at 313K (117g/EH/PID)

Power Cycle -   The power profile of 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 set 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 set at 313K. Under this condition, the reservoir temperature would change with the heat load. 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 the 350-gram thermal mass and the control temperature was placed on the thermal mass with a set point of 313K. The electrical heater was used as the reservoir control heater with a maximum power of 4W. The thermal mass temperature could be maintained at 312.5K with 0.7K oscillations at 40W, and at 313K with negligible oscillations at 80W. Its temperature temporarily rose to 315K when the power increased from 40W to 80W, and temporarily fell to 310K when the power decreased from 80W to 40W. At 20W, the thermal mass was at 313K with 2K oscillation. The thermal mass temperature rose to 320K when the power changed from 20W to 80W, and fell to 308K when the power changed from 80W to 20W. When the power dropped from 80W to 40W or 20W, the reservoir temperature must be increased to maintain the thermal mass temperature at 313K. With a maximum heater power of 4W to the reservoir, the reservoir temperature could not be raised quickly enough. A larger electrical heater power would alleviate the problem, but that would also magnify the temperature oscillations at 20W and 40W.

Figure 26 shows the temperature profiles for a similar power cycle test where the control temperature sensor was placed on the reservoir with a set point of 298K. The thermal mass temperature varied from 303K to 308K and to 319K when the heat load changed from 20W to 40W and to 80W, respectively. These temperature variations at different powers were due to the heat transfer requirement. The temperature increased and decreased smoothly during the power transients. The reservoir set point was selected at 298K because that was close to the reservoir set point temperature that was required to maintain the thermal mass at 313K at a heat load of 50W (derived from Figure 11 at powers of 40W and 60W). The heat load of 50W is the average power of 20W and 80W that were used

for this test. Smaller temperature variations were seen over the power range when the control temperature sensor was placed on the thermal mass itself.
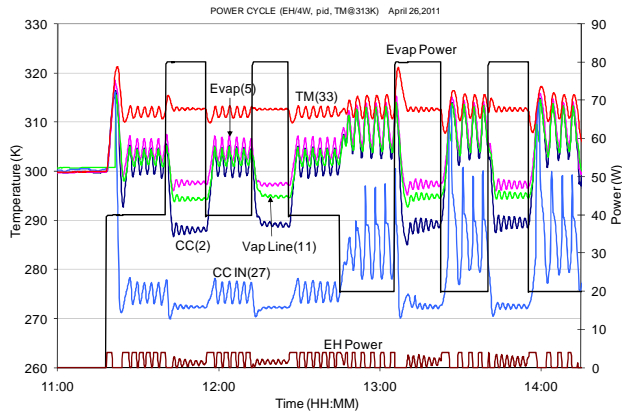

Figure 25.   Power Cycle Test with Thermal Mass Controlled at 313K (350g/EH/PID)
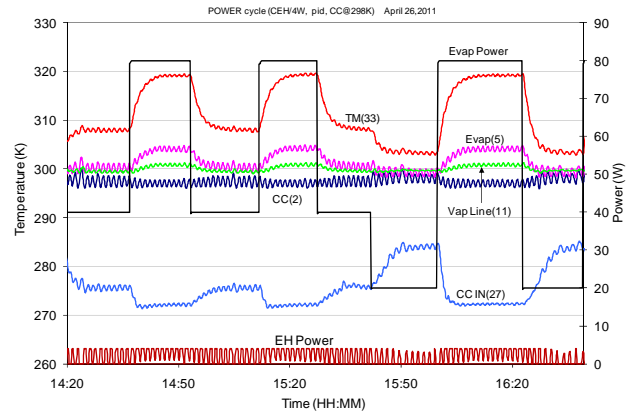

Figure 26.   Power Cycle Test with Reservoir Controlled at 298K (350g/EH/PID)

Figure 27 shows the temperature profiles for the power cycle test with the 350-gram thermal mass and the control temperature was placed on the thermal mass with a set point of 313K. The TEC was used as the reservoir control heater with 2W maximum power. 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 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 28 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. 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. The temperature increased and decreased smoothly during the power transients. Again, the thermal mass showed smaller temperature variations over the power range when the control temperature sensor was placed on the thermal mass itself instead of the reservoir.
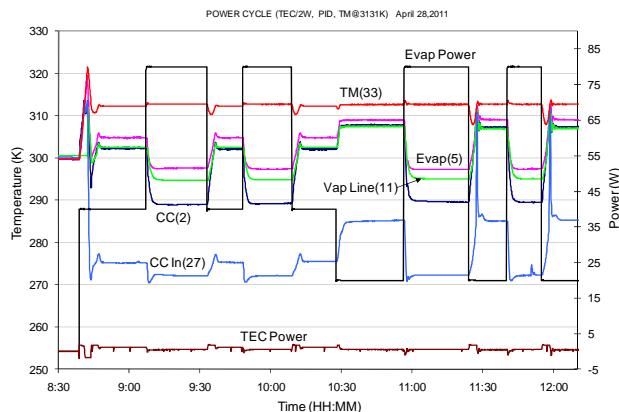

Figure 27.   Power Cycle Test with Thermal Mass Controlled at 313K (350g/TEC/PID)
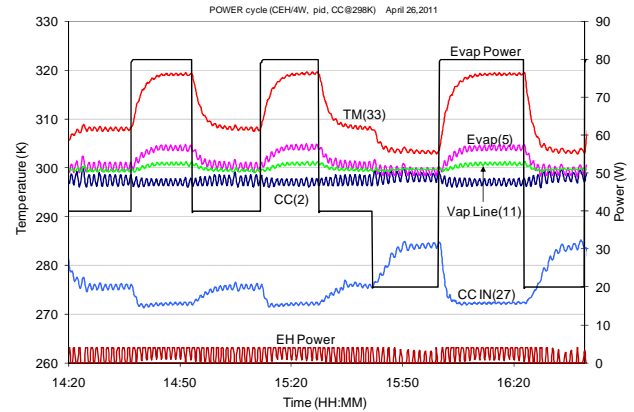

Figure 28.   Power Cycle Test with Reservoir Controlled at 298K (350g/TEC/PID)

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V. Conclusions

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 regulate the saturation temperature of the LHP reservoir, which was cold biased and heated by a control heater. As the heat output from the heat source changed, the reservoir saturation temperature must vary so as 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 among the reservoir, reservoir control heater power, mass of the heat source, and power output of the heat source can result in large temperature oscillations. In particular, the startup of the LHP can be problematic. The LHP startup is typically a low power operation and requires a superheat to generate first bubbles. This can result in an unsuccessful startup or repeated startup and shutdown cycles.

It is possible to use different reservoir control heater powers for the low power and high power operations. Smaller reservoir control heater power will enhance the startup success and mitigate the temperature oscillation issues at low powers. However, a higher reservoir control heater power may be necessary in order to overcome the liquid subcooling at high powers. Using different reservoir control heater powers for low and high power operations can be implemented, but will require more sophisticated control algorithm for autonomous LHP operation.

In this test program, a fixed set of PID control parameters were used. It is also possible to fine tune the parameters for the PID control scheme to reduce the temperature oscillations at low powers and achieve optimal temperature control for the heat source. More studies are needed. It is likely that different combinations of the LHP and heat source will require different PID control parameters for optimal performance.

Using the TEC as the reservoir control heater has advantages over the traditional electrical heater. The TEC can provide both heating and cooling to the reservoir and can eliminate or alleviate the startup and temperature oscillation problems at low powers. However, a bipolar power supply must be used so that the TEC can automatically change its operation between the heating and cooling modes. The use of a TEC to control the reservoir temperature for LHP operation has been tested in ground tests and demonstrated excellent performance. But such application has not been demonstrated in space.

The traditional method of maintaining the LHP operating temperature by controlling the reservoir saturation temperature at a constant value yields the most stable temperature profiles and the least chance for temperature oscillations at low powers. A simple control algorithm is sufficient for both steady state and transient LHP operations. On the other hand, the heat source temperature will vary with the heat load. A trade study involving requirements of the temperature control range and temperature stability, frequency of LHP shutdown and restart during the mission life, and complexity of temperature control algorithm should be conducted in deciding whether to place the control temperature sensor on the reservoir or the heat source itself.

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