Active Control of the Operating Temperature in a Loop Heat Pipe with Two Evaporators and Two Condensers

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Abstract

The operating temperature of a loop heat pipe (LHP) with multiple evaporators is a function of the total heat load, heat load distribution among evaporators, condenser temperature and ambient temperature. Because of the many variables involved, the operating temperature also showed more hystereses than an LHP with a single evaporator. Tight temperature control can be achieved by controlling its compensation chamber (CC) temperatures at the desired set point. This paper describes a test program on active control of the operating temperature in an LHP with two evaporators and two condensers. Temperature control was achieved by heating one or both CC's. Tests performed included start-up, power cycle, sink temperature cycle, CC temperature cycle, and capillary limit. Test results show that, regardless one or two CC's were heated to the set point temperature, one of CC's was always flooded with liquid. The loop could operate successfully at the desired set point temperature under most conditions, including some fast transients. At low heat loads, however, the CC temperature could suddenly increase above the set point temperature, possibly due to a sudden change of the vapor content inside the evaporator core.

Introduction

Most existing loop heat pipes (LHP's) have a single evaporator and a single condenser. Several studies of the feasibility of a multiple evaporator LHP have been presented in the literature [1-4]. References 5 and 6 presented a comprehensive experimental investigation on the operation of an LHP with two evaporators and two condensers. Test results show that the operating temperature is a function of the total system heat load, heat load distribution between the two evaporators, sink temperature and ambient temperature. Under most conditions, only one CC will contain two-phase fluid and control the loop operating temperature; the other CC will be completely flooded with liquid. As the operating condition changes, control of the loop operating temperature can switch from one CC to the other, resulting in a liquid movement between the two CC's. Because of the many factors that are involved, the loop operating temperature can swing widely, and many temperature hystereses can occur.

Many applications require the LHP to provide a stable sink temperature. One method for the LHP to achieve a steady operating temperature is to actively control the CC temperature above its natural equilibrium temperature. This method has been demonstrated to be effective for a single evaporator LHP [7,8]. For a multiple evaporator LHP, some technical issues still exist and need to be verified: 1) Is it sufficient to control just one CC temperature, or all CC's need to be controlled? 2) If all CC's are actively controlled, will the loop operation be stable? As each control heater turns on and off at different times, will liquid move quickly between CC's and cause unstable operation?

An extensive test program has been conducted to answer these questions. In this study, one or both CC's were controlled at the desired set point temperature. Tests performed included an array of even and uneven heat loads to the evaporators, high and low heat loads, high and low sink temperatures, even and uneven sink temperatures, rapid power cycle, rapid sink temperature cycle, and set point change. This paper will give detailed descriptions of the LHP operation when CC temperatures are actively controlled. The physical phenomena observed will be presented and explanations on the physical processes involved will be offered. Implications on the operation of an LHP with more than two evaporators will also be addressed.

Test Article and Test Set-up

As shown schematically in Figure 1, the test loop, built by the Dynatherm Corporation, consists of two parallel evaporators, two parallel condensers, a common vapor transport line and a common liquid return line. Each evaporator has its own integral CC. Both evaporators are made of aluminum tubing with 15.8 mm (0.63 inch) O.D. by 76.2 mm (3 inches) length. One evaporator has a titanium wick with pore radius of about 3 microns, while the other has a nickel wick with pore radius about 0.5 micron. Each CC is made of stainless steel tubing and has an O.D. of 14.8 mm(0.57 inch) and a length of 81.8 mm (3.22 inches). Both the vapor line and liquid line are made of 2.2mm O.D. (3/32 inch) stainless steel tubing, and have a length of 1168mm (46 inches). The vapor and liquid lines branch out to feed into the two evaporators and two condensers. Each condenser is made of 2.2mm O.D.(3/32 inch) stainless steel tubing and is 762mm (30 inches) long. A flow regulator made of capillary wicks is installed at the downstream of each condenser. The flow regulators prevent vapor from penetrating the wick before both condensers are fully utilized, and hence serve to balance the flows between the two condensers. Two 50.8 mm by 50.8 mm (2 inches by 2 inches) aluminum plate are installed on the vapor line. One is attached with an electrical heater while the other is attached with coolant lines. The two aluminum plates are used in the test to illustrate that in a capillary system a small amount of heat load can be added to the vapor line and dissipated to a nearby radiator. The loop is charged with 15.5 grams of anhydrous ammonia.

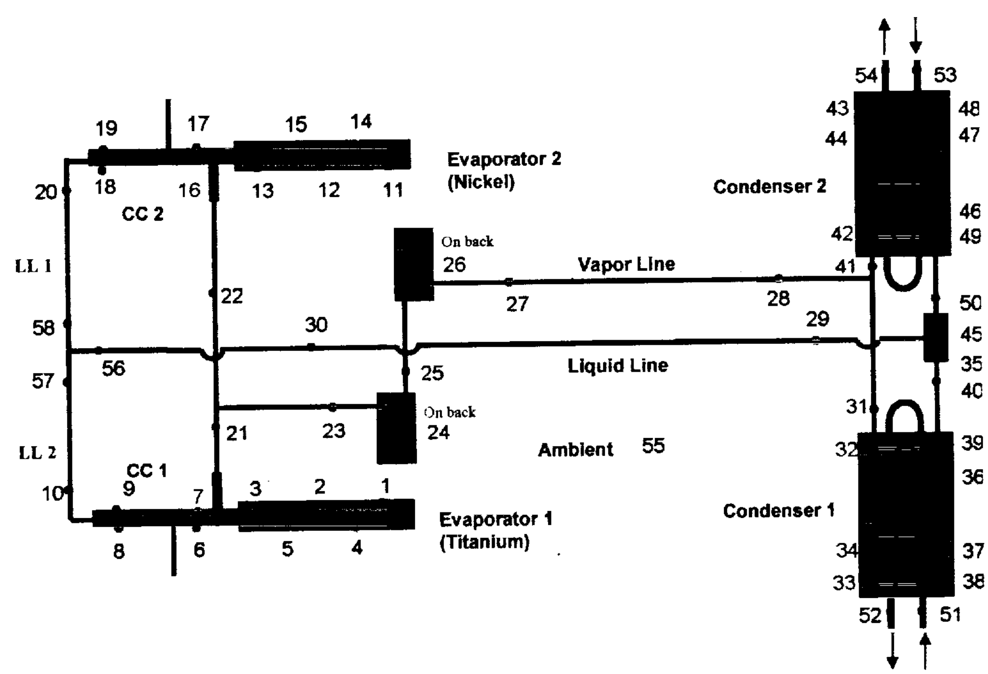

Figure 1. Schematic of an LHP with Two Evaporators and Two Condensers

Electrical heaters are attached to each evaporator and each compensation chamber, and are separately controlled. The two condensers are attached to two cold plates; each cooled by a separate chiller. Sixty thermocouples are used to monitor the loop temperatures. Notice that many thermocouples are installed on the liquid line between the two compensation chambers in order to monitor the anticipated interactions between the two elements during fast transients. A data acquisition system consisting of a datalogger, a personal computer, a CRT monitor, and Labview software programs is used to monitor and store data. The data is updated on the monitor and stored in the computer every second.

For ease of description, the following abbreviations will be used: E1=Evaporator 1, E2=Evaporaotr 2, C1=Condenser 1, C2=Condenser 2, CC1=Compensation Chamber 1, and CC2=Compensation Chamber 2. Also, the test condition will be designated as (E1 power/E2 power, C1 sink temperature/C2 sink temperature). For example, (5W/50W, 273K/273K) means that E1 and E2 received 5W and 50W of heat loads, respectively, and both condenser sinks were set at 273K. In the following figures, the number in parenthesis next to the label for each curve refers to the thermocouple number shown in Figure 1.

Theoretical Background

In an LHP with a single evaporator and a single condenser, the CC saturation temperature, which governs the loop operating temperature, is determined by an energy balance between the heat leak from the evaporator to the CC and the amount of subcooling of the returning fluid. The heat leak is a function of the heat load and the vapor void fraction inside the evaporator core. The liquid subcooling is a function of the heat load, the sink temperature and the ambient temperature. Thus, the loop operating temperature varies with the heat load, sink temperature and ambient temperature. When the ambient temperature is higher than the sink temperature, liquid is heated as it flows along the liquid line due to parasitic heat gains. When the loop operating temperature is plotted as a function of the heat load, a "V" or "U" shaped curve is obtained [9]. The curve will move up or down with an increasing or decreasing sink temperature as shown in Figure 2. Note that the loop operating temperature is little affected by the sink temperature at low heat loads. Furthermore, the "U" or "V" shaped curve is usually not a single curve because of the temperature hysteresis [7, 9].

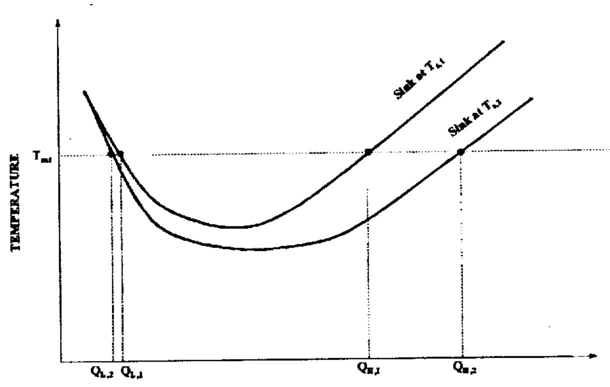

Figure 2. Active Control of the LHP Operating Temperature

The loop operating temperature can be controlled by heating the CC to a desired set point temperature as shown in Figure 2. The control heater power required is equal to mCpΔT, where m is the mass flow rate, Cp is the specific heat of the liquid, and ΔT is the difference between the set point temperature and the natural equilibrium temperature of the CC when unheated. Note that the largest heater power requirement usually does not coincide with the largest ΔT because of the mass flow rate involved. Also note that this method works only if the desired set point temperature is higher than the natural equilibrium temperature. Thus, for a given sink temperature, there is a range of heat loads that this method can be applied, taking into account the temperature hysteresis.

The concept of controlling the operating temperature for an LHP with multiple evaporators is the same as that shown in Figure 2 although the set point temperature must be set high enough to encompass all temperature hystereses. It should be noted that only one CC will contain two-phase fluid, and all other CC's will be liquid filled even if they are all maintained at the identical temperature. When uneven heat loads are applied to the evaporators, the CC's will be at different pressures. Being at the same temperature simply places all CC's at different thermodynamic states. A more rigorous analysis as the one presented in Reference 6 will lead to the same conclusion: rarely can the thermal environment surrounding the CC's satisfies the thermodynamic conditions required for all CC's to contain two-phase fluid.

Tests Performed and Results

Given the complex interaction among various components and many different ways to heat the CC's as described above, the question then is whether heating one or both CC's of the test loop can provide a stable operation. Specific tests were designed to answer this question. Tests were conducted by heating one or both of the CC's to the desired set point. Tests performed included power cycle with even and uneven heat loads to the evaporators, sink temperature cycle with even and uneven sink temperatures, set point change with one or both CC's being controlled, and capillary limit at a given CC set point temperature.

Test results show that, under most conditions, the LHP could operate successfully at the desired temperature by controlling the set point of one or both CC's. Test results also confirmed that even when the controllers of both CC's were set at the same temperature, only one CC could contain two-phase fluid; the other was completely filled with liquid. The liquid-filled CC could be at a subcooled or even a superheated state. Moreover, the CC that was liquid-filled had a tendency to remain liquid-filled unless the test condition changed significantly enough to initiate nucleate boiling. The implication is that the operating temperature could be lower than the desired set point temperature during transients.

Power Cycle

Several types of power cycle tests were conducted. One type of test had the C1/C2 sink temperatures set at 263K/258K and the heat load varied as follows: 100W/0W, 75W/25W, 50W/50W, 25W/75W, 0W/100W. Three different CC control tests were performed with this power profile: a) CC1 alone was controlled at 308K; b) CC2 alone was controlled at 308K; and c) both CC1 and CC2 were controlled at 308K. As expected, when only CC1 was heated, CC1 controlled the loop operating temperature at 308K and CC2 was flooded with liquid. Likewise, when only CC2 was heated, CC2 controlled the loop operating temperature at 308K and CC1 was flooded with liquid. When both CC1 and CC2 were controlled at 308K, only one of the CC's contained two-phase fluid, the other one was still flooded with liquid. Which one would be flooded was a function of the heat load distribution between the two evaporators. Figures 3, 4, and 5 show the loop temperatures when both CC1 and CC2 were controlled at 308K with a control band of ±0.2K. CC1 was flooded at 100W/0W and 75W/25W, and CC2 was flooded at 50W/50W, 25W/75W and 0W/100W. As the liquid flooding switched from one CC to the other, some liquid movement between the two CC's would happen. Temperature spikes of E1 inlet (TC10) and CC1 at 9:40 seem to indicate nucleate boiling in CC1. The loop operated properly at a fairly stable temperature around 308K without any problems. Any temperature deviation was probably a function of the temperature sensor location and the liquid level in the CC.

(Insert)

- Figure 3, 4, 5

Another power cycle test was conducted by setting C1/C2 sinks at 263K/258K and varying the heat load as follows: 0W/100W, 5W/100W, 100W/5W, 5W/100W, 0W/100W. The set point temperature was maintained at 308K by controlling CC1, or CC2, or both at 308K. As expected, when only one CC was actively controlled, the other CC was completely flooded with liquid. Figure 6 show the loop temperatures when both CC's were controlled at 308K. It is seen that CC2 was flooded except at the heat load of 100W/5W. The last part of the test continued until 17:00 and the loop demonstrated very stable operation.

Insert

- Figure 6

Sink Cycle

Figure 7 shows the loop temperatures in sink temperature cycle test where E1/E2 heat load was kept constant at 50W/50W. The chiller 2 temperature was cycled between 243K and 283K while chiller 1 was idle (no coolant to condenser 1) until 12:50, then chiller 1 was turned on and set at 283K and chiller 2 was turned off. The CC2 heater control was set at 308K and the CC1 heater was not used. When chiller 2 was set at 243K, condenser 2 was only partially utilized and the loop operating temperature followed the CC2 set point temperature. As chiller 2 was set at 283K, however, condenser 2 could not dissipate the total heat load, as evidenced by the rise of TC49 and TC29 temperatures. Consequently the loop operating temperature rose to 314.5K and CC2 heater was deactivated. Note that C1 could only dissipate very small amount of heat and TC39 was at the saturation temperature. The vapor (or two-phase fluid) from C1 mixed with the liquid from C2 after the flow regulators, as shown by the lower temperature of TC29. This test also verified that the flow regulators functioned properly as designed. As chiller 1 was turned on and chiller 2 was turned off at 12:50, vapor flowed through C2 and TC49 temperature rose to the saturation temperature. Because chiller 1 had a much higher capacity, C1 was not fully utilized even at a sink temperature of 283K. Thus, the loop could operate at 308K, the set point temperature of CC2.

Figure 8 shows the loop temperature in another sink temperature cycle test where chiller 1 was not used and chiller 2 temperature cycled between 243K and 283K. The E1/E2 heat load was kept constant at 5W/5W. From 19:00 to 20:40, CC2 alone was controlled at 308K. From 20:40 to 22:04, CC1 alone was controlled at 308K. From 22:04 to mid-night, both CC1 and CC2 were controlled at 308K With such a low heat load, C2 was never fully utilized and liquid line temperature TC29 changed with the chiller 2 set point temperature. . It is seen that, during the entire period, the loop operating temperature was around 308K, controlled by either CC1 or CC2.

Insert

- Figure 7.

Insert

- Figure 8.

CC Temperature Cycle

The purpose of the CC temperature cycle test was to investigate the ability of the LHP to adapt to a set point temperature change during operation. In the test, the heat load to E1/E2 and the sink temperatures were kept constant, and both CC1 and CC2 were controlled. Tests were conducted with E1/E2 heat loads of 50W/50W, 10W/10W, 100W/5W, 5W/100W, and 25W/5W. In addition, the CC control heater power was also varied. Figure 9 show the loop temperature where CC1 and CC2 set point varied between 298K and 308K with E1/E2 heat load at 50W/50W and both chillers at 273K. In this test, each CC control heater has 4.7W of heat load, which was more than enough to compensate for the liquid subcooling. Thus, the CC temperature rose quickly at each set point increase. In addition, the large heat load to each evaporator prevented the evaporators from being flooded with liquid during set point increase, and provided enough subcooled liquid to the Cc's during set point decrease. Consequently, the CC set point change was achieved very smoothly.

Insert

- Figure 9.

Figure 10 shows the set point change with 10W to each evaporator and both chillers were set at 253K. Each CC heater received 4.7W when the set point changed from 298K to 304K. The large control heat power raised the set point of each CC rapidly. As each heater was cycled on and off at the set point, a large rapid fluid movement was seen as evidenced by the large fluctuations of the CC inlet temperatures. The control heater power was reduced to 0.9W for each CC as the set point increased from 304K to 309K. The set point temperature increased at a much slower rate. CC 1 reached the set point first, followed by CC2. For the next 7 minutes, the interaction between the two CC's caused the temperature to fluctuate. During this time, neither CC had enough power to respond quickly to any changes. However, as both CC's reached an equilibrium, there were no large temperature fluctuations in the loop. As the set point temperature decreased, both CC's also responded slowly because of the low mass flow rates at low heat loads.

Insert
Figure 10.

The test shown in Figure 10 continued with an uneven heat load of 25W/5W to E1/E2. Figure 11 shows the loop temperatures. Initially, the CC control heater power remained at 0.9W each. When the set point increased to 303K, CC1 could only reach 301.5K because of higher subcooling with an E1 heat load of 25W. On the other hand, CC2 was able to reach 303K with 0.9W. The interesting part is that CC1 still controlled the loop operating temperature. CC2 remained liquid flooded and was at a superheated state. This is evidenced by the fact that all vapor line temperatures (TC23 in Figure 11) and all evaporator temperatures (not shown in the figure to avoid congestion) followed the TC7 temperature. At 13:15, the set point was increased to 308K. There was no change in the CC1 temperature, but CC2 was able to reach 305K, thus representing a 3.5 degrees of superheat. At 13:37, the control heater power was increased to 2.1W each, and both CC's reached 308K. When the set point was decreased to 298K, CC1 reached the set point first due to a higher mass flow rate and subcooling. The subsequent test was conducted to reconfirm that CC2 could become superheated. The set point temperatures for CC1 and CC2 were 304K and 308K, respectively, and each received 1.7W heat power. When CC2 reached 308K, its heater cycled on and off. Meanwhile CC1 temperature continued to rise and controlled the loop operating temperature. CC2 remained at 308K as CC1 reached 304K. Then CC1 set point was lowered to 303K, and CC2 temperature suddenly dropped to 304K, accompanying by a sudden rise of CC1 and CC2 inlet temperature. This indicates that nucleate boiling had occurred inside CC2, and CC2 began to control the loop operating temperature. When the set point was reduced to 301K, CC1 was flooded with liquid and all vapor line and evaporator temperature followed the CC2 set point temperature. Although not shown in Figure 11, CC1 temperatures TC6 to TC9 were uniform between 12:30 and 14:40, and CC2 temperatures TC16 to TC19 were uniform between 14:40 and 15:30, thus supporting the above explanations.

Insert
Figure 11.

Figure 12 shows the loop temperatures in another CC temperature cycle test with a highly uneven heat load. Both sinks were set at 273K. The test started with a heat load of 5W/100W. Both CC's were set to 298K with 4.7W of control heat power each. With a heat load of only 5W and a sink temperature of 273K, the natural equilibrium temperature for CC1 was 303K, higher than the set point. Consequently, CC1 controlled the loop operating temperature and its control heater was not activated while CC2 was flooded with liquid at 298K. When the set point increased to 309K, both CC reached the new set point rapidly with 4.7W heater power. As the set point decreased to 298K, again CC1 could only reached 303K while CC2 was flooded at 298K. Then CC1 temperature suddenly dropped 0.5 degree, possibly due to vapor bubble shrinkage inside the evaporator core as evidenced by a decrease of E1 inlet temperature (TC10). The heat load then changed to 50W/50W as an intermediate step to set up the initial condition for the next test. With such a high heat load, both CC's could be controlled at 298K. As the heat load changed to 100W/5W, both CC's continued to be controlled at 298K. From 11:15 to 14:15, CC2 temperatures TC16 to TC19 were not uniform, indicating CC2 had been flooded all along. This reduced heat leak significantly and helps explain why the CC2 temperature did not rise to 303K as CC1 did at 5W/100W. As the set point changed to 303K, CC2 temperatures (TC16 to TC19) became uniform and CC1 temperatures (TC6 to TC9) spread, suggesting that vapor bubbles were generated in CC2 and CC1 became liquid-filled. In fact, CC1 was flooded for the rest of the test. As the set point temperature was reduced from 308K to 303K (15:00 to 16:00), CC1 and CC2 temperatures decreased. However, CC2 showed two temperature increases during this period, which appeared to be the result of vapor bubble expansion inside CC2. Note that, in Figure 12, each of the four increases of TC20 indicates either vapor bubble generation or expansion. Higher vapor content means a higher leak. Because of the higher heat leak, CC2 had a higher natural equilibrium temperature of 306.5K. The loop could no longer operate at the set point temperature of 303K. The effect of vapor void fraction on the loop operating temperature has been demonstrated over and over again in other LHP's with a single evaporator [7, 10], and is the major source of temperature hysteresis.

Insert
Figure 12.

Capillary Limit

The titanium wick used in E1 is three times weaker than the nickel wick in E2. Thus, E1 will reach capillary limit first regardless of the heat load distribution. When the capillary limit is reached, vapor will penetrate the titanium wick and CC1 temperature will increase. Because of the continuous vapor penetration, CC1 temperature will exceed the set point temperature and began to control the loop operating temperature regardless which CC is in control prior to the capillary limit. Figure 13 shows the loop temperature in a capillary limit test where the heat load was applied to E1 only and CC2 was controlled at 303K. For heat loads between 50W/0W and 120W/0W, CC2 controlled the loop operating temperature at 303K and CC1 was flooded with liquid. The capillary limit was probably reached at 130W/0W with a small amount of vapor penetration. The CC1 temperature did not increase much because of a large amount of subcooled liquid available to collapse the vapor bubbles. Significant vapor penetrations did occur at 140W/0W, as indicated by a large increase in the CC1 temperature. Vapor penetration also pushed cold liquid from TC10 to TC20, causing TC20 temperature to drop temporarily. The temperature difference between E1 and CC1 also increased after the capillary limit was exceeded. Nevertheless, the loop continued to function at a higher temperature. The loop also approached another steady temperature as the heat load increased to 150W/0W. The loop only partially recovered as the heat load reduced to 120W/0W. After the loop completely recovered at 100W/0W, and the heat load could be increased to 120W/0W without exceeding the capillary limit.

Insert

- Figure 13.

Concluding Remarks

This test program has demonstrated that an LHP with two evaporators and two condensers can operate at the desired set point temperature by controlling the temperature of either or both of the CC's. Under most conditions, the loop operating temperature followed the CC whose temperature was being controlled as long as the heat load and the sink temperature were within the control limit. The LHP could adapt to rapid change of the heat load, sink temperature and set point temperature itself. From the user's point of view, this is the most important conclusion. However, there are still some technical issues to be addressed for multiple evaporator LHP's.

Test results indicated that one of the CC's was always flooded with liquid even if both CC's were controlled at the same temperature. Thus, the growth issue remains as to the number of evaporators that can be incorporated in a single loop. Since all CC's except one will be flooded with liquid anyway, it may be more power efficient to control only one of the CC's, preferably the one with a smaller heat load. This is true if one of the evaporators always carries a lower heat load. If the heat load distribution change widely with time, the heater still needs to be sized to compensate the full range of liquid subcooling requirement.

A more serious issue is the problem caused by the temperature hysteresis, especially at low heat loads. The heat leak from the evaporator to the CC is highly dependent upon the vapor void fraction inside the evaporator core. Test results show that when one of the evaporators has a very low heat load, the loop temperature may exceed the set point temperature due to a sudden vapor generation or expansion. Such an event can not be predicted and is hard to prevent. One method to alleviate the problem is to have a very cold condenser such that ample subcooling is available at the CC inlet. However, this contradicts the desire to minimize the control heater power requirement. The corollary is that preheating the returning liquid may result in loss of CC temperature control at low heat loads. This also applies to an LHP with a single evaporator.

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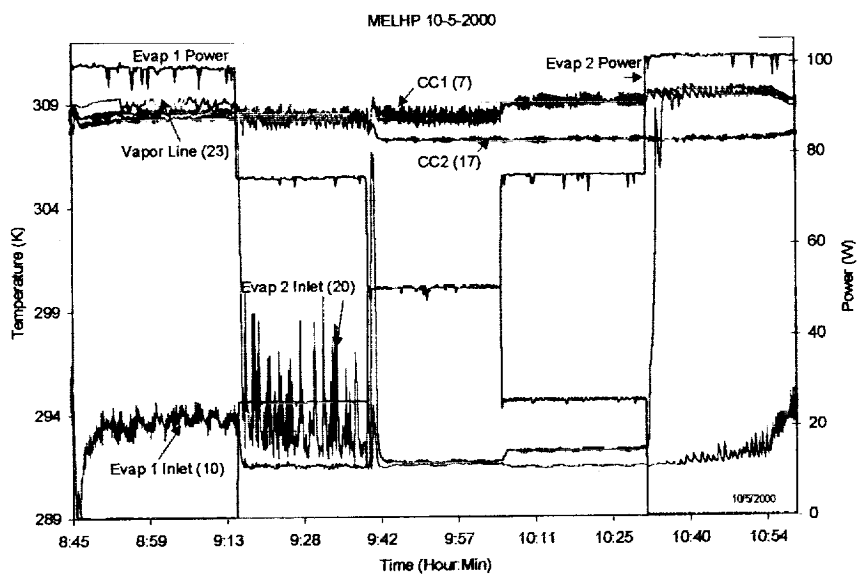

Figure 3. Loop Temperatures in Power Cycle Test with both CC1/CC2 Controlled at 308K

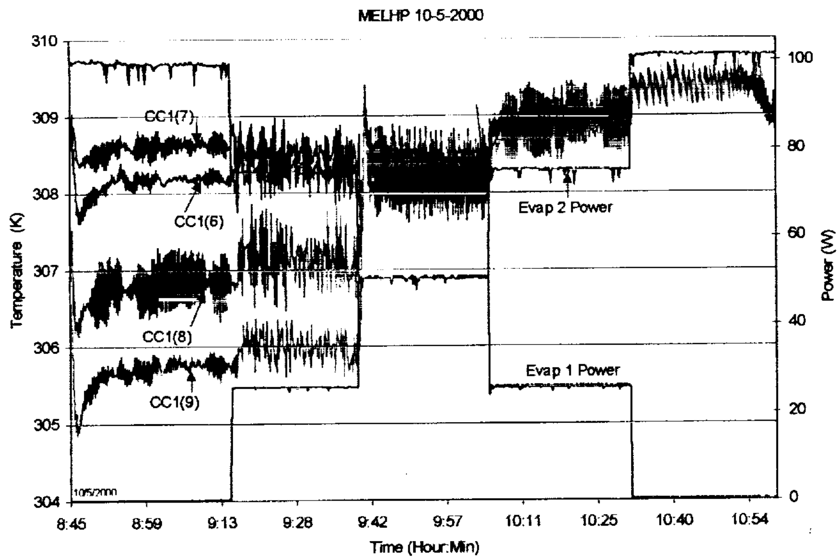

Figure 4. CC1 Temperatures in Power Cycle Test with both CC1/CC2 Controlled at 308K

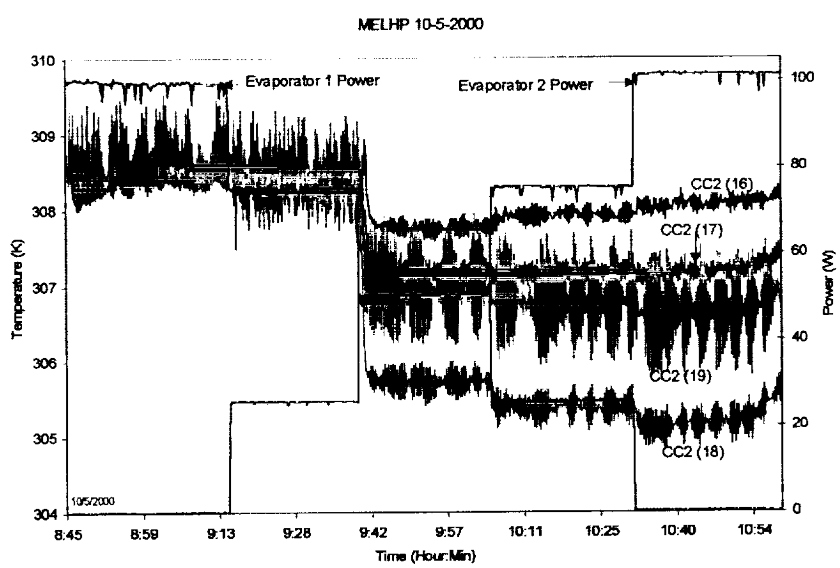

Figure 5. CC2 Temperatures in Power Cycle Test with both CC1/CC2 Controlled at 308K

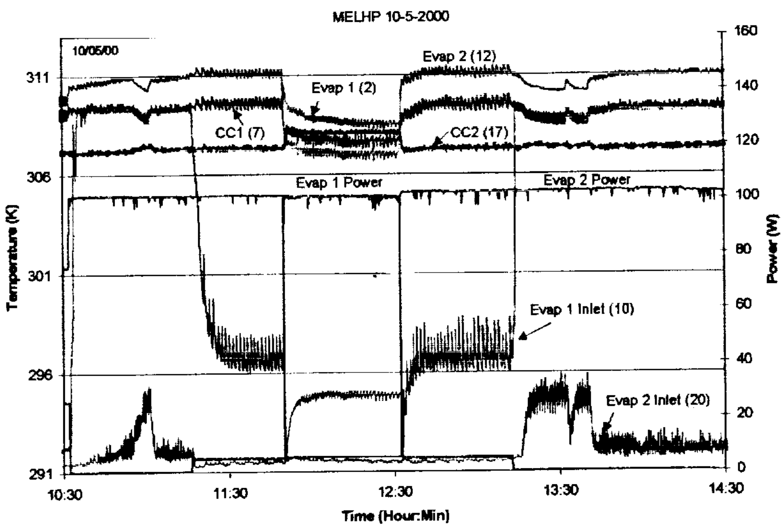

Figure 6. Loop Temperatures in Power Cycle Test with both CC1/CC2 Controlled at 308K

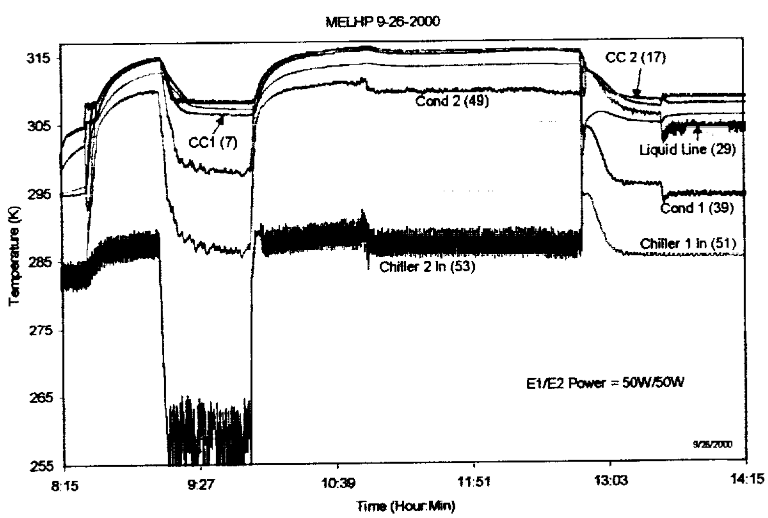

Figure 7. Loop Temperatures in Sink Temperature Cycle Test with E1/E2 Heat Load of 50W/50W

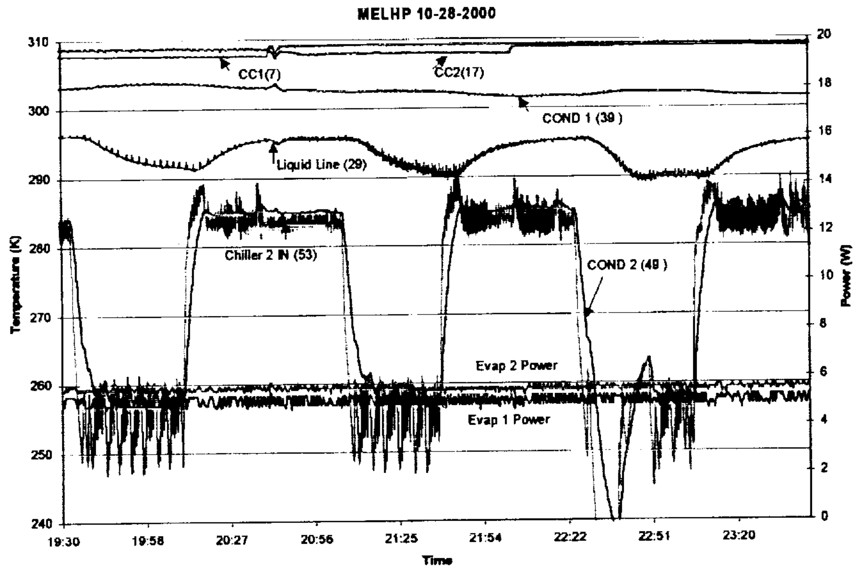

Figure 8. Loop Temperatures in Sink Temperature Cycle Test with E1/E2 Heat Load of 5W/5W

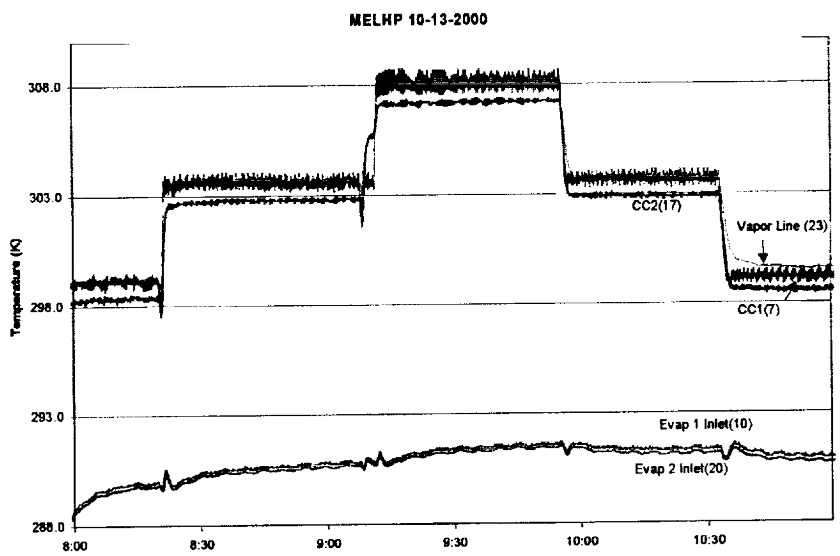

Figure 9. Loop Temperature in the CC Temperature Cycle Test with E1/E2 Heat Load of 50W/50W

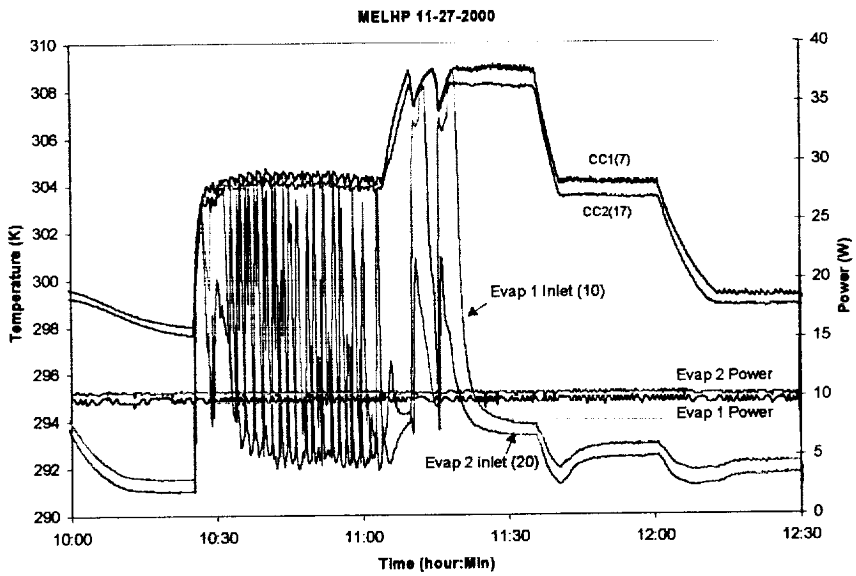

Figure 10. Loop Temperatures in CC Temperature Cycle Test with E1/E2 Heat Load of 10W/10W

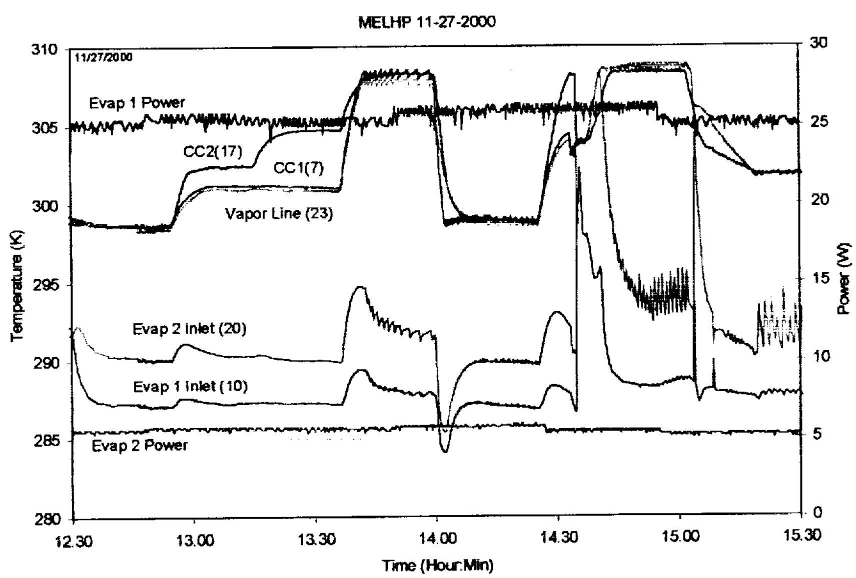

Figure 11. CC1 Temperature in CC Temperature Cycle Test with E1/E2 Heat Load of 25W/5W

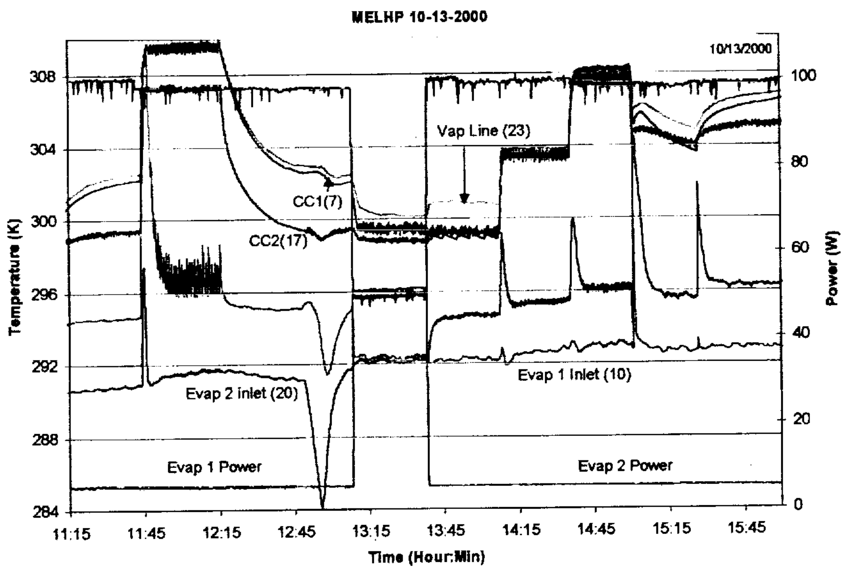

Figure 12. Loop Temperatures in CC Temperature Cycle Test with Various Heat Loads

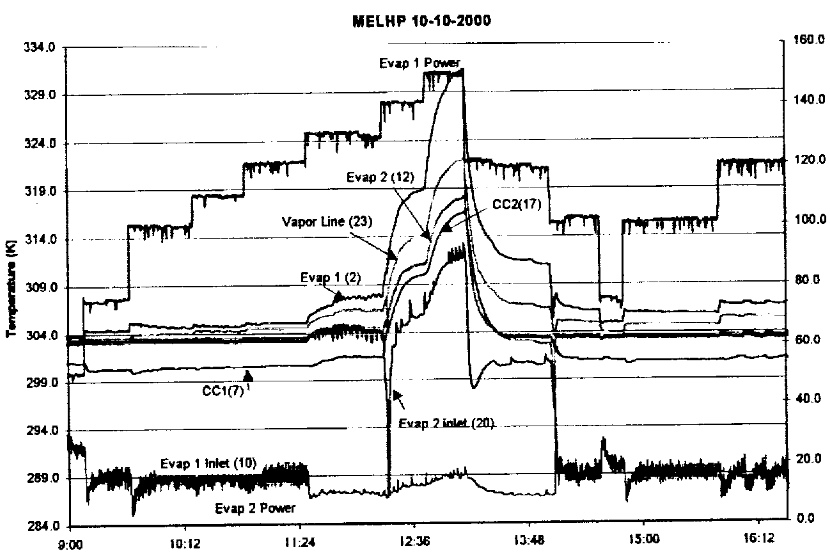

Figure 13. Loop Temperatures in Capillary Limit Test