Capillary Limit in a Loop Heat Pipe with Dual Evaporators

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Abstract

This paper describes a study on the capillary limit of a loop heat pipe (LHP) with two evaporators and two condensers. Both theoretical analysis and experimental investigation are conducted. Tests include heat load to one evaporator only, even heat loads to both evaporators and uneven heat load to both evaporators. Results show that after the capillary limit is exceeded, vapor will penetrate through the wick of the weaker evaporator and the compensation chamber (CC) of that evaporator will control the loop operating temperature regardless of which CC has been in control prior to the event. Because the evaporator can tolerate vapor bubbles, the loop may continue to work and reach a new steady state at a higher operating temperature. The loop may even function with a modest increase in the heat load past the capillary limit. With a heat load to only one evaporator, the capillary limit can be identified by rapid increases in the operating temperature and in the temperature difference between the evaporator and the CC. However, it is more difficult to tell when the capillary limit is exceeded if heat loads are applied to both evaporators. In all cases, the loop can recover by reducing the heat load to the loop.

Introduction

Most existing loop heat pipes (LHPs) have a single evaporator and a single condenser. The evaporator is made with an integral compensation chamber (CC) with a bayonet and a secondary wick connecting these two elements. The CC saturation temperature determines the loop operating temperature. Because the CC is physically near the evaporator and is located in the path of the fluid circulation, its temperature is a function of the evaporator heat load, condenser sink temperature, and ambient temperature. The overall pressure drop in the loop must not exceed the capillary pumping capability of the wick in order for the loop to work properly. In addition, the temperature difference between the evaporator and the CC must match the corresponding pressure drop across the primary wick as required by thermodynamics [1].

When multiple heat sources or a heat source with large thermal footprint needs to be cooled, an LHP with multiple evaporators will be very desirable. The feasibility of a multiple-evaporator LHP has been demonstrated [2-5]. There are several challenges for such a system. A simple thermodynamic analysis shows that, under most cases, only one of the CCs will contain two-phase fluid and control the loop operating temperature. All other CCs will be completely filled [1, 6]. This characteristic has been experimentally verified through extensive testing of an LHP with two evaporators and two condensers [6-8]. Test results also show that control of the loop operating temperature can switch from one CC to another as the operating condition changes. Other issues such as interactions between individual CCs, temperature stability, and loop's adaptability to rapid power and sink temperature cycle were also investigated.

This paper will focus on the capillary limit of an LHP with two evaporators and two condensers. A theoretical analysis will be presented first. This will be followed by a description of an extensive test program for the LHP. The physical processes that leads to evaporator deprime and the recovery from the deprime will be described in detail. Some issues related to the heat transport limit of an LHP will also be addressed.

Theoretical Background

Figures 1 and 2 depict the flow schematic and the corresponding pressure drop diagram for a typical LHP with two parallel evaporators and two parallel condensers. The capillary pressure that each wick is able to sustain can be expressed as:

$$\Delta P_i = 2\sigma_i / r_{p,i} \qquad\qquad i = 1, 2 \qquad\qquad (1)$$

where σ is the surface tension force of the working fluid and r_p is the radius of curvature of the wick at the vapor/liquid interface. As the heat load is applied to the evaporators, a liquid flow will be established and a pressure drop will incur in each component of the LHP. The mass flow rate through each evaporator can be calculated as:

$$m_i = Q_i / \lambda \qquad\qquad i = 1, 2 \qquad\qquad (2)$$

where m_i is the mass flow rate, Q_i is the heat load and λ the latent heat of vaporization of the working fluid. The total mass flow rate through the transport lines and the condenser is $m_t = m_1 + m_2$. In order for the LHP to function properly, each evaporator must be able to sustain the pressure drop imposed upon its wick.

$$\Delta P_i \geq \Delta P_{tot,i} \qquad\qquad i = 1, 2 \qquad\qquad (3)$$

The equality sign holds true when the capillary limit is reached. In Figures 1 and 2, it is assumed that evaporator 2 receives a higher heat load than evaporator 1. The pressure drop from point 5 to point 12 is common to both evaporators and is a function of the total heat loads applied to the two evaporators. The pressure drops from point 1 to point 5 and from point 12 to point 14 are dependent upon the heat load to evaporator 1 only. Likewise, the pressure drops from point 3 to point 5 and from point 12 to point 16 are dependent upon the heat load to evaporator 2 only. Thus, the total pressure drop imposed upon each evaporator is a function of the total heat load as well as the heat load distribution between the two evaporators.
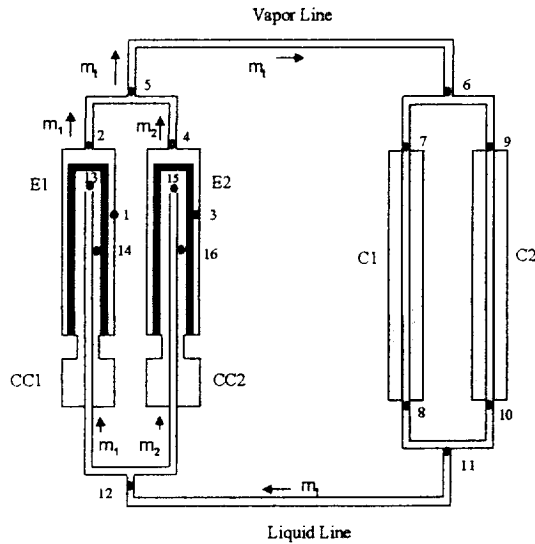

Figure 1. Flow Schematic of an LHP with Two Evaporators and Two Condensers
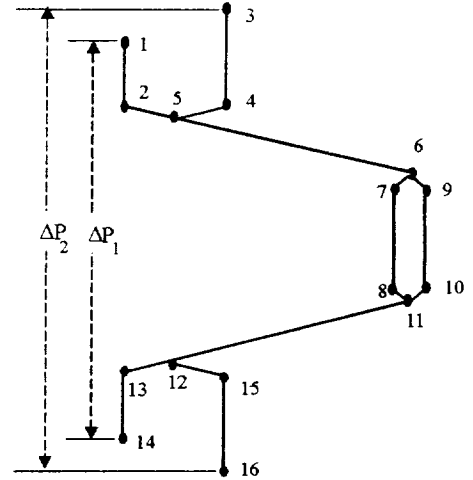
Figure 2. Pressure Drop Diagram in an LHP

When the heat load is applied to only one of the evaporators, the one receiving no heat load actually works as a condenser. Figure 3 shows the pressure drop diagram when evaporator 1 receives no external heat load. The flow from point 5 to point 12 (via point 2) is in a reverse direction. Consequently, the pressure drop that the evaporator 1 wick has to sustain could be much smaller than that shown in Figure 2. The exact amount of heat dissipation through evaporator 1 is determined by the conservation laws of mass, momentum, and energy among the two condensers and evaporator 1, and is a function of many factors, including the heat load, line sizes, condenser sink temperatures and ambient temperature. As the heat load to evaporator 2 increases, so do the heat dissipated by evaporator 1 and the pressure drops imposed upon both evaporators. Whenever the pressure drop exceeds the

capillary limit of either evaporator, the weaker evaporator will fail first. Figure 4 shows the pressure drop diagram when evaporator 2 receives no external heat load.
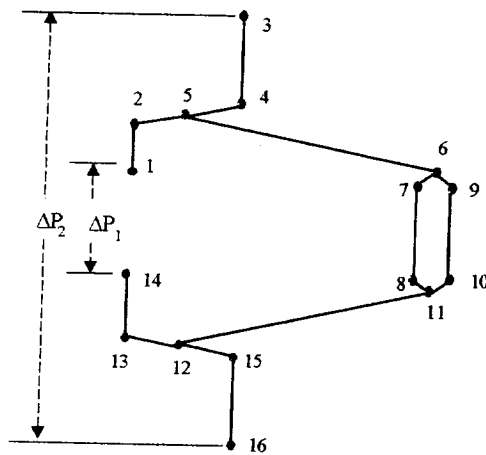

Figure 3. Pressure Drop Diagram with Heat Load to E2 Only
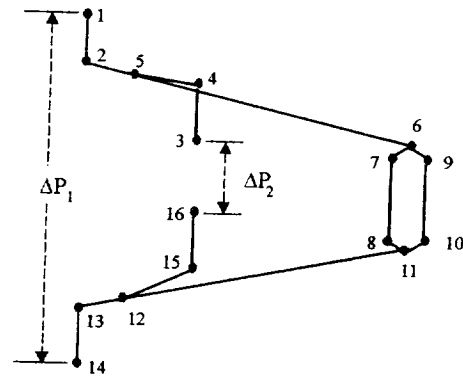

Figure 4. Pressure Drop Diagram with Heat Load to E1 Only

When the capillary limit of the wick is exceeded, vapor will penetrate through the wick and reach the evaporator core. Because the evaporator core can tolerate vapor presence, the stronger wick pores can continue to pump liquid and the loop can continue to work. However, vapor penetration means a higher heat leak to the CC, and hence a higher operating temperature. Two things happen after vapor penetrates the wick. Because the surface tension decreases with an increasing temperature, more and more pores will fail, leading to more vapor penetration and an ever-increasing operating temperature. On the other hand, the viscosities of the fluid decrease with an increasing temperature, leading to a smaller total pressure drop. Consequently, a new steady state could be reached at a higher operating temperature if the capillary limit (the heat load) is not exceeded by too much. One indication that the capillary limit is exceeded is a rapid increase of the temperature difference between the evaporator and the CC due to a decreasing thermal conductance. Another indication is that the CC of the failing evaporator will rise rapidly in temperature and begin to control the loop operating temperature regardless of which CC has been in control prior to the vapor penetration.

The heat transport capability of a capillary two-phase thermal system, is measured by the maximum heat load it can carry. The maximum heat load is reached when the total pressure drop is equal to the capillary limit. For a capillary pump loop (CPL), the heat load must be removed from the evaporator once the capillary limit is exceeded in order to avoid a temperature excursion. Thus, there is a definitive maximum heat load for a given CPL with a single evaporator. When multiple parallel evaporators are present, the transport limit is also a function of heat load distribution among the evaporators, and thus there is a small range of values for the maximum heat load. Nevertheless, the heat load must be removed from any failed evaporator. Because the LHP can reach a new steady state even after the capillary limit is exceeded, the concept of a heat transport limit becomes more ambiguous. Both the capillary limit and the pressure drop are functions of the temperature, and there are many factors that can affect the LHP temperature. This becomes more complex when there are more than one evaporator in the system. The effect of various parameters on the capillary limit of an LHP with two evaporators is the subject of this investigation.

Test Article and Test Set-up

As shown schematically in Figure 5, 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 concentric CC. Both evaporators are made of aluminum tubing with 15.8 mm (0.63 inch) O.D. by 76.2 mm (3 inches) length. Based on its size, this LHP is classified as a miniature LHP. One evaporator has a titanium wick with a pore radius of about 3 microns, while the other has a nickel wick with a 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 plates are installed on the vapor line. One is attached with coolant lines while the other is attached with an electrical heater. The two aluminum plates are used in the test to illustrate that in a capillary system a heat load can be added to the vapor line after some energy has been dissipated to a nearby radiator. The loop is charged with 15.5 grams of anhydrous ammonia.

For ease of description, the following abbreviations will be used: E1 = Evaporator 1, E2 = Evaporator 2, C1 = Condenser 1, C2 = Condenser 2, CC1 = Compensation Chamber 1, and CC2 = Compensation Chamber 2. In the following figures, the number in parenthesis next to the label for each curve refers to the thermocouple number shown in Figure 5.

Test Results

Several different types of the capillary limit test were conducted under this test program. In some tests, the CC temperatures were not controlled, i.e. each CC was allowed to reach its natural equilibrium temperature for the given test condition. In other tests, one or both of the CCs were kept at 303K through external heating. Power profiles included heat load to one evaporator only, even heat loads to both evaporators, and uneven heat loads to both evaporators. In most tests, the system heat load was raised to a higher level after the capillary limit had been exceeded so as to demonstrate that the loop could reach another steady state at a higher temperature. Recovery of the evaporator was verified by reducing the heat load to the evaporators near the end of each test.

Table 1 presents all the capillary limit tests that were performed. Included in the table for each test are the power profile, condenser sink temperatures, and whether or not the CC temperatures were actively controlled.

In an LHP with multiple evaporators, only one of the CCs will contain two-phase fluid and control the loop operating temperature; all other CCs will be filled with liquid [6-8]. Moreover, control of the loop operating temperature may shift from one CC to another as the operating condition changes. In this test program, there were four thermocouples attached to each CC. It was observed throughout the test program that the CC containing two-phase fluid displayed a uniform temperature while the liquid-filled CC displayed non-uniform, subcooled temperatures. Since the titanium wick used in E1 has a much larger pore size than the nickel wick in E2, E1 always reached its capillary limit first irrespective of the heat load distribution. In fact, the loop was intentionally designed in this manner in order to study such a phenomenon.

<u>No Active Control of CC Temperatures</u>

The surface tension force of the working fluid is a function of the loop saturation temperature, which in turn is a function of the sink temperature and the heat load distribution between the two evaporators when the CC temperatures are not actively controlled. The total pressure drop imposed on each evaporator is mainly a function of the heat load distribution between the two evaporators although it is also dependent on the loop temperatures to a lesser extent. Thus, the heat load distribution has a direct impact on the capillary limit and the total pressure drop through its influence on the loop saturation temperature.

Figure 6 shows the loop temperature in a capillary limit test where the heat load was applied to E1 only. The C1 and C2 sink temperatures were set at 263K and 258K, respectively. Since E2 received no heat load, E2/CC2 worked as a condenser. Under such a condition, CC2 would always control the loop operating temperature prior to the loop reaching its capillary limit [6]. This was experimentally verified in this test for heat loads between 50W/0W and 120W/0W. As shown in Figure 7 and 8, in this power range, the CC2 temperatures TC16 to TC19 were uniform and were higher than the CC1 temperatures TC6 to TC9 which were subcooled and spread. The capillary limit of E1 was exceeded at 130W/0W as evidenced by four accompanying events. First, CC1 temperatures TC6 to TC9 became uniform and exceeded the CC2 temperatures TC16 to TC19, which became subcooled and spread. This suggested that vapor had penetrated through the E1 wick and CC1 began to control the loop operating temperature. Second,

immediately following the vapor penetration (at 13:07), cold liquid was pushed from TC10 to TC20 along the liquid line, causing E2 inlet temperature TC20 to drop temporarily. Third, the CC1 temperature increased rapidly for a modest power increase. Fourth, the temperature difference between E1 and CC1 also increased rapidly for a modest power increase due to a decreasing thermal conductance after the vapor penetration. Nevertheless, the loop continued to function at a higher temperature because the secondary wick continued to draw liquid from CC1 to E1. The loop also approached another steady temperature as the heat load further increased to 140W/0W. The loop completely recovered as the heat load was reduced to 100W/0W, and the heat load could subsequently be increased to 115W/0W without exceeding the capillary limit. The reason that the loop can operate at a new steady state after the capillary limit has been exceeded is due to the decrease in the fluid viscosity (and hence the pressure drop) with an increasing temperature as outline in the Theoretical Background section..

Figure 6. End of text.
[9/12/01, 9:00-18:00, existing, TC2, 7, 17, 10, 20, power. Power to E1 only. Show control shifted from CC2 to CC1 after E1 deprimed. Also show recovery. (Used in 2189).]
Figure7. CC1 Temperatures
Figure 8. CC2 Temperatures

Figure 9 shows the loop temperatures when the heat load was applied to E2 only. The C1 and C2 sink temperatures were set at 263K and 258K, respectively. The loop started with a heat load of 0W/75W to E1/E2 (not shown in Figure 9), then the heat load increased to 0W/100W, 0W/150W, and 0W/175W. Since E1/CC1 worked as a condenser, CC1 controlled the loop operating temperature and CC2 was liquid-filled throughout the test. Between 0W/75W and 0W/125W, CC1 temperature remained nearly constant at 297.5K. At 0W/150W, the CC1 temperature rose rapidly to 307.5K, indicating that vapor had penetrated the E1 wick. The E1 inlet temperature began to oscillate, possibly caused by a periodic vapor injection into the E1 liquid core. Nevertheless, the loop reached a new steady state and continued to function. The loop reached a new and higher steady temperature as the heat load was further increased to 0W/175W. The heat load was then changed to 50W/125W. Even though E1 was subjected to a higher pressure drop at 50W/125W than at 0W/175W, CC1 temperature actually decreased because cold liquid was brought back to CC1 to lower its temperature, as evidenced by a sudden drop of E1 inlet temperature TC10. The CC1 temperature dropped further as the heat load was reduced to 25W/125W. However, E1 did not fully recover even when the heat load was reduced to 0W/125W. The periodic vapor penetration persisted. In fact, the loop temperatures at 0W/125W looked more like those at 0W/150W prior to the vapor penetration. Only when the heat load was reduced to 0W/100W did the E1 wick recover completely.

Figure 9. Capillary limit with uneven heat loads.
[9/11/01, 10:30-17:00, existing, TC2, 7, 17, 10, 20, power. Power to E2 only. Show E1 deprime and E1 inlet temperature oscillation after deprime. Also show recovery. (used in 2190)]

Figure 9 indicates that vapor penetrated the E1 wick at 0W/150W and the wick recovered as the heat load decreased to 0W/100W. Several tests were conducted to study the loop thermal response when it was subjected to a repeated deprime and recovery cycles. Figure 10 illustrates the loop temperature for one of these tests where the heat load varied between 0W/100W and 0W/150W. Throughout the test, CC1 controlled the loop operating temperature. At a heat load of 0W/100W, CC1 was at 299K. At 0W/150W, vapor penetrated the E1 wick. Also, the CC1 temperature rose above 313K and the E1 inlet temperature oscillated. As the heat load decreased to 0W/100W, the loop seemed to recover, but with some residual effect. Specifically, the CC1 temperature was 303K compared to 299K at the beginning of the test, and the E1 inlet temperature still showed small oscillations. The residual effect is a manifestation of the temperature hysteresis caused by the change of vapor void fraction inside the evaporator core. In other words, the vapor void fraction inside the E1 core was larger after the vapor penetration, leading to a higher CC1 temperature. The subsequent test with power cycles between 0W/150W and 0W/100W seemed to yield repeatable results, suggesting that the residual effect did not worsen.

Figure 10.
[11/16/01. 8:30 to 17:30, existing, TC7, 17, 10, 20, 23, Power to E2 only. Illustrate repeated deprime/recovery. E1 inlet oscillated when E1 deprimed.]

The maximum power that can be applied to the loop before the capillary limit is exceeded, under a given operating condition, is a function of the heat load distribution between the two evaporators. For a geometrically symmetric

loop as the one being studied and shown in Figure 5, the heat load of 130W/0W (heat load to E1 alone) represents the low end and 0W/150W (heat load to E2 alone) represents the high end of the maximum power that can be applied to the loop prior to the vapor penetration for a given sink temperature. Any other combinations of heat loads will yield a system heat transport limit between 130W and 150W.

Figure 11 depicts the loop temperatures in a test where the heat load to E2 was fixed at 50W and the heat load to E1 varied between 50W and 130W with 10W increments. Throughout the test, it was seen that CC1 controlled the loop operating temperature. At each power increase, the CC 1 temperature increased and so did the E1 and E2 temperatures. Moreover, the CC2 temperature also increased with the heat load due to an increasing shared heat load from E1 and a higher heat leak resulting from a larger temperature difference between E2 and CC2. Unlike those shown in Figures 6 and 9 where the heat load was applied to one evaporator only, the heat load at which E1 reached its capillary limit was more difficult to identify when both evaporators received heat loads. This is because the higher heat leak into CC1 after the vapor penetration was partially overcome by an increasing liquid subcooling resulting from the higher mass flow rate (heat load). One may argue that the capillary limit was reached anywhere between heat loads of 80W/50W and 110W/50W. Since E1 reached its capillary limit at 0W/150W as shown in Figure 9, in theory the vapor penetration should have occurred for a heat load less than 100W/50W in Figure 10. As the heat load was reduced to 70W/50W, the CC1 temperature dropped from 328K to 301K, indicating a recovery of the E1 wick. However, the CC1 temperature was 9K higher than that at 70W/50W prior to the vapor penetration, suggesting a residual effect.

Figure 11.
[9/13/01. 9:00 to 18:00. E2 power fixed at 50W, E1 increased from 50W until deprimed.]

Figure 12 shows the results of a similar test where the E1 heat load was fixed at 50W and the E2 heat load varied between 50W and 90W. Again, with heat loads to both evaporators, it is difficult to tell whether the capillary limit had been exceeded at 50W/90W. The fact that control of the loop operation switched from CC2 to CC1 at 50W/80W does not necessarily mean that the vapor penetration had occurred because CC2 simply had more liquid subcooling as the E2 heat load increased. However, the higher operating temperature at 50W/50W and 50W/90W near the end of the test (the residual effect mentioned earlier) seemed to indicate that the vapor penetration had occurred earlier either at 50W/80W or at 50W/90W. A new test was conducted with a higher power to E2 as shown in Figure 13. The heat load to E1 was fixed at 50W and the heat load to E2 varied between 50W and 103W in the first two cycles, and between 50W and 110W in the last two cycles. Notice that the CC1 temperature increased by at least 5K at 50W/110W compared to that at 50W/103W. The large increase in the operating temperature due to a small power increase indicates that the capillary limit was exceeded at 50W/110W, and possibly at 50W/103W or lower.

Figure 12.
[11/13/01, 8:30-15:00, existing, TC7, 17, 10, 20, 23, power, E1 fixed at 50W.]

Figure 13.
[11/14/01, 8:30 – 17:30, (Need to change to 8:00 to 17:00), E1 fixed at 50W, E2 varied between 50W and 110W. Difficult to tell whether the loop deprime other than knowing CC temperature (vapor temperature) went up sharply. Same issue as in capillary limit with a single evaporator.]

Active Control of CC Temperatures

The CC temperature can be controlled at a fixed set point that is higher than its natural equilibrium temperature for a given test condition through external heating. When one of the CCs is controlled at the desired temperature, the other CC will be liquid-filled. Even when both CCs are controlled at the same temperature, one of them will still be liquid-filled [8]. For this reason, only one of the CCs was controlled at 303K under this test program. With the loop operating at a fixed temperature, the surface tension force and the capillary limit of each evaporator as expressed in Equation (1) is fixed. However, the pressure drop imposed upon each evaporator is still dependent upon the sink temperature and the heat load distribution between the two evaporators. As shown in Table 1, in all tests where CC temperature was controlled, the C1/C2 sink temperatures were set at 263K/258K. Test results show that the

condensers were able to dissipate all the heat loads in all tests, i.e. the condenser heat dissipation capability was never a limiting factor.

Figure 14 shows the loop temperatures in a test where the CC1 temperature was controlled at 303K and the heat load was applied to E2 only. CC1 was able to control the loop saturation temperature at 303K for heat loads between 0W/50W and 0W/125W. CC2 was hard filled with liquid and became increasingly subcooled at higher powers because more subcooled liquid returned to CC2. As E1 reached its capillary limit at 0W/150W, vapor penetrated through the E1 wick and the CC1 temperature rose above the set point temperature of 303K. The vapor penetration became rather severe at 0W/175W and the CC1 temperature rose rapidly. The oscillation of E1 inlet temperature TC10 was the result of a periodic vapor penetration. The heat load was then changed to 25W/150W. The addition of a heat load to E1 caused the E1 inlet temperature to drop sharply due to the return of cold liquid. This led to a drop in the CC1 temperature although the E1 wick was more stressed at 25W/150W than at 0W/175W. The vapor penetration most likely persisted at heat loads of 25W/150W and 25W/125W; the oscillation of E1 inlet temperature was simply suppressed by the returning cold liquid. In fact, the E1 inlet temperature oscillated again at 0W/125W, indicating the vapor penetration persisted at this power level. CC2 did not resume its temperature control until the heat load was reduced to 0W/100W. After E1 fully recovered, the heat load could be increased to 0W/125W without exceeding the capillary limit.

Figure 15 shows the loop temperatures in a test similar to that shown in Figure 14 except that the CC2 temperature was controlled at 303K instead. Before E1 reached its capillary limit, CC2 controlled the loop saturation temperature at 303K. Once E1 exceeded its capillary limit at 0W/150W, CC1 controlled the loop operating temperature and the loop displayed a very similar behavior as those shown in Figure 14. This is expected because the loop worked under the same condition in both cases and the CC temperature control heater was no longer active after the vapor penetration.

Figure 14.
[10/11/01, 7:00 to 16:00, existing, TC7, 17, 10, 20, 23, power. Power to E2 only. CC1 controlled at 303K, E1 inlet oscillated when E1 deprimed.]

Figure 15.
[10/12/01, 9:00 to 15:30, existing, TC7, 17, 10, 20, 23, power to E2 only. CC2 controlled at 303K, E1 inlet oscillated when E1 deprime.]

Figure 16 shows the loop temperatures where the CC2 temperature was controlled at 303K and the heat load was applied to E1 only. For heat loads between 50W/0W and 120W/0W, CC2 controlled the loop operating temperature at 303K and CC1 was liquid-filled. The E1 capillary limit was exceeded at 130W/0W. A more severe vapor penetration occurred at 140W/0W, as indicated by a much larger increase in the CC1 temperature. In addition, CC1 began to control the loop operating temperature and CC2 became liquid-filled with its control heater deactivated. Vapor penetration also pushed cold liquid from TC10 to TC20 along the liquid line, causing TC20 temperature to drop temporarily. Moreover, the temperature difference between E1 and CC1 increased rapidly 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 was reduced to 120W/0W. Full recovery occurred at 100W/0W, and the heat load could subsequently be increased to 120W/0W without exceeding the capillary limit.

Figure 16.
[10/10/01, 9:00-16:15, existing, TC2, 12, 7, 17, 10, 20, power. Power to E1 only. (Used in 2188)].

Figure 17 shows the results of the test with the same power profile except that CC1 temperature control was set at 303K. Again, small vapor penetration occurred at 130W/0W. Significant vapor penetration occurred at 140W/0W where CC1 temperature increased rapidly. The loop showed a similar behavior as that shown in Figure 16 after the capillary limit was exceeded. The loop completely recovered at 100W/0W and the heat load could subsequently be increased to 110W/0W without exceeding the capillary limit.

Figure 17.

Figure 18 shows the loop temperatures in another test where CC2 was controlled at 303K and even heat loads were applied to both E1 and E2. For heat loads of 65W/65W or lower, CC2 was able to control the loop operating temperature at 303K. Temperature oscillations of CC2, E1 inlet and E2 inlet were caused by the on/off cycle of the CC2 heater. As the heat load increased to 70W/70W, vapor penetrated the E1 wick and the CC1 temperature rose above the set point temperature of 303K, controlling the loop operating temperature. At each power increase, the CC1 temperature increased to a higher steady temperature and CC2 became more subcooled. The heat load could further be increased to 80W/80W and 90W/90W, and the loop reached new steady states. When the heat load was reduced to 65W/65W, the E1 wick probably recovered. However, the loop operating temperature was still controlled by CC1 at 305K due to the residual effect mentioned previously. CC2 resumed it temperature control only after the heat load was reduced to 50W/50W. Moreover, during the power step down, the CC1 temperature and hence the loop operating temperature continued to drop below 303K although the CC2 heater was cycled on. When CC1 temperature dropped to 295K, vapor bubbles were generated in CC2 and CC2 began to control the loop operating temperature at 303K. This represented 8 degrees of superheat for boiling nucleation in CC2. The loop temperatures were similar to those at 50W/50W prior to vapor penetration.

The difficulty in identifying when the capillary limit was reached with heat loads to both evaporators was mentioned previously when discussing Figures 11 to 13. With the CC2 temperature controlled at a fixed set point, vapor penetration through the E1 wick can be easily identified by the increase of its CC temperature, as shown in Figure 18. Note that, if the CC2 temperature had not been controlled at 303K initially, one would have faced the same difficulty in identifying whether vapor penetration occurred at 70W/70W, 80W/80W, or 90W/90W.

Figure 18, 10/19/01, 8:00-17:00, existing, TC2, 7, 17, 10, 20, existing, Even power to E1/E2. (Used in 2190)

Concluding Remarks

When the capillary limit of an LHP is exceeded, vapor will penetrate through the wick and the heat leak from the evaporator to the CC will increase drastically. This will lead to a sudden and rapid increase of the loop operating temperature. Because the evaporator is tolerant of the presence of vapor bubbles, the LHP may continue to operate past the capillary limit and reach a new steady state at a higher temperature if the heat flux is not too high. Test results show that, in an LHP with a single evaporator, the capillary limit can be exceeded repeatedly at progressively higher operating temperature as the heat load continues to increase [9].

The situation becomes even more complex in an LHP with multiple evaporators. At the outset, the maximum heat transport capability in any capillary two-phase systems with multiple evaporators is a function of the heat load distribution among the evaporators; the evaporator with the highest heat load is subjected to the highest pressure drop and is usually the one to fail first. In a capillary pumped loop, the failed evaporator will encounter a temperature excursion after the capillary limit is exceeded because the evaporator can not tolerate vapor bubbles. In an LHP, exceeding the capillary limit may only lead to an increase of the operating temperature. Moreover, where multiple evaporators/CCs are present, the loop operating temperature, the pressure drop imposed on each evaporator, and the capillary limit (a function of the surface tension force) are all dependent upon the heat load distribution. In theory, once the capillary limit is exceeded, vapor will penetrate through the weakest wick and the loop operating temperature will rise rapidly. However, the flow circulation will continue because the evaporator will keep pumping the fluid. Thus, the rising temperature in the failing evaporator will be partially compensated by the higher liquid subcooling due to a higher flow rate at the higher heat load. All these make it difficult to identify when the capillary limit has been exceeded. One exception is when the CC temperature is controlled at a fixed set point. Under such a condition, the capillary limit is fixed at the given temperature. Thus, the capillary limit is reached if the operating temperature rises above the CC set point temperature provided that the condenser heat dissipation capability has not been exhausted. This is true regardless which CC or CCs are being controlled. After the CC set point temperature is exceeded, the CC heater controller will become inactive and the loop will continue to function as in the case of no active control of the CC temperature.

The phenomenon becomes more complex as the number of evaporator increases. Although a pressure transducer can be a useful tool to identify when the capillary limit is reached, its importance is probably limited to research

projects. In practical applications, the user is most concerned with the maximum allowable temperature that can not be violated. As long as the instrument temperature is below the maximum allowable temperature, what happens inside the LHP may not be of great interest even if the capillary limit of the LHP has been exceeded repeatedly at lower temperatures. It is the responsibility of the LHP designer to ensure that enough a margin is provided so that the loop will meet the heat transport requirement without exceeding the maximum temperature.

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Table 1 Capillary Limit Test

| E1/E2 Power (W)	C1/C2 Temp. (K)	Test Date	E1/E2 Power at Capillary Limit (W)	Comments
CC1 and CC2 were not actively controlled				
0/100, 0/125, 0/150/, 0/175, 25/125, 25/100, 25/75	263/263	9/8/00	0/150	CC1 controlled the loop temperature throughout
0/75, 0/100, 0/125, 0/150, 0/175, 25/150, 25/125, 0/125, 0/100	263/258	9/11/00	0/150	CC1 controlled the loop temperature throughout
50/0, 75/0, 100/0, 120/0, 130/0, 140/0, 150/0, 100/0, 110/0, 115/0	263/258	9/12/00	120/0	Control shifted from CC2 to CC1 at 130/0, back to CC2 at 100/0
50/60, 50/70, 50/80, 50/90, 50/50, 50/90, 50/50	273/273, then 263/258	11/13/00	50/90?	Last 50/90 and 50/50 at 263K/258K
50/50, 50/100, 50/50, 50/100, 50/50, 50/110, 50/50, 50/110	273/273	11/14/00		Repeated dry-out and recovery
50/50, 60/50, 70/50, 80/50, 90/50, 100/50, 110/50, 120/50, 130/50, 70/50	263/258	9/13/00	80/50	CC1 controlled throughout
0/100, 0/150, 0/100, 0/150, 0/100, 0/150, 0/100	273/273	11/16/00		Repeated dry-out and recovery
0/100, 0/125, 0/150, 0/100, 0/150	273/273, then 263/258	11/15/00	0/150	Last 0/150 at 263K/258K CC1 in control throughout Repeated dry-out and recovery
100/0, 120/0, 140/0, 150/0, 100/0, 150/0, 100/0	273/273, then 263/258	11/9/00		Last 150/0, 100/0 at 263/258
CCC1/CC2 Controlled at set point				
0/75, 0/100, 0/125, 0/150, 0/175, 25/150, 25/125, 0/125, 0/100	263/258	10/11/00	0/150	CC1 control set at 303K
0/50, 0/75, 0/100, 0/125, 0/150, 0/175, 25/150, 25/125, 0/125, 0/100, 0/125, 50/100, 50/50, 0/125, 50/50, 0/100	263/258	10/12/00	0/150	CC2 control set at 303K
50/0, 75/0, 100/0, 110/0, 120/0, 130/0, 140/0, 150/0, 120/0, 100/0, 75/0, 100/0, 110/0	263/258	10/4/00	130/0	CC1 control set at 303K.
50/0, 75/0, 100/0, 110/0, 120/0, 130/0, 140/0, 150/0, 120/0, 100/0, 75/0, 100/0, 120/0	263/258	10/10/00	130/0	CC2 control set at 303K
25/25, 50/50, 60/60, 65/65, 70/70, 75/75, 80/80, 85/85, 90/90, 65/65, 50/50	263/258	10/19/00	70/70?	CC2 control set at 303K
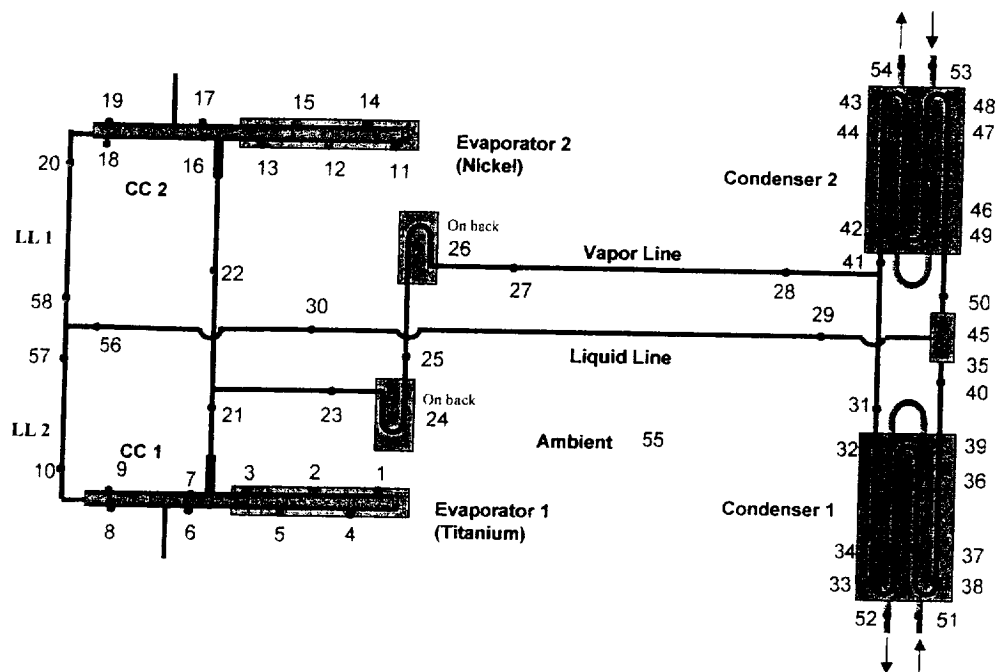
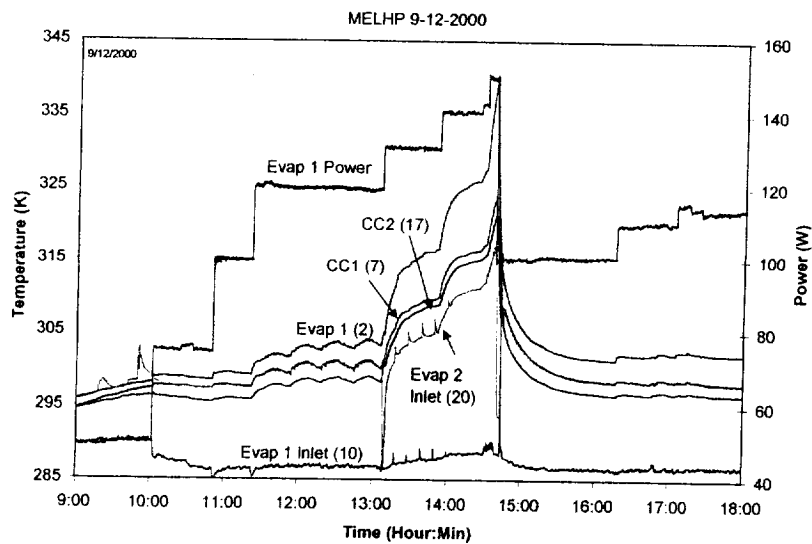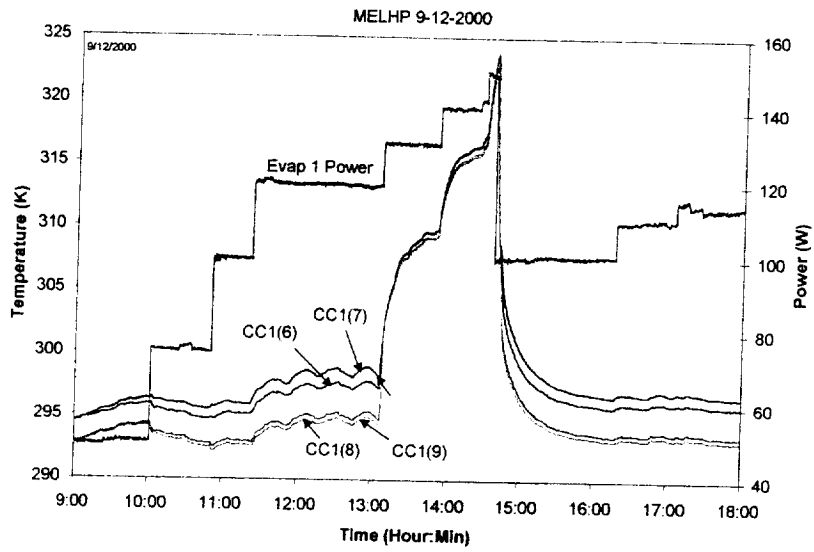Figure 5. Schematic of a Loop Heat Pipe with Two Evaporators and Two Condensers
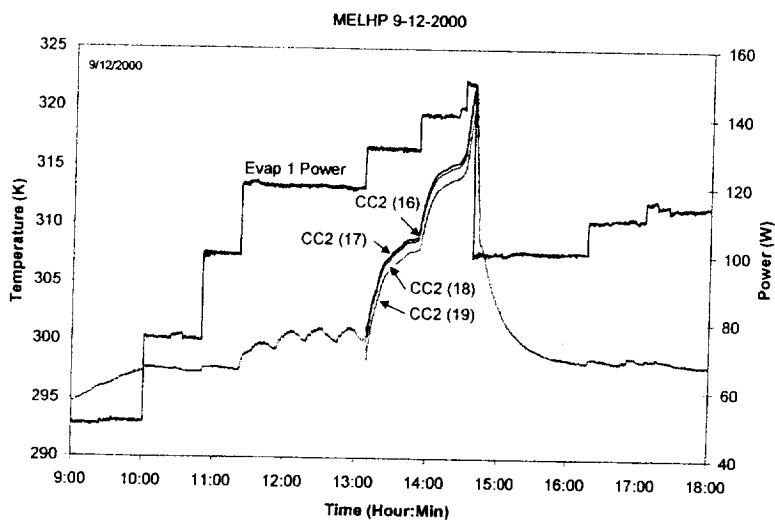

Figure 6
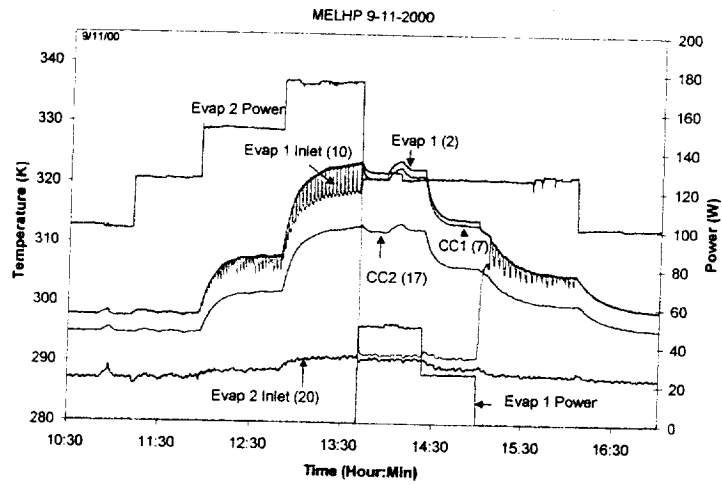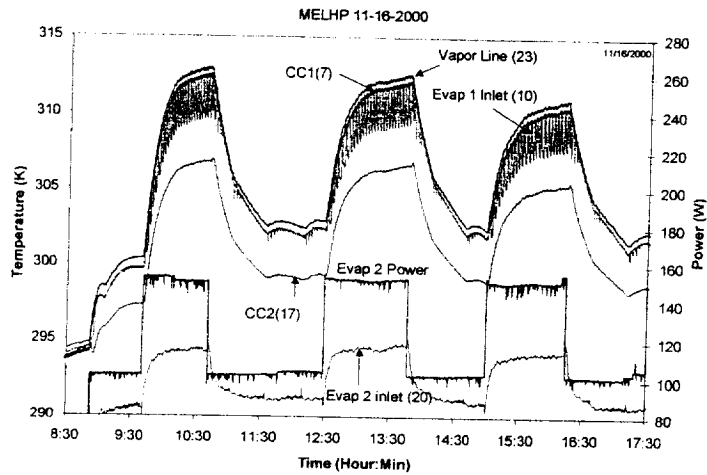
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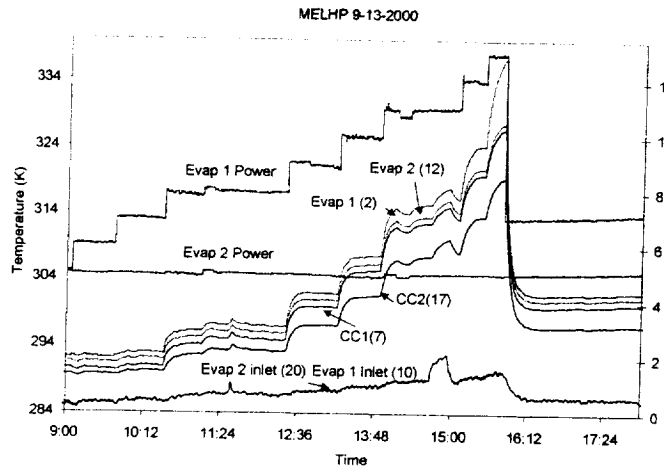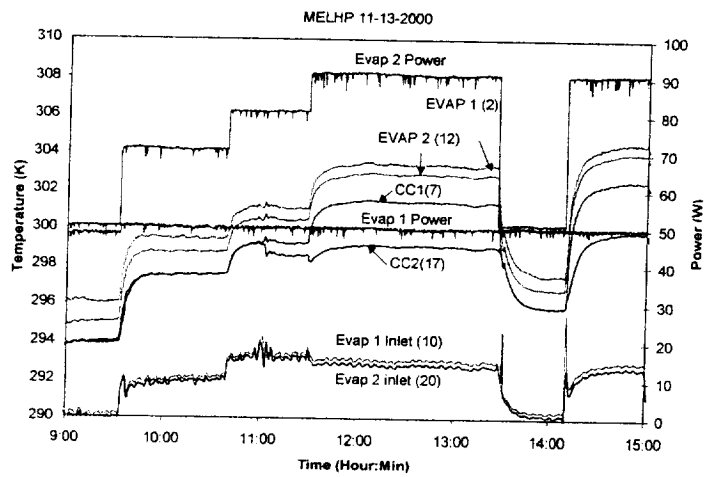Figure 7

MELHP 9-12-2000
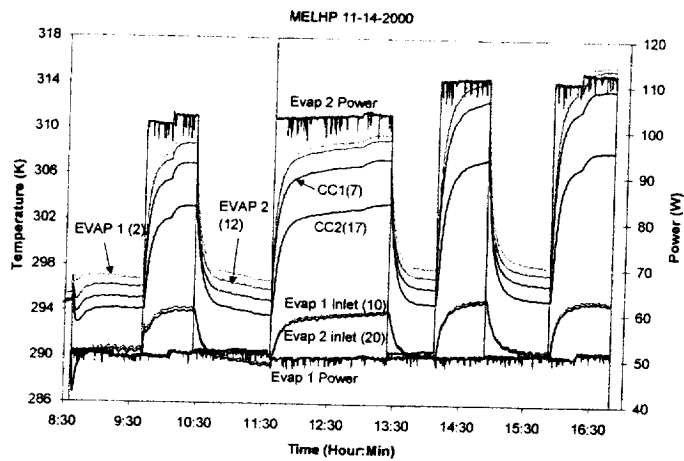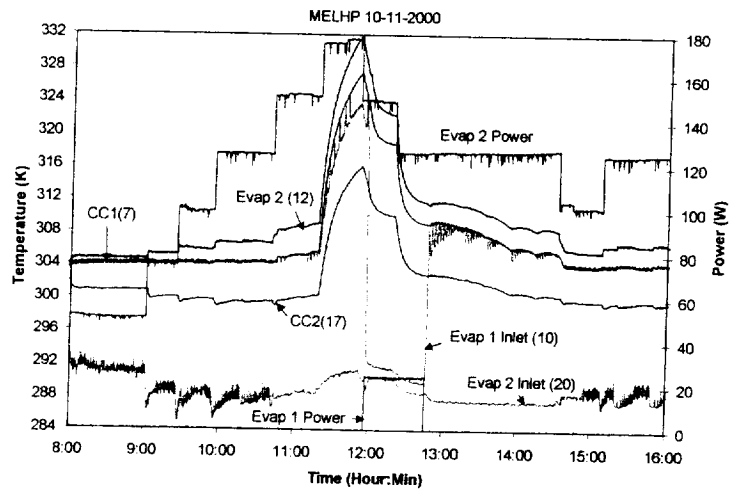
Figure 8.

Figure 9.

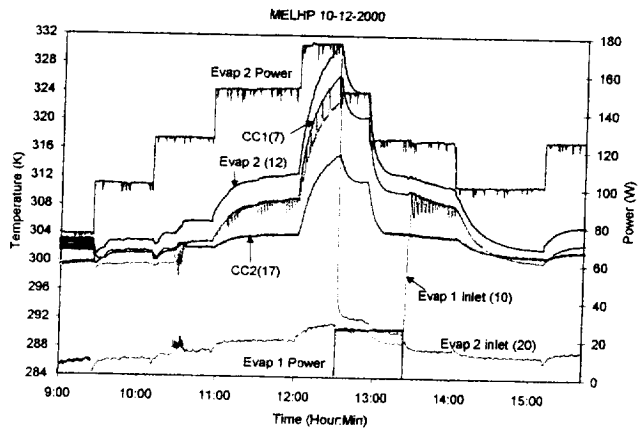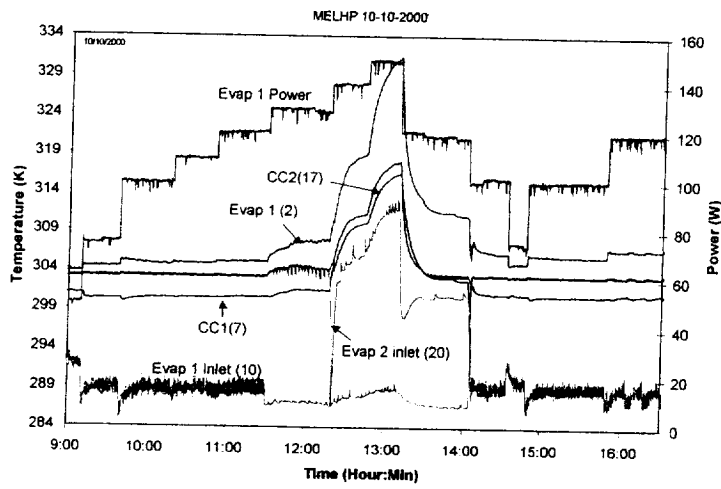Figure 10.

Figure 11.

Figure 12

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Figure 13.

Figure 14.

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Figure 15.

Figure 16

Figure 17

Figure 18.

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