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Loop Heat Pipe for Spacecraft Thermal Control, Part 2: Ambient Condition Tests

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Detailed results are presented of two ground-based tests carried out in September 1999 under ambient conditions (room temperature air and atmospheric conditions) to determine the thermal characteristics of loop heat pipes (LHP). One test (test 1) was carried out to quantify the effects that heat leaks have on the operational characteristics of the loop. In test 1, at various evaporator primary input power levels, auxiliary heating was applied to simulate heat leaks into the system. The intentional heat inputs representing heat leaks were located at the liquid return line and the compensation chamber. A second test (test 2) was conducted to verify the feasibility of temperature control of the LHP. Test 2 is motivated by the observation that it is desirable to control the temperature of an LHP to set the operating temperature for the system to which the LHP is attached. Test 1 revealed that the LHP is a robust device that can continue operation while subjected to auxiliary heating of the compensation chamber up to 20% of primary input power and slightly more for auxiliary heating of the liquid return line. The loop automatically compensates for this additional heat input by increasing the operating temperature of the loop and decreasing the active length of the condenser, thereby devoting more condenser length to the subcooler. Eventual failure of the loop is experienced when no more length can be dedicated to the subcooler, a significant amount of vapor bubbles return through the liquid return line, and inadequate amounts of liquid reach the wick for evaporation. This is an important realization when considering the location of the LHP in actual applications. Test 2 showed that LHP temperature control is indeed feasible and power efficient. It can be a viable alternative to payload global heaters, which essentially replace the payload power that is shut off with an adequate amount of heater power to maintain appropriate temperatures and may require a hundred times more power for the same effect. As in Part 1, both tests have been conducted with a view for application in spacecraft thermal control.

Nomenclature

Q = heat, W
T = temperature, °C, K
T_{cc} = compensation chamber temperature
T_{co} = condensor temperature
T_{db} = dual bore pipe temperature
T_{evap} = evaporator temperature
T_{lrl} = liquid return line temperature
T_{sat} = saturation temperature

Subscripts

cc = compensation chamber
co = condenser
db = dual bore
evap = evaporator
lrl = liquid return line
sat = saturated

Introduction

AS stated in Part 1 of this paper,[1] we have carried out extensive ground-based and outer space testing to understand and predict loop heat pipe (LHP) behavior with a view for application in spacecraft thermal control.[2–6] The ground-based tests included two performed in a thermal vacuum chamber described in Part 1[1] and two more under ambient conditions that are described in this paper. We have numerically modeled the vacuum chamber test, and this is described in Part 3.[3] The space-based tests were conducted aboard the space shuttle STS-87 in 1997 and are described in Part 4.[4] In this paper (Part 2), we present results and discussions of the tests carried out under ambient conditions. In Part 1,[1] we have provided a detailed introduction to the LHP, and in this paper we will not repeat that for the sake of brevity. Also, the contributions to LHP literature made in Refs. 7–21 are discussed in Part 1.[1]

The ground-based tests under ambient conditions described in this paper were conducted in September 1999 at what is now Boeing Satellite Systems, El Segundo, California, under ambient conditions: room temperature air and atmospheric conditions. The acknowledgment of the impact heat leaks into the system had on the LHP performance was made apparent by the study described in Part 1.[1] Briefly, test 2, carried out in a vacuum chamber and described in Part 1, clearly showed the effects of zone-to-zone heat leaks and indicated that the LHP condensers could have significant impact on each other. The data presented there also showed that an LHP condenser can have significant effects on itself where cold portions of the condenser lines have been located in the vicinity of hot portions, essentially reducing the amount of subcooling and raising the operation temperature of the LHP. These observations made it desirable to quantify systematically the effects that heat leaks have on the operational characteristics of the loop, and the first test described here was conducted primarily to investigate this effect. In test 1, reported in the present paper, at various evaporator primary input power levels, auxiliary heating was applied to simulate heat leaks into the system. Using one LHP of the previous ground-based two LHP/deployable radiator test,[1] we have investigated the effects of auxiliary heating, that is, intentional heat input representing heat

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leaks at the liquid return line and compensation chamber. The compensation chamber is indeed an ideal location for the heater because the compensation chamber sets the operating temperature of the loop. Any change in temperature of the compensation chamber will have an effect on the overall saturation temperature of the LHP. Furthermore, when compared to the heater located on the compensation chamber, heaters on the liquid return line required more power for the same temperature increase.

A second test (test 2) was conducted to verify the feasibility of temperature control for the LHP, essentially thermostatically controlling the temperature of the LHP, and this is described in a later section of the present paper. We note that it is desirable to control the temperature of an LHP to set the operating temperature for the system to which the LHP is attached. Often times, heaters are required to maintain satellite system temperatures above a specified minimum temperature, or to maintain a constant temperature throughout the life of the system. This may be attained by large amounts (∼2000 W) of heater power being placed throughout the system, or alternatively, by a small amount of heater power (∼20 W) being placed on the compensation chamber of the LHP. Because the LHP option represents such significant savings in power and enables close regulation of temperature, it is desirable to design the thermal control of the system around the LHP. This offers a very attractive alternative to significantly higher payload global heaters. Test 2 described in this paper was conducted to investigate this concept and gain a better understanding of the process. Next we provide the details of the first test.

Test 1: Effects of Auxiliary (Liquid Return Line/Compensation Chamber) Heating

As noted earlier, this test is conducted to quantify the effects of heat leaks on the operational characteristics of the loop.

Test Description

The objectives of this test were 1) to determine the effect of auxiliary heating on the LHP (impact on operating temperature as a function of auxiliary heat input), 2) to compare the impact of auxiliary heating at the liquid return line vs the compensation chamber, 3) to determine the location of the liquid–vapor front as a function of auxiliary heating, and 4) to determine the amount of heat necessary to shutdown (stop operation of) the LHP.

The test utilized the equipment from the test described in Part 1[1]; however, only the upper LHP (LHP1) was made operational and the dual-bore heat pipe mounted to the upper flange of LHP1's evaporator was removed. Thus, the test consisted of one LHP whose evaporator, compensation chamber, and transport lines were well insulated from the environment using Rubatex (trademark of RBS industries, Inc.) insulation material. Care was taken to minimize heat transfer between the evaporator and compensation chamber. The condenser was bonded to a simulated deployable radiator in a serpentine fashion (Fig. 1). The deployable radiator was able to reject heat from both its frontside and backside to the ambient (room temperature) environment. The lower portion of the radiator previously dedicated to LHP2 in test 1, described in Part 1, was insulated on both sides with Rubatex to prevent an increased radiator area for the upper zone. The modes of heat rejection from the upper zone were by convection and radiation. The working fluid of the LHP was ammonia, and the body was aluminum and stainless steel.

Heat was supplied to the evaporator via a conventional dual-bore heat pipe mounted to the lower flange of the evaporator. The dual-bore heat pipe received its heat from Chromalox heaters mounted to its lower flange. Heat was supplied to the lower flange so that we were ensured of supplying it to the liquid at the wick surface rather than to the vapor. Note that at 0 g, this location would be liquid on all surfaces of the wick. These heaters provided the primary heat input to the LHP and were capable of supplying up to 1100 W of heat. Two other heaters were installed in the setup: one on the compensation chamber and one on the liquid return line. These heaters were Kapton® patch heaters and were capable of supplying 50 W of heat at each location. Each heater circuit (dual bore, compensation chamber, liquid return line) was controlled manually. There was the capability for thermostatic control; it was not used for this portion of the tests but will be discussed for the next test (test 2).

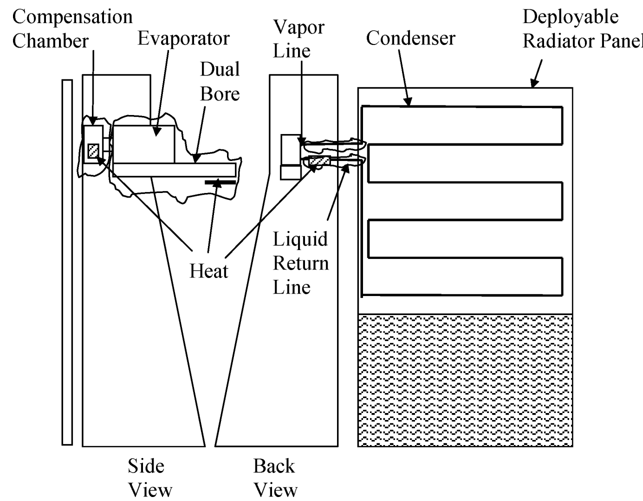

Fig. 1 Auxiliary heating test setup.

The test setup was instrumented with 60 type E thermocouples. All critical components had sensors installed; evaporator (3), dual-bore heat pipe (3), condenser and deployable radiator (36), compensation chamber (4), vapor line (1), liquid line (2), chromalox heaters (3), insulation (3), and ambient air temperature (2). Locations of the temperature sensors are shown in Fig. 2. Note that the liquid return line thermocouples are located before and after the liquid return line heater.

Data acquisition was accomplished using LabView software. Temperature and power were read continuously and were nominally saved to disk every 60 s. The save to disk rate was selectable, and data saves were conducted more frequently during highly transient events (such as just before shutdown of the loop caused by too much auxiliary heating). Temperature was recorded to the nearest 10th of a degree; heater data included power, voltage, and current.

Heater operation was manually controlled for each test step. Tests were conducted at 30, 40, 50, and 100 W of primary input power at the evaporator. At each of these input powers, auxiliary heat was first input at the liquid return line. This auxiliary heat was stepped up from 1 W systematically to the point where it caused the LHP to stop operating. At each step, steady state was achieved before moving to the next auxiliary power level. The same process was then repeated at each primary input power with the auxiliary heat being supplied at the compensation chamber and systematically increased until operation ceased.

No attempt was made to control the ambient environment or the convection occurring from the deployable radiator. This means that the room temperature or convective conditions could have varied due to external influences such as air conditioning or heating cycling on or off, but no detrimental effects of these types were observed.

Results of Test 1

Theoretically, the LHP could react to the additional heat in two ways: 1) extend the length of the active (two-phase) condenser to allow increased heat rejection at the same operating temperature or 2) raise the operating temperature of the LHP. Results of each test step are shown in Figs. 3 and 4. T_{sat} is measured along the first rung of the condenser [thermocouples (TCs) 1–3] and liquid return line temperature is measured at TC 33. Figure 3 shows additional heat input caused an increase in operating temperature of the loop. It also caused a position change of the liquid–vapor interface in the condenser, reducing the length of active condenser (Fig. 4). The data for Fig. 4 are obtained by noting the location of the liquid–vapor front, indicated by a significant decrease in temperature between two TC locations. This combination, temperature increase with reduction in active condenser, shows that the LHP is rejecting the input heat from a shorter length of condenser at a higher temperature,

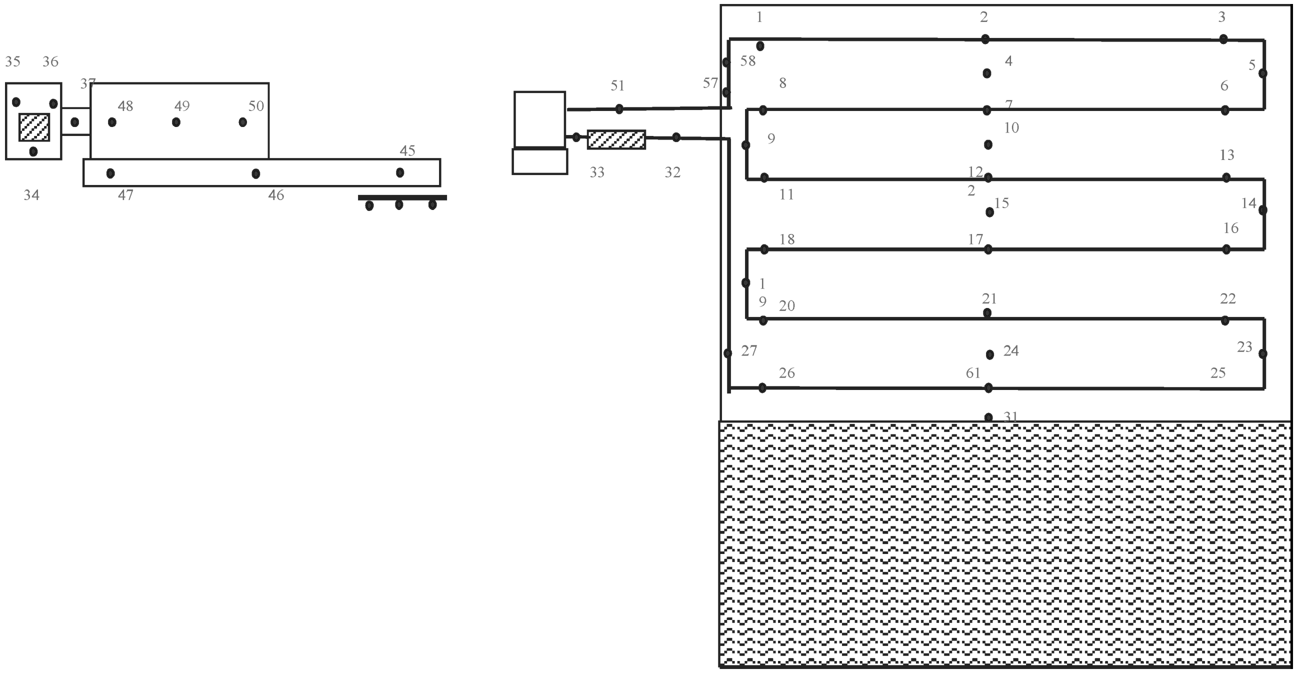

Fig. 2 Auxiliary heating thermocouple locations.

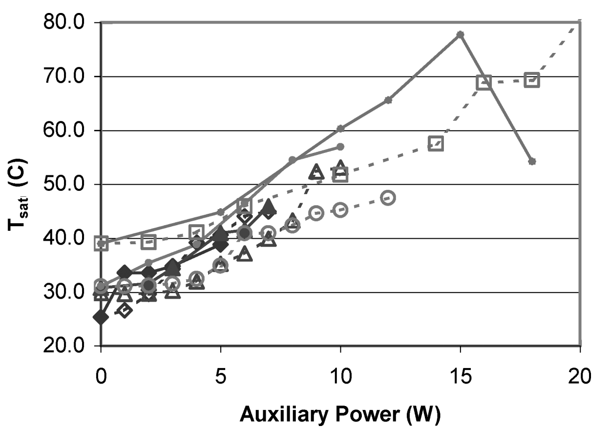

Fig. 3 T_{sat} vs auxiliary power: ◆, $Q_{in} = 30$ W, CC; ◇, $Q_{in} = 30$ W, LRL; ▲, $Q_{in} = 40$ W, CC; △, $Q_{in} = 40$ W, LRL; ●, $Q_{in} = 50$ W, CC; ○, $Q_{in} = 50$ W, LRL; ■, $Q_{in} = 100$ W, CC; and □, $Q_{in} = 100$ W, LRL.

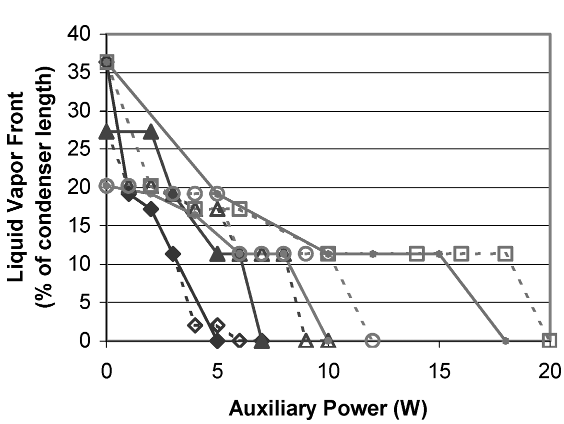

Fig. 4 Liquid vapor front location vs auxiliary power: ◆, $Q_{in} = 30$ W, CC; ◇, $Q_{in} = 30$ W, LRL; ▲, $Q_{in} = 40$ W, CC; △, $Q_{in} = 40$ W, LRL; ●, $Q_{in} = 50$ W, CC; ○, $Q_{in} = 50$ W, LRL; ■, $Q_{in} = 100$ W, CC; and □, $Q_{in} = 100$ W, LRL.

Table 1 T_{lrl} exceeding T_{sat}

Primary power, W	LRL auxiliary power, W	T_{sat}, C	T_{lrl}, C
30	5	40.9	41.0
30	6	44.4	44.6
40	3	30.3	30.5
40	4	32.0	32.3
40	5	35.2	35.4
40	6	37.2	37.4
40	7	39.8	40.0
40	8	43.2	43.4
40	9	52.4	54.4
50	7	40.8	41.0
50	8	42.2	43.3
50	9	44.1	44.8
50	10	45.1	45.4

thus, leaving more of the condenser to use as a subcooler. This addition of subcooler length must compensate for the auxiliary heat input. One generally accepted operating constraint of the LHP is the requirement for adequate subcooling of the liquid returning to the compensation chamber. However, previous work has shown that an LHP may successfully operate with a slightly saturated returning fluid,[2,4–6] and this test again supports that theory (Table 1). The LHP, when subjected to auxiliary heating, will attempt to increase the portion of the condenser dedicated to subcooling and thereby return a fluid at a temperature capable of offsetting the additional heat. Obviously, there is a finite length to the condenser line and the liquid–vapor front can only be pushed back so far. Once the liquid–vapor front has moved to the beginning of the condenser (position 0 in Fig. 4), the LHP cannot offset any further increase in auxiliary heating. At this point, significant amounts of vapor will be introduced to the core of the wick and operation of the LHP will cease.

When the primary input power (at the evaporator) is compared to the auxiliary heat required to shutdown the loop, it becomes apparent that this amount is essentially a constant percentage of the primary heat input (Table 2). The percentage varies slightly between liquid return line heating and compensation chamber heating, with the LHP able to handle slightly more liquid return line heating as a percentage of primary heat input.

Table 2 Auxiliary power required for shutdown

Primary input power, W	Heater power at shutdown, W	% of input power
	LRL	
30	7	23
40	9	23
50	12	24
100	20	20
	CC	
30	5	17
40	7	18
50	10	20
100	18	18

It would be expected that the amount of auxiliary heat that can be handled would increase with increasing primary input power because the amount of subcooling that can be achieved is greater, and the mass flow rate increases with increasing primary input, leading to a greater rate of cooling at the heated areas.

The data from this experiment show that the LHP can handle some auxiliary heat input at the compensation chamber (up to 18% of primary input power) and at the liquid return line (up to 22% of primary input power). The LHP's response to increasing auxiliary heat input is to increase operating temperature, shorten active (two-phase) condenser length, and dedicate more condenser length to subcooling. There is also evidence that the loop can operate when there is nonsubcooled (saturated) fluid returning to the compensation chamber. In many cases where liquid return line heating is applied, it can be seen in Table 1 that the temperature of the fluid exiting the liquid return line (LRL) is above the saturation temperature of the loop, indicating nonsubcooled fluid returning to the compensation chamber. It is proposed that the LHP can operate with low-quality fluid returning to the compensation chamber (CC); however, as auxiliary heat input increases, the vapor bubbles present in the returning fluid become excessive, not enough liquid is supplied to the wick, and subsequent dryout and shutdown occur.

Conclusions Based on Test 1

This experiment has proven that the LHP is a robust device that can continue operation while subjected to auxiliary heating up to 20% of primary input power. The loop will automatically compensate for this additional heat input by increasing the operating temperature of the loop and decreasing the active length of the condenser, thereby devoting more condenser length to the subcooler. Eventual failure of the loop is experienced when no more length can be dedicated to the subcooler, a significant amount of vapor bubbles return through the LRL, and inadequate amounts of liquid reach the wick for evaporation.

This is an important realization when considering location of the LHP in actual applications. It implies that the operating temperature of the LHP can be impacted by the environment of the CC and LRL. If the LHP is to be placed in or near a hot environment, care should be taken to minimize thermal interactions between the CC and LRL and this hot environment, or alternatively, the impact of these interactions should be well understood and considered during the system-level design phase. The experimental uncertainty in this test is $\pm 3^{\circ}$C based on thermocouple sensitivity and data acquisition accuracy.

Test 2: Temperature Control

The theory behind temperature control of the LHP is that the two-phase CC sets the operating temperature of the loop, and knowing this, it should be possible to thermostatically control the temperature of the CC and, in turn, control the temperature of the loop and whatever components might be attached to the LHP. This can be accomplished by installing a heater directly on the CC body or by supplying heat to the LRL. The heater power required for this control would be significantly less than would be necessary to control an entire spacecraft payload by conventional global heaters placed on and around the payload units (20 vs 2000 W). Because this option represents such significant savings in power and enables close regulation of temperature, it was very attractive at a system level as an alternative to significantly higher power payload global heaters, and a ground test was designed and conducted to test out the concept.

Test Description

The objectives of the test were 1) to prove the feasibility of the temperature control concept, 2) to determine the optimum heat input location, 3) to determine the necessary heater power for adequate control, 4) to determine the optimum temperature control point, 5) to determine necessary sampling rate for temperature control to ensure stable LHP behavior, 6) to simulate on-orbit conditions (power cycles), and 7) to simulate anomalous condition (rapid power steps).

The equipment used was identical to that used for the auxiliary heating ground test described in the preceding section (Fig. 1, test 1). It was conducted in September 1999, at what is now Boeing Satellite Systems, El Segundo, California, under ambient conditions. Test instrumentation and data acquisition were also the same as for the auxiliary heating test (Fig. 2, test 1). The additional capability of thermostatic control was programmed into the LabView software. This logic allowed the on/off status of the auxiliary heaters on the LRL and CC to be controlled based on the temperature of the CC, temperature of the evaporator, or temperature of the dual-bore heat pipe mounted to the LHP evaporator. The heater control was a simple thermostatic routine that commanded the auxiliary heaters either full on or full off. This is the simplest approach that can be employed in spacecraft applications and worked well. The heat input zone was selectable; heat could be input at the CC body or at the LRL just before the fluid returning to the CC.

Results of Test 2

The first step of this test was to obtain a characterization plot, that is a plot of operating temperature vs primary input power with no auxiliary heating. This gave a baseline of nominal LHP operation for the test conditions. Primary input powers were increased from a minimum of 50 W through a maximum of 700 W. The characterization is shown in Fig. 5. Note in Fig. 5 the variable conductance regime indicated by the constant evaporator temperature between 200 and 400 W. This is where the condenser is not yet fully open and increased heat input is accommodated by increasing the active condenser length. In this way the heat rejection area is increased and more power can be rejected at the same temperature as the previous lower power step. This increasing of condenser length continues until the liquid–vapor front is at the exit of the condenser, that is, the condenser is fully open. Once the condenser is fully open (500 W), a constant conductance mode of the LHP is obtained and further increases to the input power cause an increase in the operating temperature of the loop. Both of these regimes, variable conductance and constant conductance, were identified as areas where testing of temperature control would be conducted. Based on Fig. 5, primary input powers were selected for further testing as 300 and 700 W.

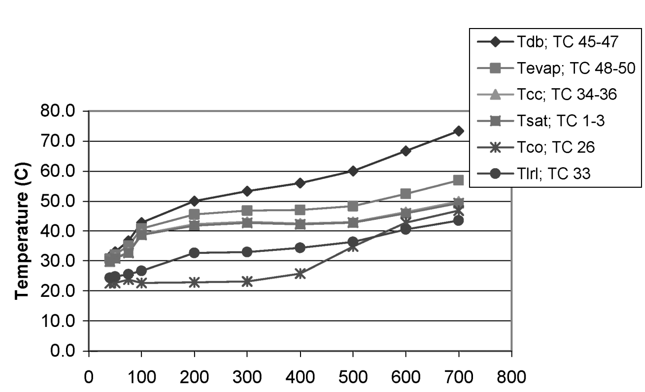

Fig. 5 Characterization plot.

The second step was to gain some baseline data on the effects of different levels of auxiliary heating at the selected primary input powers. This information would be used to select the optimum auxiliary heater power for the temperature control portion of the test. For this, the primary input power was set, that is, 300 or 700 W, and the auxiliary heat input was systematically increased, first at the LRL, then at the CC, and the effects of the auxiliary heat input were recorded at each step. Figure 6 shows the dual-bore temperature increase as a function of auxiliary heat input power and input location. Note that in Fig. 6 the temperature increase for the 500-W CC heating case is above the 300-W CC heating case. At the outset it appears that this observation is not consistent with the LRL results. However, note that the 300-W input case represents LHP operation in the nonlinear regime (not fully opened condenser). It is postulated that being in the nonlinear regime causes the 300-W case to behave differently between CC heating and LRL heating. Figure 7 shows the temperature effect on the different components of the LHP as a function of auxiliary heat input power and input location for a primary input power of 300 W. It can be seen that the CC heater has a much larger effect on temperatures than the LRL heater.

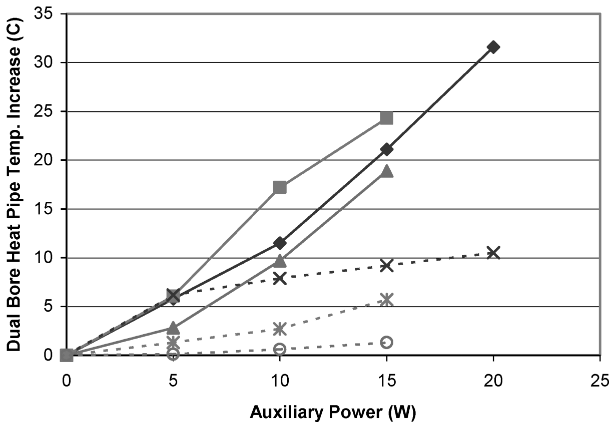

Fig. 6 Dual-bore heat pipe temperature as a function of auxiliary heat input: ◆, $Q_{in} = 300$, CC; ■, $Q_{in} = 500$, CC; ▲, $Q_{in} = 700$, CC; ×, $Q_{in} = 300$, LRL; ∗, $Q_{in} = 500$, LRL; and ○, $Q_{in} = 700$, LRL.

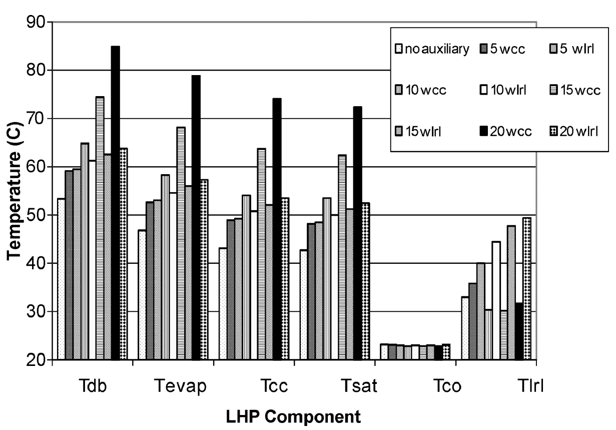

Fig. 7 Impact on components of LHP of auxiliary heat input; 300-W primary input power.

Results are also given in Table 3. The experimental uncertainty in this test is $\pm 3°C$ based on TC sensitivity and data acquisition accuracy. From this information, auxiliary heater powers and location could be selected for the temperature control portion of the test based on the desired response. For example, for a given primary input power, for example, 300 W, and a desired temperature response, for example, $\Delta T = +10°C$, a sufficient auxiliary heater power could be selected from the previously gathered data. With use of this approach, various temperature control tests were performed at different primary input power levels, different auxiliary input power levels, different temperature control points, and different auxiliary heat input locations.

In regard to the sampling rate objective, although we did test different sampling rates, they have not been included in detail here. In general, a 30-s sampling rate was determined to be appropriate for temperature control with the tested LHP, allowing smooth temperature control with no feedback issues.

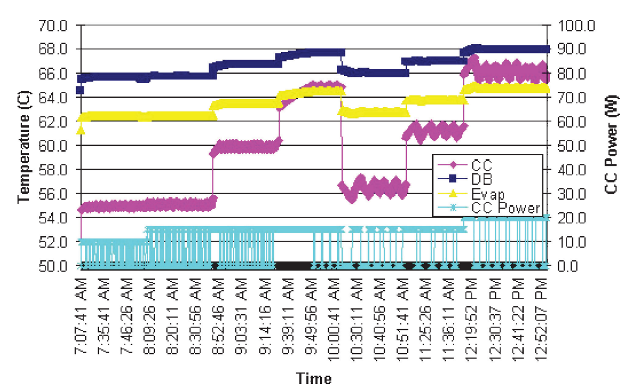

Fig. 9 Temperature control of LHP; 700-W primary input power.

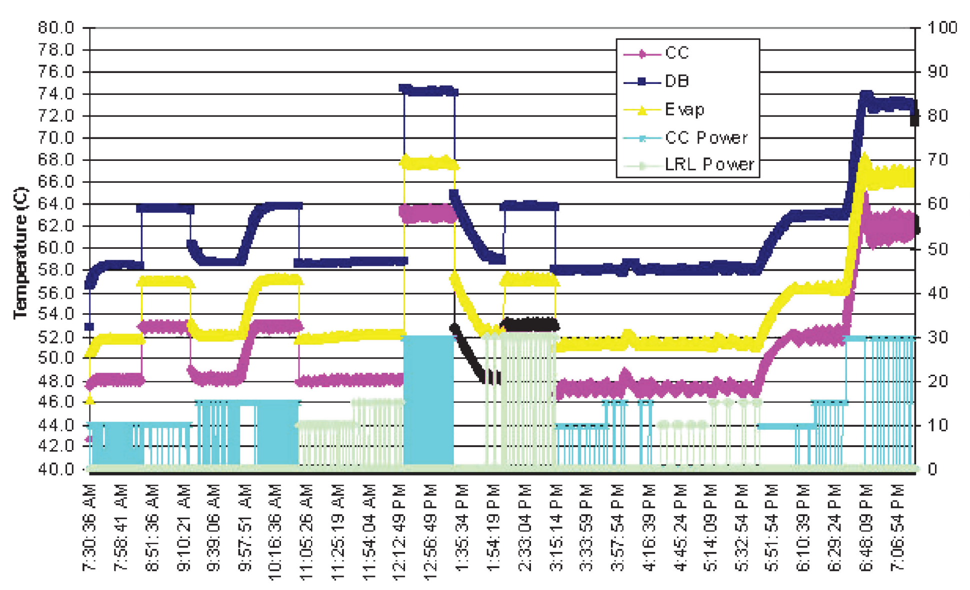

Fig. 8 Temperature control of LHP; 300-W primary input power.

Table 3 Impact of auxiliary heating on LHP

Auxiliary power, W	Input power, W	T_{db}, °C	T_{evap}, °C	T_{cc}, °C	T_{sat}, °C	T_{co}, °C	T_{lrl}, °C	Increase to dual bore, °C	Increase to evaporator, °C	Increase to CC, °C
CC_{heat} 0	300	53.3	46.8	43.1	42.7	23.2	33	0	0	0
CC_{heat} 5	300	59.1	52.6	48.9	48.2	23.1	35.8	5.8	5.8	5.8
CC_{heat} 10	300	64.8	58.3	54.1	53.5	22.9	30.4	11.5	11.5	11
CC_{heat} 15	300	74.4	68.2	63.7	62.4	22.9	30.2	21.1	21.4	20.6
CC_{heat} 20	300	84.9	78.8	74.1	72.4	22.9	31.7	31.6	32	31
LRL 0	300	53.3	46.8	43.1	42.7	23.2	33	0	0	0
LRL 5	300	59.5	53	49.2	48.5	23.0	40.	6.2	6.2	6.1
LRL 10	300	61.2	54.6	50.8	50	23	44.5	7.9	7.8	7.7
LRL 15	300	62.5	56	52.1	51.2	23	47.7	9.2	9.2	9
LRL 20	300	63.8	57.3	53.5	52.5	23.1	49.4	10.5	10.5	10.4
CC_{heat} 0	500	60	48.3	43	42.8	34.8	36.4	0.0	0.0	0
CC_{heat} 5	500	66.1	54.6	49.1	48.6	25.8	36.6	6.1	6.3	6.1
CC_{heat} 10	500	77.2	65.9	59.8	59.2	23.4	37.6	17.2	17.6	16.8
CC_{heat} 15	500	84.3	73.1	66.7	66.1	23.1	35.3	24.3	24.8	23.7
LRL 0	500	60	48.3	43	42.8	34.8	36.4	0.0	0.0	0
LRL 5	500	61.3	49.7	44	43.7	29.1	37.9	1.3	1.4	1
LRL 10	500	62.7	51.2	45.6	45.1	27.7	41	2.7	2.9	2.6
LRL 15	500	65.7	54.2	48.7	48	26.3	44.4	5.7	5.9	5.7
CC_{heat} 0	700	73.3	56.9	49.8	49.3	46.8	43.5	0.0	0.0	0
CC_{heat} 5	700	76.1	59.9	52.5	52.1	31.3	38.8	2.8	3.0	2.7
CC_{heat} 10	700	83	67	59.4	59	26.1	37.4	9.7	10.1	9.6
CC_{heat} 15	700	92.2	76.3	68.6	68.1	24.5	38.6	18.9	19.4	18.8
LRL 0	700	73.3	56.9	49.8	49.3	46.8	43.5	0.0	0.0	0
LRL 5	700	73.4	57	50	49.5	41.4	44.1	0.1	0.1	0.2
LRL 10	700	73.9	57.6	50.5	50	38.1	44.8	0.6	0.7	0.7
LRL 15	700	74.6	58.4	51.2	50.7	36.3	46.3	1.3	1.5	1.4

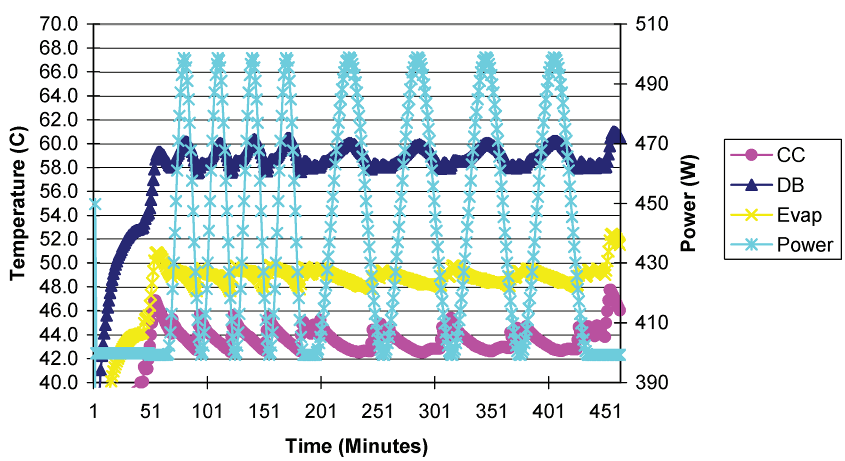

Fig. 10 Power cycles.

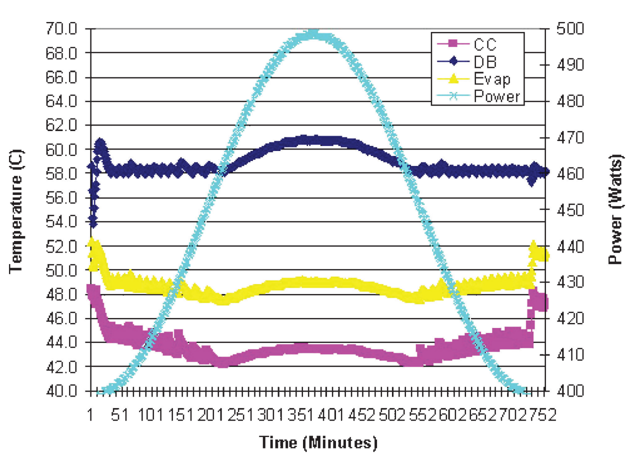

Fig. 11 Power ramp.

Figures 8 and 9 show results for constant primary input powers with other parameters varied [heat input location, setpoint, temperature control point, dual-bore set point (DBSP), and CC setpoint (CCSP)]. Figures 10 and 11 show power ramps/cycles as might be caused on-orbit by daily variation in solar loads. Finally, results shown in Figs. 12 and 13 show rapid power steps as might be experienced during an anomalous situation. All phases of the test were able to maintain the temperature control point at the prescribed setpoint temperature.

One interesting result occurred during the rapid power step test when the power was abruptly stepped down. During the initial power step test, the following parameters were used: a setpoint of 70°C, an auxiliary heater power of 15 W installed on the CC, and a primary input power, which started at 300 W, stepped up to 700 W, and then back down to 300 W. The thermostatic control was set slightly lower than the nominal operating temperature so that the LHP would be under necessary temperature control at a primary input power of 300 W, off temperature control at 700 W, and back on when the

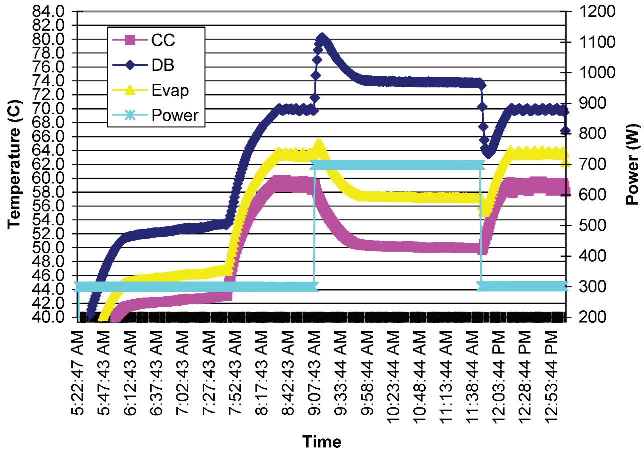

Fig. 12 Rapid power steps; CC heater = 15 W.

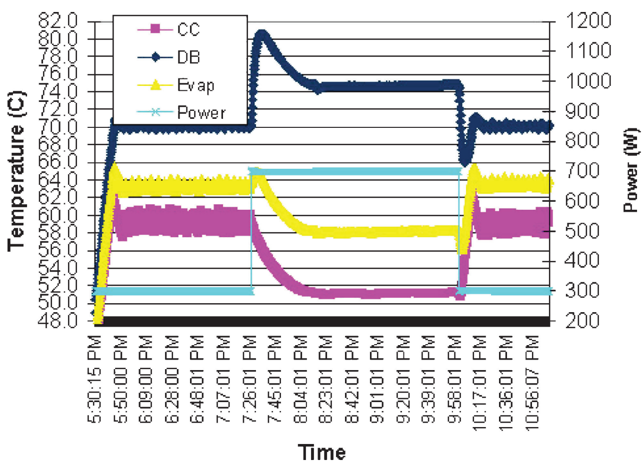

Fig. 13 Rapid power steps; CC heater = 30 W.

primary input power stepped back down to 300 W. The step up from 300 to 700 W went smoothly, and the heater cycled off as expected. During the step down to 300 W, the heater cycled on, but the fall in CC temperature was too rapid to be offset by the auxiliary heater. Subsequently the CC temperature dipped lower than the setpoint for a duration of 10 min until the auxiliary heater power was able to stop the fall. Eventually after 30 min, the CC temperature returned to its setpoint. To try to reduce the time spent under the setpoint temperature, the test was rerun with an auxiliary heater power of 30 W. The rapid drop in CC temperature is still apparent, but the duration of time spent under the setpoint temperature and the recovery time were both significantly reduced (Fig. 13). A reviewer has suggested that a properly designed proportional controller instead of an on/off controller would have improved the temperature control during power down. We note that although a proportional controller may be an improvement, the implementation would be more difficult for satellite onboard processor and heater. This test represents interesting data and reinforces that design conditions must be well understood. If the temperature-controlled LHP will be subjected to an operating condition with rapid power steps, this must be considered when selecting the appropriate auxiliary heater power level.

Conclusions

From the results of this ground-based LHP temperature control test, it was determined that LHP temperature control is indeed feasible and power efficient. It can be a viable alternative to payload global heaters, which essentially replace the payload power that is shut off with an adequate amount of heater power to maintain appropriate temperatures and may require a hundred times more power for the same effect. Data accumulated during the test can be used to select the optimum auxiliary heater power and the temperature control point. Results show that the CC is the optimum location for auxiliary heat input and that excellent temperature control is achievable in both the variable conductance and constant conductance regime of the LHP. One possible explanation as to why the CC heating is more effective than the LRL heating may be that the former allows more conduction through the wick. LRL heating delivers warm fluid to the inner core of the wick, thus, lessening the temperature differential between the outer surface of the wick and the inner surface and decreasing the heat leak into the working fluid. Here we are using the expression heat leak to denote heat transfer. The terminology heat leak has been commonly used in this technology, possibly based on experience in orbit when heat is thought to have leaked in through blankets or warm adjacent components and caused detrimental impacts to LHP operation. The CC heating heats the fluid in the CC, but the liquid returning to the core of the wick from the LRL is still relatively cool, resulting in a higher temperature differential and heat transfer through the wick. Therefore, although the auxiliary heat input may be the same at the two locations, the total heat leak into the CC is greater when heat is input at the CC and a larger heat leak is possible through the wick. This finding also supports that the CC and the inner core of the wick, usually considered as one volume at the same temperature, in fact may be at different temperatures and should be considered as such. This test represents an important step in greater understanding of LHP operation and capabilities and should serve to promote the temperature control aspect of the LHP.

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