Testing of A Loop Heat Pipe Subjected to Variable Accelerations
Part 1: Start-up

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ABSTRACT

The effect of accelerating forces on the performance of loop heat pipes (LHP) is of interest and importance to terrestrial and space applications. They are being considered for cooling of military combat vehicles and for spinning spacecraft. In order to investigate the effect of an accelerating force on LHP operation, a miniature LHP was installed on a spin table. Variable accelerating forces were imposed on the LHP by spinning the table at different angular speeds. Several patterns of accelerating forces were applied, i.e. continuous spin at different speeds and periodic spin at different speeds and frequencies. The resulting accelerations ranged from 1.17 g's to 4.7 g's. This paper presents the first part of the experimental study, i.e. the effects of a centrifugal force on the LHP start-up. Tests were conducted by varying the heat load to the evaporator, sink temperature, magnitude and frequency of centrifugal force, and LHP orientation relative to the direction of the accelerating force. The accelerating force seems to have little effect on the loop start-up in terms of temperature overshoot and superheat at boiling incipience. Changes in these parameters seem to be stochastic with or without centrifugal accelerating forces. The LHP started successfully in all tests.

INTRODUCTION

A loop heat pipe (LHP) is a two-phase heat transport device which transfers large amounts of energy over long distances with very small temperature differences. It was first invented in the former Soviet Unions about two decades ago [1]. Basic LHP operating principles can be found in References 1 and 2. LHP's offer many advantages over the traditional heat pipes and have gained rapid acceptance for space and terrestrial applications. A dozen of LHP's are currently in service on a commercial communications satellite; transferring about 10 kW of heat loads . The LHP is also the baseline for instrument thermal control of NASA's GLAS, SWIFT, GOES and EOS- Chemistry spacecraft. In addition, LHPs are being considered for use in combat vehicles and spinning nano-satellites, where the LHPs will be subjected to accelerating forces. An experimental study was conducted to investigate the effect of an accelerating force on the LHP operation. Specifically, the influence of variable accelerating forces on the LHP performance in terms of start-up, operating temperature, temperature stability, and robustness were experimentally investigated by installing a miniature LHP on a spin table. Variable accelerating forces were imposed on the LHP by spinning the table at different angular speeds.

This paper presents the first part of the experimental study, i.e. the effects of a centrifugal force on the LHP start-up. The second part of the study, i.e. effects on the loop operating temperature and temperature stability, are discussed in a separate paper. The remainder of the paper is arranged as follows: the test article and test set-up are presented first, followed by descriptions of various test conditions. Measured centrifugal and tangential accelerations are summarized. Effects of accelerating forces on the LHP start-up are discussed in detail, followed by some concluding remarks.

TEST ARTICLE

The article used for this study is a miniature LHP purchased by NASA/GSFC from the Dynatherm Corporation. Because of its small mass and size, this miniature LHP provides many advantages for the investigation of the effect of accelerations. The miniature LHP can easily be mounted on the spin table and oriented in different directions relative to the centrifugal force. A picture of the miniature LHP is shown in Figure 1.
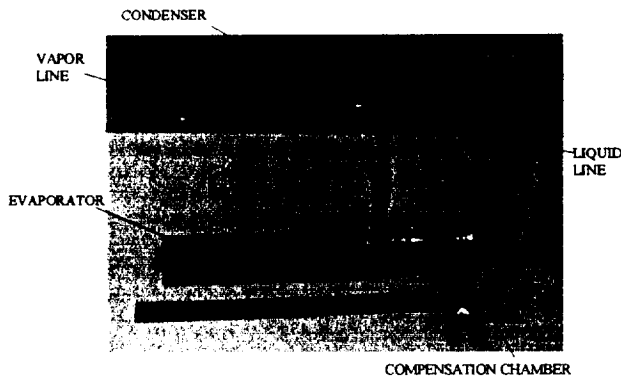

Figure 1. Picture of the Miniature LHP

The miniature LHP consists of an evaporator, a compensation chamber, a condenser, a vapor line and a liquid line. It is constructed primarily of aluminum and weighs less than 160 grams. Using ammonia as the working fluid, the unit has a heat transport capability of over 200 W. It can easily be positioned between a heat source and a heat sink.

Major design parameters are described below.

- Evaporator:
  - Envelope
    - Aluminum 6063
    - OD: 13mm, ID: 10 mm, length: 120 mm
  - Primary Wick
    - Sintered Nickel
    - OD: 10mm, ID: 4mm, length: 120mm
    - Pore Size: <1.2 microns
    - Permeability: 4×10^{-14} m^2
    - Porosity: 60%
    - Longitudinal and circumferential grooves
- Compensation Chamber
  - Envelope
    - Aluminum 6061/stainless steel 304L bimetallic
    - OD: 13mm, ID: 10mm, length: 30mm
  - Secondary wick
    - Stainless steel screen
    - 250 x 1400 mesh
    - Pore size: 15.4 microns
- Vapor line
  - Aluminum 6063 extrusion
  - OD: 15.2mm, ID: 2.8mm, length: 160 mm

- Liquid Line
  - Aluminum 6063 extrusion
  - OD: 15.2mm, ID: 2.8mm, length: 130 mm
- Condenser
  - Aluminum 6063 extrusion
  - OD: 15.2mm, ID: 2.8mm, length: 100 mm
- Working fluid
  - Anhydrous ammonia

TEST SET-UP

For testing, the LHP is contained in a box-like frame structure along with the heater and coolant blocks, as shown in Figure 2. The entire frame is mounted on the spin table and can be rotated so that the system can be tested in a number of different orientations.
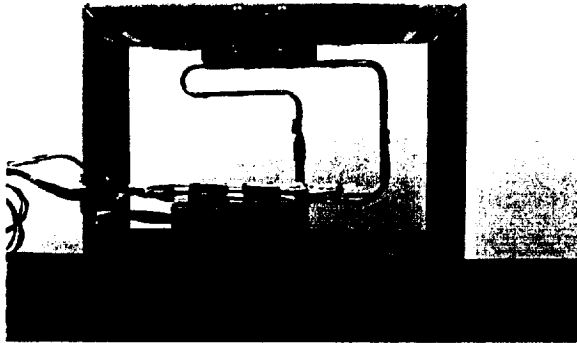

Figure 2 Miniature LHP in a Frame Structure

A spin table is used to generate the accelerating forces. The spin table consists of a motor and two spinning arms on opposite sides of the rotating axis, each about 1.5 meters (5 feet) long. The LHP is mounted near the end of one of the arms. The spin table can rotate at a speed between 0 to 1740 rpm over the full range. However, a Boston Gear speed reducer with a gear ratio of 15 to 1 is added to the test setup. The speed reducer provides additonal safety and very accurate control of the rotating speed. Although the maximum speed capability is 116 rpm, the maximum rotating speed tested is limited to 60 rpm. A control panel and software are used to provide inputs to the motor controller which drives the spin table motor. The control panel provides a lock-out mechanism so that the table does not spin when people are near the table. Labview software is used to control both the spin rate and the spin direction. An accelerometer is used to measure either radial or tangential acceleration while the system is spinning. A tachometer mounted on the stationary portion of the spin table is used to measure rotation speed.

A copper heater block is bolted to the evaporator flange, and thermal grease is used as the thermal interface material between the heater block and the evaporator flange. A cartridge heater with the capability of 0 to 500 W is embedded inside the heater block. Power measurements are made using a watt transducer that is located near the spin table. Power is supplied to the evaporator heater through slip rings on the spin table. A thermostat is installed on the heater block to prevent temperature excursion. The data acquisition software also provides relay control if any temperature exceeds the pre-set limit.

A stationary refrigerator provides the necessary cooling for the condenser. Two coolant circulating loops are employed, using a reservoir as the interface. A stationary loop delivers the coolant from the refrigerator to the reservoir, which is mounted around the spin axis. A second loop, which rotates with the test article, delivers
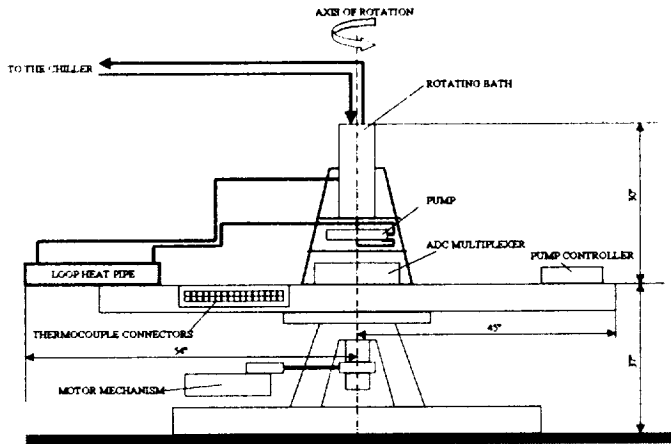
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Figure 3 Schematic of the Miniature LHP Test Set-up

coolant from the reservoir to the LHP condenser. A copper cooling block is attached to the condenser section of the LHP. A mechanical pump is used to circulate coolant through two parallel passes in the cooling block.

Fifty-three type T thermocouples are used to monitor the temperatures of the loop. The temperature data is collected on a data logger mounted to the spin table. The RS-232 output of this data logger is fed through three slip rings to a data acquisition system. The data acquisition system, which consists of two data loggers, a screen monitor, and a personal computer, is used to record, display, and store the data. The data is updated every second on the screen and can be stored at any rates of multiple seconds.

A schematic of the test set-up is shown in Figure 3 and locations of the thermocouples are shown in Figure 4.
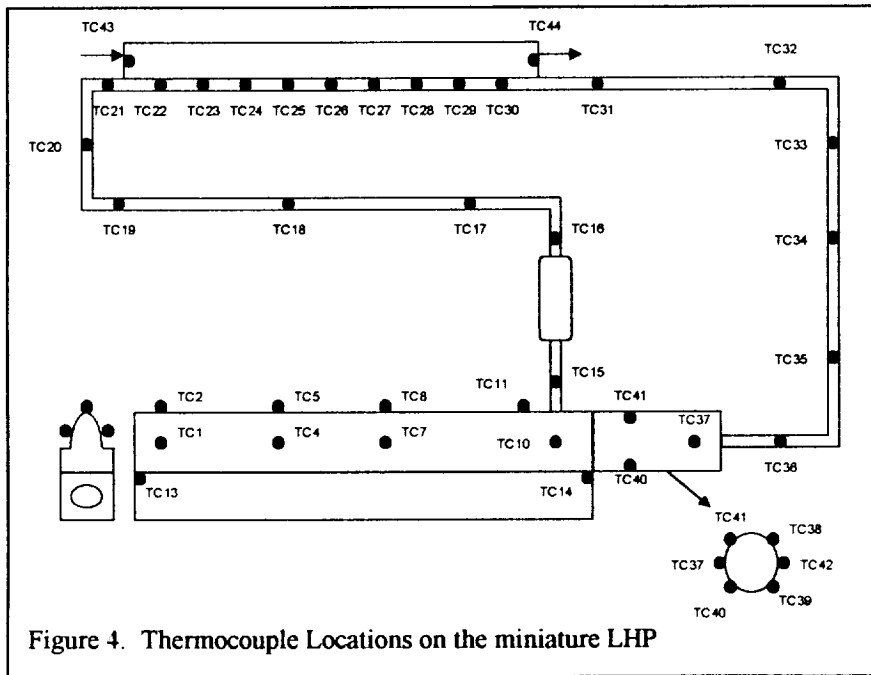

Figure 4. Thermocouple Locations on the miniature LHP

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TEST CONFIGURATIONS

The main purpose of subjecting the test article to an accelerating force is to investigate the effect of body forces on the LHP operation. There are three possible forces acting on the LHP during rotation. The first is the gravitational force, which is always present. The second is the centripetal force acting in the radial direction. This force exists as long as the spin table rotates. The third is the tangential acceleration that is perpendicular to the centrifugal force. This force exists only during transients when the spin rate changes. The forces acting on the LHP depend on how the LHP is oriented. Tests were conducted with the following five different configurations.

- Configuration A: The axis between the evaporator and the compensation chamber is aligned with the direction of the centrifugal force, and the compensation chamber and the liquid line are placed at the outer edge of the spin table.
- Configuration B: The axis between the evaporator and the compensation chamber is aligned with the direction of the centrifugal force, and the evaporator and vapor line are placed at the outer edge of the spin table.
- Configuration C: The axis between the evaporator and the compensation chamber is parallel to the gravitational force with the evaporator above the compensation chamber. The spin table is stationary.
- Configuration D: The axis between the evaporator and the compensation chamber is parallel to the gravitational force with the evaporator below the compensation chamber. The spin table is stationary.
- Configuration E: The test article lies flat with the evaporator, compensation chamber and condenser all placed in a horizontal plane. The spin table is stationary.

SPIN PATTERNS

Under stationary condition, there are many variables in a start-up test, e.g. evaporator power and condenser sink temperature. The accelerating force adds another dimension to the test variables. Many parameters affect the accelerating force imposed upon the LHP, including spin rate and the way it spins. In order to make meaningful comparisons between different tests, some pre-determined spin patterns are necessary. The following spin patterns are used in this test program.

- Pattern 1: Stationary, 0rpm
- Pattern 2: Rotating at a constant speed of 30 rpm
- Pattern 3: Rotating at a constant speed of 60 rpm
- Pattern 4: A combination of Patters 2 and 3
- Pattern 5: Rotating at 30 rpm for 30 seconds followed by 0 rpm for 300 seconds, and repeat.
- Pattern 6: Rotating at 60 rpm for 30 seconds followed by 0 rpm for 300 seconds, and repeat.
- Pattern 7: A combination of Patterns 5 and 6.

START-UP TEST CONDITIONS

The main goal of this study is to investigate the functionality and reliability of the LHP operation under various accelerations. The most important LHP function to be verified is the start-up without which there will be no LHP operation. Test conditions for start-up are as follows.
- Chiller set point: $-20\ ^\circ C$ to $+25\ ^\circ C$
- Evaporator power: 5W, 25W, 50W, or 100W.
- Configuration: A through E
- Spin Pattern: 1 through 7

MEASUREMENTS OF ACCELERATIONS

An accelerometer was installed on the spin table to measure the magnitude of the accelerating force. Different tests were conducted to measure the centrifugal and tangential accelerations separately. The centrifugal force can be expressed as

$$a_r = (2\pi f)^2 r \qquad (1)$$

where a_r is the centrifugal acceleration, f is the spin rate (revolutions per second), and r is the distance from the center of the axis of rotation. The LHP extends from r = 1092mm to 1270mm (43 inches to 50 inches) with the accelerometer located at the mid-point with r = 1181 mm (46.5 inches). Thus the accelerating forces will differ by 15 percent on the LHP from end to end. At 30 rpm and 60 rpm, the theoretical accelerations at r= 1181 mm are 11.66 m/s^2 (1.19g's) and 46.624 m/s^2 (4.76 g's), respectively.

Figures 6 to 8 depict the measured centrifugal accelerations measured by the accelerometer at various spin rates. The measured accelerations are very close to the theoretical values. Since many of the thermal performance tests would be conducted with the LHP rotating both clockwise and counterclockwise, measurements of the centrifugal accelerations were made with the LHP rotating in both directions even though in theory there should be no difference between them. Test results confirmed that the centrifugal accelerations are almost identical for the two different rotating directions.

Figures 5 to 7 also show that during the start and the stop of the rotation, the spin rate changes during the transient and the centrifugal acceleration changes accordingly. Another accelerating force also acts tangentially on the LHP whenever there is a change in the spin rate. Such a tangential acceleration can be expressed as

$$a_t = 2\pi \, (df/dt) \, r \qquad (2)$$

where a_t is the tangential acceleration and (df/dt) is the time derivative of the spin rate. To measure the tangential accelerations during transients, the accelerometer was turned 90 degrees. Figures 9 to 12 show the tangential accelerations when the spin rates change. Note that when the LHP was rotating clockwise, the tangential acceleration is positive during the start and negative during the stop. When the direction of the rotation changes (no change on the accelerometer installation), the tangential accelerations change accordingly, as can be seen by comparing Figure 11 and 12.

It is not the intention of this test program to investigate the effect of accelerating force on the heat transport capability of the LHP. That can be better accomplished by testing an LHP with long transport lines separating the evaporator and the condenser at various an adverse elevations. Rather, the objective is to study the effect of various acceleration patterns on the loop operation. Figures 5 illustrate that the centrifugal accelerations increase from 0 to 1.2 g's at 30 rpm in two seconds while Figure 8 shows that the tangential acceleration increase from 0 to 0.32 g and back to 0 in 2 seconds. Similarly, Figures 6 and 9 show that the centrifugal acceleration is much higher than the tangential acceleration during start and stop transients. Thus, there is no need to orient the LHP such that the axis of the evaporator and compensation chamber is perpendicular to the rotating arm. Testing under Configurations A or B provides higher accelerating forces.
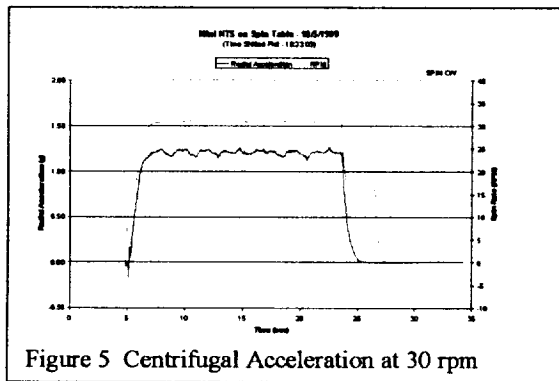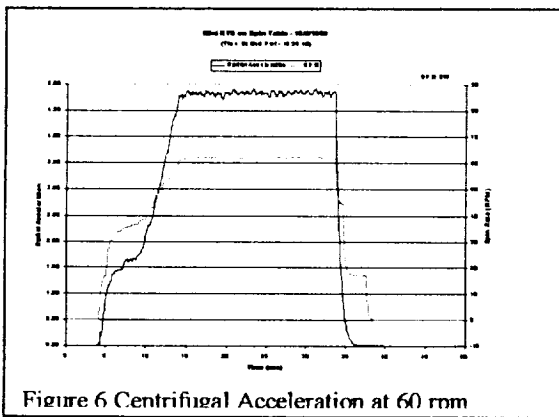
Figure 5 Centrifugal Acceleration at 30 rpm

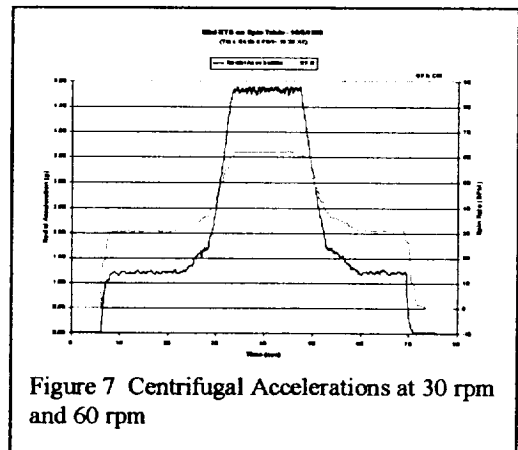Figure 6 Centrifugal Acceleration at 60 rpm

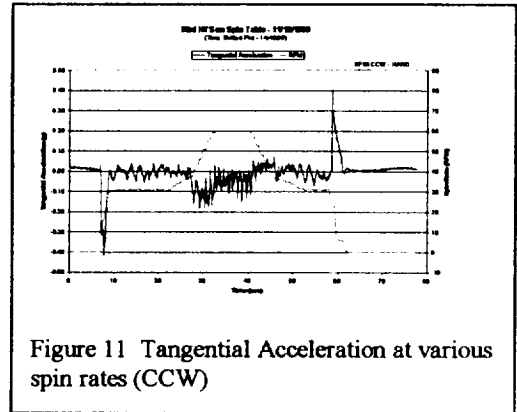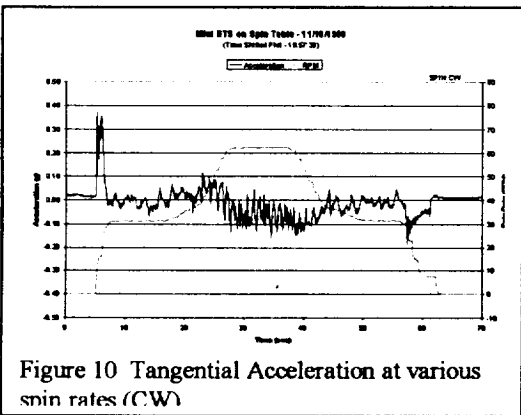Figure 7 Centrifugal Accelerations at 30 rpm and 60 rpm

Figure 8 Tangential Acceleration at 30 rpm (CW)

Figure 9 Tangential Acceleration at 60 rpm (CW)

Figure 10 Tangential Acceleration at various spin rates (CW)

Figure 11 Tangential Acceleration at various spin rates (CCW)

(a) Configuration A

(b) Configuration B

Figure 12 LHP Schematic with Acceleration Vector in Test Configurations A and B

(a) Situation 1

(c) Situation 3

(b) Situation 2

(d) Situation 4

Figure 13 Four Possible Start-up Scenarios

START-UP TEST RESULTS

A LHP must be successfully started before it can be put into service. LHP's are known for their ability to self-start without the need of pre-conditioning. However, self-start does not necessarily imply an instant start or a quick start, especially if a large thermal mass is attached to the evaporator. Two important parameters concerning LHP start-up are the temperature overshoot and superheat at the onset of nucleate boiling. If the peak temperature of the evaporator during start-up exceeds the maximum temperature specified, start-up has to be aborted.

The superheat is required if the evaporator grooves are completely filled with liquid. The required superheat for nucleate boiling is mostly random, and typically ranges from 0 to 10 °C for LHP's. The temperature overshoot is a function of the heat leak from the evaporator to the compensation chamber, which in turn depends on the two-phase fluid distributions in vapor grooves of the primary wick and in the evaporator liquid core, as shown in Figure 13. If the vapor grooves are filled with liquid, superheat is required for liquid boiling; otherwise liquid evaporation will prevail without superheat. If the evaporator core is filled with liquid, the heat leak from the evaporator to the compensation will be small, resulting in a small temperature overshoot. If the evaporator core contains two-phase fluid, a larger heat leak and a higher temperature overshoot can be expected. The least desirable situation is the evaporator core contains two-phase fluid and the vapor grooves are filled with liquid, especially a large thermal mass is attached to the evaporator and/or a small heat load is applied.

It is expected that the accelerating force will change the two-phase fluid distribution inside the evaporator and compensation chamber. Figures 14 (a) to 14(c) illustrate the possible liquid/vapor interface inside the compensation chamber under stationary, 30rpm and 60 rpm rotations, respectively. Such illustrations are highly idealized because the interface would likely be 'wavy' due to the variation of centrifugal forces from the nominal value. Under Configuration A, the liquid will be pushed away from the evaporator end. In addition, some liquid will be pulled off the evaporator core and pushed into the compensation chamber. This will increase the heat leak from the evaporator to the compensation chamber and results in a higher temperature overshoot. Under Configuration B, however, the liquid will be pushed toward the evaporator end, filling the evaporator with more liquid. This will reduce the heat leak and hence the temperature overshoot during start-up.

Figure 14. Fluid Distribution Along Axial Direction inside Compensation Chamber under Various Conditions
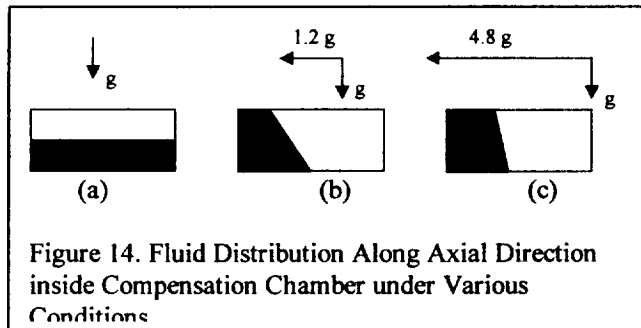
Start-up of the miniature LHP was successfully demonstrated with combinations of the following operating conditions: heat load of 5W, 25W, 50 W and 100W, sink temperature of 20 °C, 15 °C, 10 °C, 0 °C, -10 °C, and -20 °C, spin rates of 0 rpm, 30 rpm, and 60 rpm. Table 1 shows the results of all 49 start-up tests performed.

(Insert Table 1)

The superheat during the start-up in all tests was either zero or less than 2.2 °C, and did not appear to be affected by accelerating forces. This seems to indicate that the vapor grooves were filled with liquid most of the time. The superheat was not affected by the evaporator power or the sink temperature, either. These results confirmed that superheat at the boiling incipience is stochastic

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Table 1. Temperature Overshoot and Superheat During Start-up

Date	Conf. for the day	CW/ CCW	Spin Pattern	Power (W)	Sink temp. (°C)	Temp. Overshoot (°C)	Superheat (°C)	Spinning time w.r.t. power application (min)
2/25/00	B	-	Stationary[a]	25	-10	0	1.2	
8/23/99	A	-	Stationary	25	0	2.2	0	
9/15/99	A	-	Stationary	25	0	0.2	1.2	
9/24/99	A	-	Stationary	25	0	0.1	1.0	
10/1/99	A	-	Stationary	25	0	0.7	1.3	
3/10/00	B	-	Stationary	25	0	0.5	1.2	
9/17/99	A	-	Stationary	25	+10	0	0.9	
12/1/99	B	-	Stationary	25	+15	0	1.2	
11/30/99	B	-	Stationary	25	+18	18.0	1.8	
12/2/99	B	-	Stationary	25	+18	0	1.4	
11/19/99	B	-	Stationary	25	+20	20.8	1.9	
10/19/99	B	-	Stationary	25	+25	0	2.2	
10/14/99	C (Evap> CC)	-	Stationary	25	0	9.1	0.8	
8/18/99	A	CW	Cont. 30 rpm	25	0	6.3	1.1	12 min prior
10/8/99	A	CCW	Periodic 30/0	25	0	0	1.2	simultaneous
10/8/99	A	CW	Periodic 30/0	25	0	0.3	1.4	simultaneous
8/20/99	A	CW	Cont. 60 rpm	25	0	0	1.1	9 min. prior
9/28/99	A	CCW	Periodic, 60/0	25	0	0.7	1.3	3 min. after
10/4/99	A	CW	Periodic 30/0/60/0	25	0	0	1.2	5 min. after
10/6/99	A	CCW	Periodic 30/0/60/0	25	0	0.6	1.2	5 min. after
11/1/99	B	CW	Cont. 30 rpm	25	0	0	1.1	40 min prior
10/20/99	B	CCW	Cont. 30 rpm	25	0	44.8	1.7	48 min. prior
10/13/99	D	-	Stationary	25	0	16.0	2.1	
10/26/99	B	CCW	Cont. 60 rpm	25	0	0	0.6	3 min. prior
11/17/99	B	CW	Periodic 30/0	25	+10	0	1.0	3 min. prior
11/22/99	B	CW	Cont. 30 rpm	25	+15	0	1.1	9 min. prior
11/23/99	B	CW	Periodic 30/0	25	+15	0	1.2	1 min. prior
10/27/99	B	CCW	Periodic 30/0	25	0	0	1.2	3 min. after
10/28/99	B	CCW	Periodic 60/0	25	0	0	1.1	3 min. after
10/29/99	B	CCW	Periodic 30/0/60/0	25	0	0	1.2	5 min. after
11/3/99	B	CW	Stationary	5	0	7.8	1.0	
11/8/99	B	-	Stationary	5	0	3.6	0.8	
9/16/99	A	-	Stationary	50	+10	0	1.7	
9/30/99	A	-	Stationary	50	+10	0	1.1	
11/2/99	B	CCW	Stationary	50	+10	0	1.1	
12/13/99	B	-	Stationary	50	+10	0	1.2	
1/27/00	B	-	Stationary	50	-5	0	1.3	
3/8/00	B	-	Stationary	50	12	0	2.1	
3/9/00	B	-	Stationary	50	10	0	1.0	
10/19/99	B	-	Stationary	100	+25	0	0.8	
10/25/99	B		Stationary	100	0	0	0.9	
11/9/99	B	-	Stationary	100	0	0	1.3	
11/10/99	B	CCW	Cont. 30rpm	100	0	0	0.9	3 min. prior
10/12/99	D	-	Stationary	100	0	0	1.1	
11/22/99	B	CCW	Cont. 60 rpm	100	-40	0	0.6	12 min. prior
11/10/99	B	CCW	Cont. 60rpm	100	-20	0	0.6	9 min. prior
9/20/99	A	CCW	Periodic 30/0	100	0	0	1.2	3 min. after
10/7/99	A	CCW	Periodic 30/0/60/0	100	0	0	1.2	simultaneous
11/18/99	B	CCW	Periodic 30/0/60/0	100	0	0	1.2	1 min. after

(a) Stationary means no spin within 15 minutes after power application.

The temperature overshoot was a function of the heat load and the accelerating force. For all start-ups with an evaporator power of 50 W or 100W, there is no noticeable temperature overshoot regardless of the condenser sink temperature or the spin pattern. This is because with such a large heat load to a miniature LHP, evaporation or nucleation occurred shortly after the application of the heat load with very little time to allow for heat transmission

from the evaporator to the compensation chamber. Figures 15 presents a typical 50W/10°C start-up under a stationary condition, while Figure 16 shows the 100W/0 °C start-up with the loop spinning under Configuration B for 40 minutes prior to applying power to the evaporator.
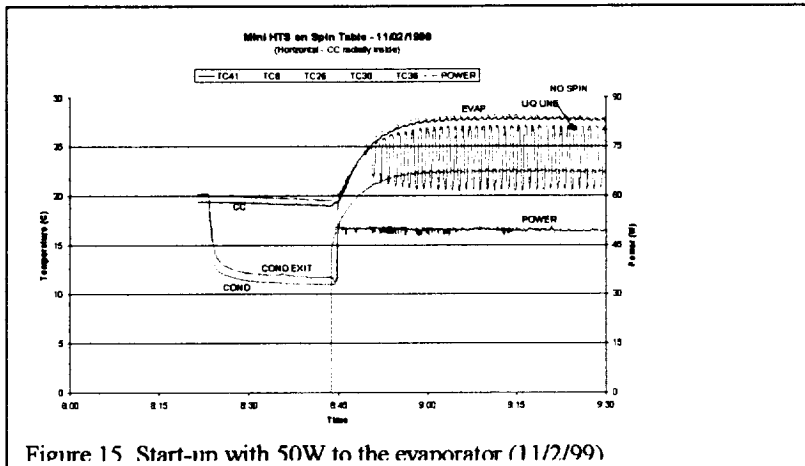

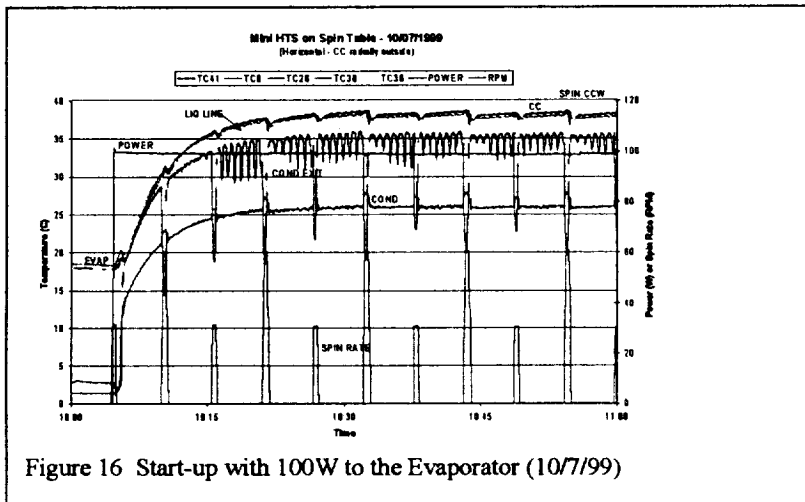Figure 15 Start-up with 50W to the evaporator (11/2/99)

Figure 16 Start-up with 100W to the Evaporator (10/7/99)

Start-ups with 5W to the evaporator, however, always showed some temperature overshoot. Figure 17 illustrate a typical start-up with 5W to the evaporator. Even though the superheat was low, the heat leak as a percentage of the total heat load was not small. It took about 30 minutes for the evaporator to build up the required superheat in order to initiate nucleate boiling. During this period, the compensation chamber was gradually warmed up by heat transmitted from the evaporator. When nucleate boiling finally occurred, the compensation chamber had already been raised to a much higher temperature. This is the reason for the temperature overshoot at the start-up. Unless the temperature of the evaporator can rise at a faster rate than that of the compensation chamber, the loop will not start. Note that the start-up was initiated by nucleate boiling in the evaporator groove, not by the more benign evaporation process, which required no superheat. This is evidenced by a sudden, sharp

drop of the compensation chamber temperature and a sudden, sharp increase of the condenser temperature right after the boiling incipience. Another evidence is that, following the sharp changes, all temperatures gradually reached their equilibrium values. All temperature changes during start-up transient would have been gradual had the flow circulation been initiated by the evaporation process.
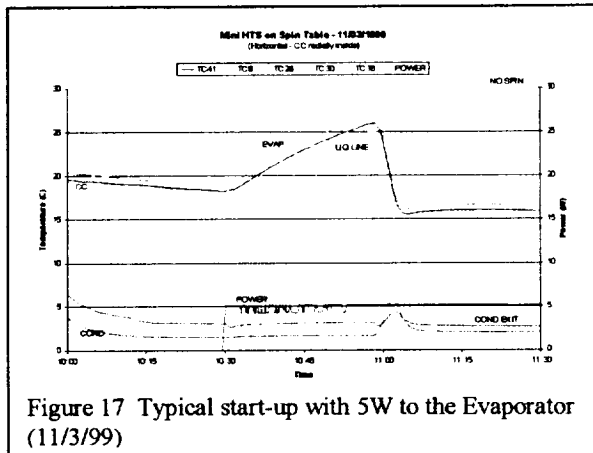

Figure 17 Typical start-up with 5W to the Evaporator (11/3/99)

The majority of start-up tests were conducted by applying 25W to the evaporator. Although there was not much difference in the superheat, a large spectrum of the temperature overshoot was observed, ranging from 0 °C to 45 °C. Furthermore, no good correlation can be found between the temperature overshoot and the test parameters. At the outset, most of the start-ups under the stationary condition with 25 W to the evaporator at 0 °C sink temperature showed no temperature overshoot except for a few cases of 1 °C or 2 °C overshoot. Changes in the sink temperature and/or accelerating forces yielded similar results in most cases, although a few high temperature overshoots did occur. As discussed below, high temperature overshoot seemed to occur sporadically and no clear trend could be established.

As shown in Table 1, when the sink temperature was set at 18 °C, one test (12/2/99) showed no temperature overshoot, yet another test (11/30/99) yielded 18 °C overshoot. As the sink temperature increased to 20 °C and 25 °C, the overshoots were 21 °C and 0 °C, respectively. In theory, the sink temperature can affect the liquid inventory in the compensation chamber due to a change in the liquid density, thus affecting the heat leak from the evaporator to the compensation chamber. However, the test article used in this study has a very small condenser volume (0.6 cm^3), such an effect should be negligible. A comparison of the two tests at 18 °C sink temperature is shown in Figures 18 and 19.

When the miniature LHP was subjected to a centrifugal force, the difference in temperature overshoot was even more pronounced in some cases. With the LHP spinning at a constant rate of 30 rpm and sink temperature at 0 °C, the temperature overshoot was 0 °C in one test (11/1/99), and 45 °C in another (10/20/99). Both tests were conducted under configuration B, where the evaporator was placed at the outer edge of the spin table. Since the evaporator core would be filled more with liquid under this configuration, in theory the heat leak and thus the temperature overshoot should be smaller when compared to the stationary cases. Test data showed contradictory results. On the other hand, the test conducted at a higher spinning rate of 60 rpm under the same test configuration (10/26/99) showed no temperature overshoot, the same as the stationary case.

Under configuration C where the evaporator was placed above the compensation chamber without rotation, the liquid in the compensation chamber will puddle at the bottom of the compensation chamber away from the evaporator. This will be similar to Configuration A with the LHP rotating at 60 rpm as shown in Figure 14. Test of 10/14/99 shows a temperature overshoot of 11 °C, compared to 0 °C for 8/20/99 test (60 rpm). As another example, the fluid distribution inside the compensation chamber under Configuration D (compensation chamber above the evaporator without rotation) will be similar to that under Configuration B with LHP rotating at

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60 rpm. Yet the temperature overshoot was 17 °C under Configuration D (10/13/99) and 0 °C under Configuration B (10/26/99).
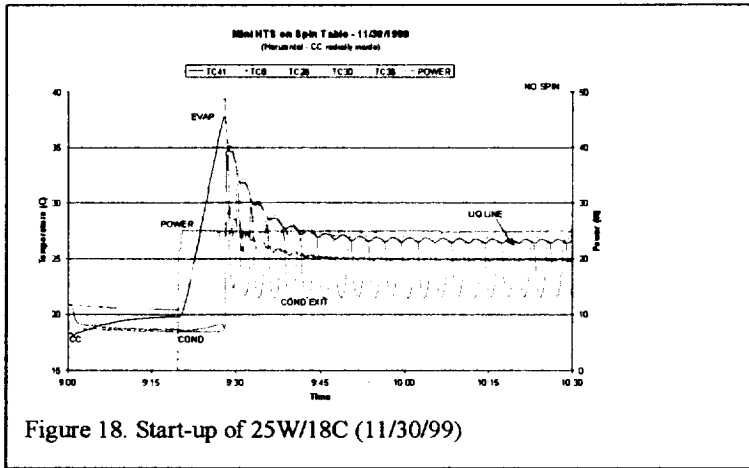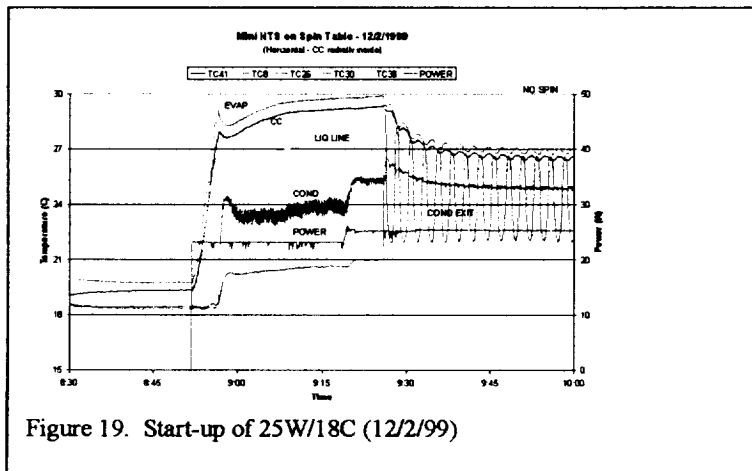

Figure 18. Start-up of 25W/18C (11/30/99)

Figure 19. Start-up of 25W/18C (12/2/99)

SUMMARY AND CONCLUDING REMARKS

The effect of accelerating force on the LHP start-up was experimentally studied by installing a miniature LHP on a spin table. The accelerating force was acting in a direction along the axis of the evaporator and compensation chamber. Start-up tests were conducted under various combinations of heat load, sink temperature, and accelerating forces. The superheat and temperature overshoot during start-up were monitored.

The miniature LHP started successfully in all tests. Test results indicated that the superheat and temperature overshoot during start-up were random. The superheat ranged from 0 °C to 2.2 °C in all tests. The temperature overshoot covered a much larger spectrum, ranging from 0 °C to 45 °C. The high temperature overshoot seen in several tests seems to be statistical with no good correlation to any test parameters. In all cases with high temperature overshoots, the evaporator power was 25W or less. High temperature overshoot is a concern and may not be acceptable in some applications. It can be avoid if a flow circulation can be initiated soon after the

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heat load is applied to the evaporator. A starter heater with a small heating area has been considered for this purpose.

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