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Testing of A Loop Heat Pipe Subjected to Variable Accelerations
Part 2: Temperature Stability

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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 second part of the experimental study, i.e. the effect of an accelerating force on the LHP operating temperature. It has been known that in stationary tests the LHP operating temperature is a function of the evaporator power and the condenser sink temperature when the compensation temperature is not actively controlled. Results of this test program indicate that any change in the accelerating force will result in a change in the LHP operating temperature through its influence on the fluid distribution in the evaporator, condenser and compensation chamber. However, the effect is not universal, rather it is a function of other test conditions. A steady, constant acceleration may result in an increase or decrease of the operating temperature, while a periodic spin will lead to a quasi-steady operating temperature over a sufficient time interval. In addition, an accelerating force may lead to temperature hysteresis and changes in the temperature oscillation. In spite of all these effects, the LHP continued to operate without any problems in all tests.

INTRODUCTION

An experimental study has been conducted to investigate the effect of accelerating force on the loop heat pipe (LHP) operation [1] by installing a miniature LHP on a spin table. Accelerating forces were applied by rotating the LHP about a central axis with pre-determined spin patterns that encompassed both continuous and periodic spins. The LHP was oriented such that the axis of the evaporator and compensation chamber was parallel to the direction of the centrifugal acceleration. The centrifugal forces applied are equivalent to 1.17 and 4.7 times of gravitational force. The study focused upon the effects of accelerations on the start-up and loop operating temperature. Tests were conducted with various combinations of the heat load, sink temperature, centrifugal force, LHP orientation, and spin pattern. The LHP operation to be verified includes start-up reliability, operating temperature stability, and robustness.

Results of the start-up tests under the influence of an accelerating force were presented in a previous paper [1]. This paper will discuss the effect of an accelerating force on the loop operating temperature.

TEST ARTICLE AND TEST SET-UP

The article used for this study is a miniature LHP with an envelope dimension of 178 mm x 127 mm x 51 mm (7 in. x 5 in. x 2 in.) and a mass about 160 grams. The evaporator is made of aluminum and has an outer diameter of 13 mm and a length of 120 mm. The compensation chamber is made of stainless steel with an outer diameter and length of 13 mm and 30 mm, respectively. The condenser, vapor line and liquid line are all made of 13mm O.D. by 2.8 mm I.D. aluminum tubing with lengths of 100mm, 160mm, and 130 mm, respectively. A flange is attached to the condenser section for easy mounting with the coolant lines.

For testing, the LHP is contained in a box-like frame structure along with the heater and coolant blocks. 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. The spin table can rotate up to 119 rpm. A control panel and software are used to provide inputs to the motor controller which drives the spin table motor. Labview software is used to control both the spin rate and the spin direction. 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 a cartridge heater with the capability of 0 to 500 W is embedded inside the heater block. Power is supplied to the evaporator heater through slip rings on the spin table. 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 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.

A schematic of the miniature LHP with thermocouple locations is shown in Figure 1. More detailed information on the test article and test set-up can be found in Reference 1.
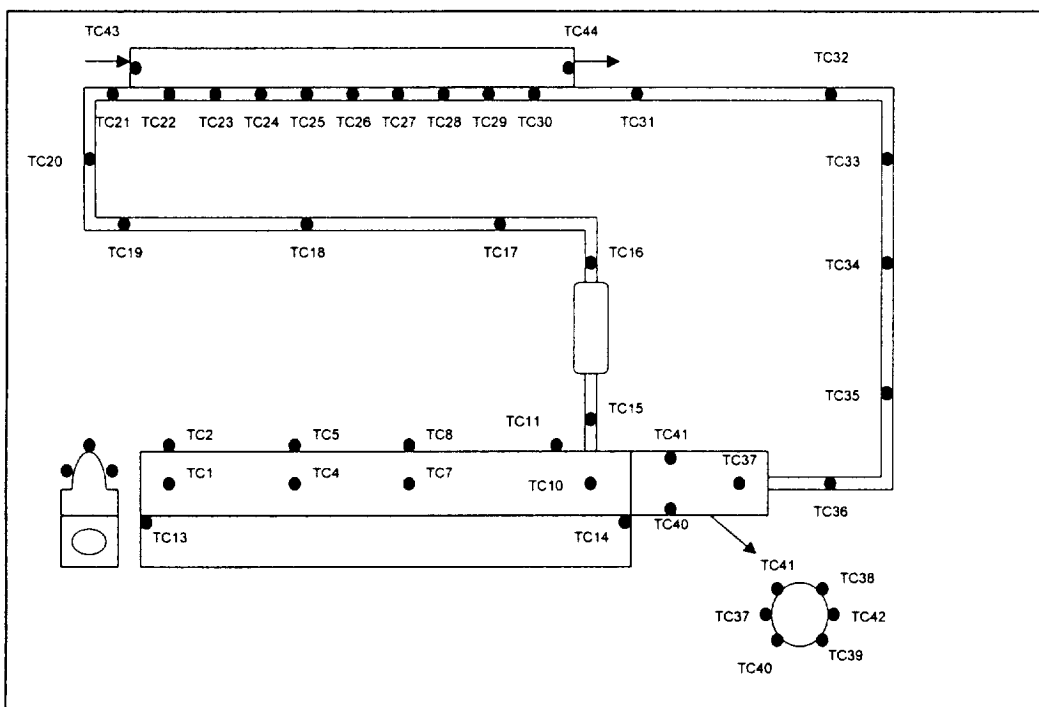

Figure 1. Schematic of the Miniature LHP with Thermocouple Locations

TESTS PERFORMED

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. 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 Pattern

Under Configurations A and B, the accelerating forces acting on the LHP depend on the spin rate and how the spin table rotates. Several patterns of the acceleration are applied in this test program as described below.

- 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.

Types of Tests

The main goal of this study is to investigate the functionality and reliability of the LHP operation under various accelerations. Important characteristics of the LHP operation include transient phenomena during start-up, evaporator power change, sink temperature change, and spin rate change, and the steady state operating temperature. The following testes were conducted after the LHP has been successfully started.

- Power Cycle
    - Power profile: 100W/5W/100W, 25W/100W/25W, 100W/150W/25W.
    - Chiller set point: -40 °C,–20 °C, 0 °C, or +20 °C
- Sink Temperature Cycle
    - Evaporator power: 100W, 50W, 25W –40 °C and 0 °C
    - Chiller set point: between –40 °C and +20 °C
- Low Power
    - Evaporator power: 5W
    - Chiller set point: 0 °C

Model Profile

With the combination of various test configurations, types of tests, and magnitude and frequency of acceleration, a myriad of tests can be performed. To simplify the test procedure and make meaningful comparisons among different tests, a model profile for power and sink temperature was used as part of the test program. This model profile was used in all test configurations along with various spin patterns. In each test, sufficient time was given to allow the loop to reach a steady or quasi-steady state at all possible.

- Start-up
    - Chiller set point: 0 °C
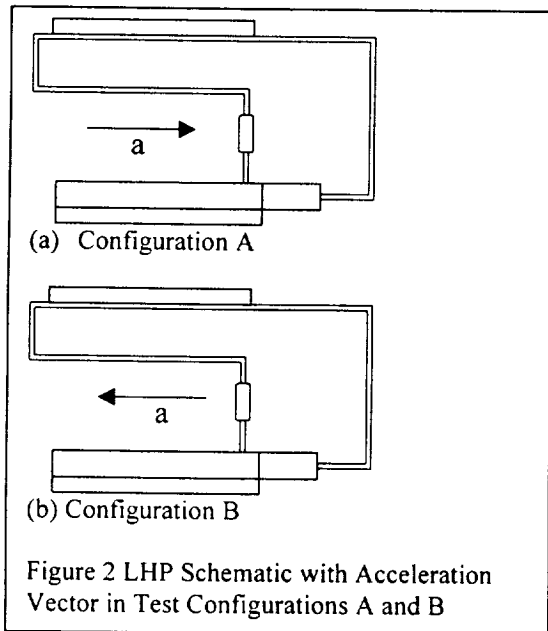   - Evaporator power: 25W
- Power Cycle

- Chiller set point: 0 °C
- Evaporator power profile: 25W/100W/25W
- Sink Temperature Cycle
  - Evaporator power: 100W
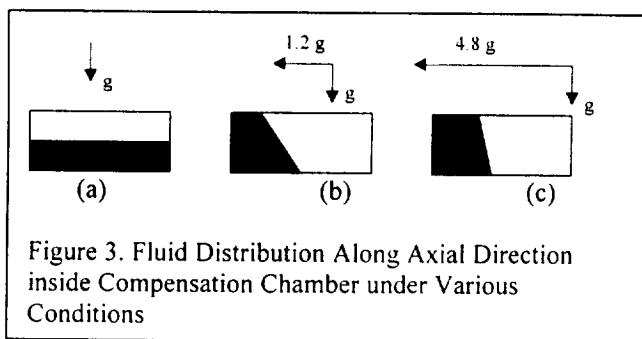 - Chiller set points: 0°C/-40°C/0°C

TEST RESULTS

The LHP operating temperature is determined by the saturation temperature of its compensation chamber. Thus, any parameter that affects the compensation chamber will also affect the operating temperature. It has been well established that, under the stationary condition, the LHP operating temperature is a function of the evaporator heat load, condenser sink temperature, and ambient temperature unless the compensation chamber temperature is externally controlled. The accelerating force affects the loop operating temperature through its influences on the fluid distribution within the evaporator, condenser, and compensation chamber. In particular, the fluid distribution inside the evaporator core is a major factor that determines the heat leak from the evaporator to the compensation chamber. The fluid distribution among the LHP components is mostly affected by the test configuration and the magnitude of acceleration; however, it is also a function of the heat load and sink temperature. When the effect of the accelerating force is superimposed upon those due to other factors, the thermal and fluid interactions become very complex.

In order to investigate the effect of acceleration on the loop operation, many tests were conducted with different combinations of the test configuration, evaporator heat load, condenser sink temperature, and spin pattern. Test results are summarized in Tables 2 to 4, and the operating temperature as a function of various parameters are described in detail in the following sections. Some explanations for possible physical processes involved are offered. Since direct flow visualization was not possible, these explanations are inferred from the temperature responses, with some educated guesses.

To help understand the test results and explanations, a schematics of the LHP with acceleration vectors under both test configurations are shown in Figure 2. Figure 3 depicts the two-phase fluid distribution inside the compensation chamber along the axial direction. Note these are highly idealized schematics and are for illustration purpose only.

(a) Configuration A

(b) Configuration B

Figure 2 LHP Schematic with Acceleration Vector in Test Configurations A and B

Figure 3. Fluid Distribution Along Axial Direction inside Compensation Chamber under Various Conditions

Continuous Acceleration

Continuous acceleration refers to Spin Patterns 2 to 4 where the LHP was continuously spinning without interruptions during the test. Tests were performed under both Configurations A and B.

Configuration A: In Configuration A, the axis of the evaporator and compensation chamber is parallel to the direction of the accelerating force, and the compensation chamber is placed at the outer edge of the spin table. Tests were conducted with various spin patterns and combinations of the heat load and sink temperature including 25W/0 °C, 50W/10 °C, 100W/0 °C, and 100W/-40 °C. Test results shown in Table 2 indicate that the effect of the spin rate (magnitude of acceleration) on the loop operating temperature is a function of the evaporator heat load. For heat loads of 25W and 50W, the operating temperature increased as the spin rate increased from 0 rpm to 30 rpm, and decreased as the spin rate increased from 30 rpm to 60 rpm. The operating temperature is highest at 60 rpm and lowest at 0 rpm. At a heat load of 100W, the operating temperature decreased as the spin rate increased from 0 rpm to 30 rpm, and decreased further as the spin rate increased from 30 rpm to 60 rpm.

Loop temperatures in the 50W/10 °C and 100W/0 °C tests are shown in Figures 4 and 5, respectively. In both tests, the heat load and the sink temperature were kept constant while the spin rate changed. At any given spin rate, the loop was allowed to reach a steady state before changing test conditions. In the model profile tests, the spin rate was kept constant while the heat load varied between 25W and 100W and the sink temperature varied between 0 °C and 40 °C. Figures 6 through 8 depict the temperature profiles at the spin rate of 0 rpm, 30 rpm, and 60 rpm, respectively. The trend of the loop operating temperature change as a function of the spin rate for the combinations of 25W/0 °C, 100W/0 °C, and 100W/-40 °C is consistent with those shown in Table 1.

Analysis of Test Results Under Configuration A: The loop operating temperature is controlled by the saturation temperature of the compensation chamber. For a well-insulated compensation chamber, the saturation temperature is determined by the energy balance between the heat leak from the evaporator and the subcooled liquid returning from the condenser. If the evaporator core is completely filled with liquid, the heat leak will be small. If vapor is present in the evaporator core, the core become part of the compensation chamber and the heat leak will be large. Furthermore, the higher the void fraction in the evaporator core, the larger the heat leak. At low heat loads, the condenser is not fully utilized, and the operating temperature is dominated by the heat leak. At high heat loads, the condenser is more fully utilized, and the operating temperature is dominated by the amount of subcooling of liquid leaving the condenser. In order to understand the effect of the accelerating force on the loop operating temperature, it is necessary to investigate its effect on the heat leak and liquid subcooling.

Depending on the spin rate, the liquid/vapor interface inside the compensation chamber will be formed as shown in Figure 3(a), 3(b) or 3(c). In Configuration A, the liquid is pushed toward the far end connecting to the liquid return line, while in Configuration B, the liquid is pushed toward the evaporator end. Similar liquid/vapor interface may also form in the condenser. At 0rpm, the only force acting on the liquid is the gravitational force and the amount of liquid sitting at the bottom of the condenser line is dependent upon the tube diameter, the surface tension of the fluid, and the mass flow rate (i.e. heat load to the evaporator). A higher heat load means a larger void fraction and hence a smaller amount of liquid at the bottom. When the spin table rotates, the accelerating force pushes the liquid toward the outer edge and the flow in the condenser becomes less stratified. A higher centrifugal force means a higher likelihood that a liquid plug will be formed near the outlet of the condenser.

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Similarly, liquid stratification can also occur in the evaporator core. However, the situation becomes more complex because of the presence of the bayonet at the center and the secondary wick between the primary wick and bayonet. Nevertheless, a higher accelerating force will tear more liquid off the wall and it into the compensation chamber, thus resulting in a higher vapor fraction and a higher heat leak.

At low heat loads, liquid stratification in the condenser may or may not extend over the full length of the condenser at 0 rpm. If it does, liquid plug will form at the condenser exit at a higher spin rate, thus increasing the liquid subcooling. If liquid plug already form at the condenser outlet, higher spin rates will not affect liquid subcooling. Inside the evaporator core, more liquid could be pushed to the compensation chamber at a higher spin rate, resulting in an increase of the heat leak. Therefore, increasing the spin rate yields a competition between a possible lower liquid subcooling and a possible higher heat leak. The operating temperature can increase or decrease depending on which factor prevails. Usually the liquid/vapor interface can be traced by looking at the temperatures along the condenser line. In the present test set-up, the condenser is made of thick wall tubing and a relatively large cooling block is attached. Thus, the thermocouple readings will not be close to the saturation temperature. Nevertheless, the vapor front can still be traced by observing the rise and fall of condenser temperatures along the flow direction. In particular, the temperature of TC30 can be used to check whether the vapor reached the condenser exit.

In the 50W/10 °C test shown in Figure 4, TC 30 temperature indicates that the vapor reached the condenser exit periodically at 0 rpm, with its peak temperature very close the loop saturation temperature. In fact, the temperature oscillation extended along the liquid line all the way to TC 36. When the spin rate increased to 30 rpm, TC 30 temperature decreased rapidly below the saturation temperature with a substantial reduction in oscillation. The lower operating temperature at 30 rpm indicates that the increase in liquid subcooling overcame the higher heat leak. As the spin rate increased to 60 rpm, a higher operating temperature and much lower temperatures of TC 30 and TC 36 indicates that a much high heat leak occurred. This is further evidenced by the recession of the liquid/vapor interface inside the condenser, as illustrated by the temperature oscillation of TC 26. As the spin rate decreased from 60 rpm to 30 rpm and then to 0 rpm, the physical processes simply reversed.

At high heat loads, liquid stratification extends to the condenser outlet at 0 rpm. As the spin rate increases, a liquid plug will form at the condenser outlet, reducing the temperature of the exiting liquid (higher subcooling). Higher spin rates will further increase the liquid subcooling. Even though a higher spin rate will also increase the heat leak for reasons described previously, higher liquid subcooling will almost always prevail because of high mass flow rates at high heat loads. In the 100W/0 °C test shown in Figure 5, the vapor reached the condenser outlet at TC 30, whose temperature was near the saturation. In fact, the entire liquid line was at near saturation temperature. As the spin rate increased to 30 rpm, TC 30 temperature began to oscillate with its peak temperature close to the saturation. The change of the TC 30 temperature from a near steady temperature at 0 rpm to an oscillatory one at 30 rpm indicates that the liquid/vapor interface extended into the liquid line at 0rpm and then receded near TC 30 at 30 rpm. As the spin rate increased to 60 rpm, the liquid/vapor interface further receded into TC 29. Consequently, TC 30 reached a steady temperature that was substantially lower than the saturation. The loop operating temperature decreased with increasing spin rates and increased with decreasing spin rates.

Configuration B: In Configuration B, the axis of axis of the evaporator and compensation chamber is parallel to the direction of the accelerating force, and the evaporator and the vapor line are placed at the outer edge of the spin table. Depending on the spin rate, the liquid/vapor interface inside the compensation chamber will forma shape shown in Figures 3(a) 3(b) or 3(c), with the liquid being pushing toward the far end connecting to the evaporator. Tests were conducted with various spin patterns and combinations of the heat load and sink temperature including 25W/0 °C, 50W/10 °C, 100W/0 °C, and 100W/-40 °C. Test results are included in Table 1. Again, the effect of the spin rate on the loop operating temperature depends on the evaporator heat load. The 25W/0 °C test demonstrated that the loop operating temperature increased with an increasing spin rate. At 50W, the operating temperature changed little as the spin rate increased from 0 rpm to 30 rpm, and increased as the spin rate increased to 60 rpm. The 100W tests showed that the operating temperature increased as the spin rate increased from 0 rpm to 30 rpm, and decreased as the spin rate increased to 60 rpm. Figures 9 and 10 show the loop temperatures in the 25W/0 °C and 100W/0 °C tests, respectively. The model profiles were also tested with constant spin rates of 30 rpm and 60 rpm. The results are shown in Table 2. In general, the dependency of the loop operating temperature as a function of the spin rate and the heat load is the same as those shown in Table 1. Figure 11 shows the loop temperatures in

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the model profile test where the sink temperature changed between +15 °C and –25 °C, deviating from the regular model profiles tests where the sink temperature changed between 0 C and –40C

Analysis of Test Results Under Configuration B: In Configuration B, the evaporator core will be more filled with liquid as the spin rate increases. Thus, the heat leak decreases with an increasing spin rate. The physical process is more complex in the condenser section since the fluid flows in a direction opposite to the acceleration vector. Higher spin rates will push more liquid toward the condenser inlet. At low heat loads, the mass flow rate is low and the inertial force may not be strong enough to carry much liquid with it. Thus, increasing the spin rate will result in more vapor on the condenser exit end. Consequently, a higher spin rate usually means a higher operating temperature. In the 25W/0 °C test shown in Figure 9, the liquid/vapor interface was near TC 28, and TC 30 was at a steady temperature much lower the saturation. As the spin rate increased to 30 rpm, TC 30 temperature began to oscillate with the peak temperature close to the saturation. The temperature oscillation extended throughout the entire liquid line. As the spin rate increased to 60 rpm, TC 30 temperature increased with similar oscillation. The operating temperature decreased as the spin rate decreased to 30 rpm, and became steady again at 0 rpm.

At high heat loads, the liquid will stratify and the vapor front will reach the condenser outlet at 0 rpm. As the spin rate increases, more liquid will be pushed toward the condenser inlet end, making it easier for the vapor to reach the condenser exit end. This tends to increase the operating temperature. On the other hand, a higher spin rate could help thin the liquid layer on the condenser wall and increase the heat transfer coefficient. The inertial force at a high heat load can also counter the centrifugal force and send some liquid back to the exit end. Thus, the net effect on the operating temperature is more difficult to predict. In the 100W/0 °C test shown in Figure 11, the vapor front pass TC 30 at 0 rpm. As the spin rate increased to 30 rpm, TC 30 temperature and the loop operating temperature increased slightly. At 60 rpm, TC 30 and the operating temperature decreased by several degrees. It is interesting that TC 30 showed little oscillation over the entire period except near the end of the test when the spin rate reduced to 0 rpm again. The oscillation of TC 30 indicated the liquid/vapor interface had receded into the condenser at 0 rpm.

Periodic Acceleration

Periodic acceleration refers to "stop and go" spin patterns. Periodic spin generates both centrifugal and tangential accelerations whenever the spin rate changes. Measured accelerations for some pre-determined spin rate changes were presented in the previous paper [1]. Changing the spin rate will change the fluid distribution within the loop and hence the operating temperature even when the heat load and the sink temperature remain constant. Many tests were performed with various spin rates including those represented by Spin Patterns 5 to 7 under both Configurations A and B.

Figure 12 depicts loop temperatures in a 100W/0 °C test under Configuration A. Initially, the loop was under a stationary condition and the loop was operating at a steady temperature of 38.8 °C. The spin table then rotated at 30 rpm for 2 minutes, followed by 0 rpm for 3 minutes for four cycles. Subsequently, the spin pattern changed to 60 rpm for 2 minutes and 0 rpm for 3 minutes for four cycles. The loop continued to operate at 0 rpm afterwards until steady state. The figure shows that the loop established a quasi-steady state quickly with the 30rpm/0rpm spin, but did not reach a quasi-steady state in four cycles of the 60rpm/0rpm spin. The loop operated at about the same temperature at 0 rpm before and after the spins, except for the difference in the temperature oscillation. Such a temperature hysteresis will be discussed later. Note from Figure 5 that the loop operating temperature decreased with an increasing spin rate in the continuous spin test. With periodic spin, the loop operating temperature decreased when the loop was spinning and increased the spin stopped. The quasi-steady operating temperature was between those under the continuous spin and no spin conditions.

Figure 13 shows the loop temperatures in the 25W/0 °C test under configuration B where the loop was subjected to continuous and periodic spins. Note that the temperature changed whenever the spin rate changed. The quasi-steady temperature during periodic spin of 60rpm/0rpms is between the steady temperatures at 0 rpm and continuous spin at 60 rpm.

Periodic spin tests were also conducted with the model profile with Spin Patterns 5, 6 and 7 under both Configurations A and B. The loop temperatures for Spin Pattern 5 (30rpm/0rpm) and Spin Pattern 7

(30rpm/0rpm/60rpm/0rpm) under Configuration A are shown in Figures 14 and 15, respectively. In all tests, the quasi-steady temperatures are between the steady temperatures at 0rpm and at respective continuos spin rates.

Power Cycle Test

The purpose of the power cycle test is to investigate the loop's ability to adapt to a rapid change of the heat load. The highest heat load tested was 200W. This high power was limited by the condenser cooling capability rather than the capillary pumping capability of the evaporator wick. Above 200W, the loop operating temperature exceeded 65 °C °C even with the chiller set at –40 °C. The lowest power tested was 5W. Several power cycle tests were conducted, including 100W/5W/100W, 100W/25W/100W, and 150W/25W/150W under both configurations A and B. In all tests, the LHP operated properly without any problems. In some cases, a temperature hysteresis was observed, as will be discussed later. Figure 16 shows the loop temperatures in the 100W/5W/100W/5W/100W test under Configuration A. The sink temperature was maintained at 0 °C throughout and the LHP was subjected to Spin Pattern 7 (0 rpm/30 rpm/0 rpm/60 rpm). The variation of the heat load is not shown in the figure, but can easily be identified from the temperature profiles.

Low Power Test

The low power operation of an LHP is of interest because of stability issues related to the extremely low mass flow rate. The low power operation under the influence of centrifugal acceleration is of particular interest since it is perceived the loop will be more susceptible to any dynamic change at low mass flow rates. Three low power tests were conducted with a heat load of 5W at a sink temperature of °C. Figure 17 illustrates the loop temperatures in the 5W/0 °C test with the loop subjected to continuous and periodic spins. Note the loop started at 8:40 with a large temperature overshoot. This is very typical with low power start-ups. With a heat load of 5W, it took a very long time for the loop to reach a steady state. Nevertheless, it can be seen that the quasi-steady temperature during periodic spin was between the steady temperatures at 0 rpm and at 60 rpm. A similar test was conducted under configuration A. The loop temperatures were more stable under Configuration A because the accelerating force was acting in the same direction as the fluid flow. In addition, the loop operated at 5W in two of the power cycle tests. Test results show few differences in low power and high power operation with the exceptions of a high temperature overshoot at start-up and a much longer time to reach quasi-steady or steady states at low powers.

Temperature Oscillation

Temperature oscillations have been seen in many LHP tests, and were observed in almost every test, at one point or another, throughout this test program. The temperature oscillation and temperature hysteresis are complex phenomena and will require a separate paper for complete descriptions. Suffice it to say that whenever the liquid/vapor interface reaches the condenser outlet, temperature oscillation will occur and can persist along the liquid line. Since the accelerating force can move the liquid/vapor interface inside the condenser toward or away from the outlet, spinning the LHP will affect the temperature oscillation. It can increase or decrease the magnitude of the oscillation, and can even produce or eliminate the oscillation without changing the heat load or condenser sink temperature.

Several tests were conducted to illustrate how the temperature oscillation might be affected by various parameters. Figure 18 shows the loop temperatures at constant heat load of 25W and varying sink temperature under stationary condition. Notice that a change in the sink temperature by one or two degrees change the magnitudes of temperature oscillations, presumably due to the change of liquid/vapor interface in the condenser.

Large temperature oscillations are usually confined to the condenser and the liquid return line. The temperature oscillation in the compensation chamber is much smaller as shown in previous figures. Despite the presence of temperature oscillation, large or small, the loop never had a deprime or showed any adverse effects in its operation in all tests.

Temperature Hysteresis

The temperature hysteresis refers to the change of the LHP operating temperature for seemingly identical operating conditions, i.e. heat load, sink temperature and ambient temperature. Temperature hystereses were first reported in Reference 2, where the loop operating temperature increased after a large sudden power decrease. The authors argued that the temperature hysteresis was caused by the change of two-phase fluid distribution inside the evaporator core, which in turn changes the heat leak from the evaporator to the compensation chamber. In the present test program, temperature hystereses were seen quite often. Some occurred on tests conducted on different days for the same test conditions; others occurred after the loop had been subjected to changes in the heat load and/or sink temperature. However, most of temperature hystereses took place after a accelerating force had been applied to the loop. The results seem to support the theory presented in Reference 2 since accelerating force changed the two-phase fluid distribution inside the evaporator core as described in previous sections.

SUMMARY AND CONCLUSIONS

The effects of an accelerating force on the transient and steady behaviors of a miniature LHP were investigated. Test results indicate that loop start-up, both in terms of temperature overshoot and superheat, is little affected by the centrifugal force [1]. Any changes in these parameters appear to be random. The loop operating temperature, however, can be affected by each of the parameters. The effects of the heat load and sink temperature on the loop operating temperature have been well established in stationary systems. The centrifugal force affects the operating temperature through its influence on the two-phase fluid distributions in the evaporator core, compensation chamber and condenser. Since the fluid distributions also depend on the heat load and sink temperature, the centrifugal acceleration represents another dimension whose effects must be superimposed upon those due to the heat load and sink temperature. Therefore, any change in the centrifugal force will result in a change in loop operating temperature. In addition, the centrifugal force may lead to temperature hysteresis and changes on the temperature oscillation.

In ground tests, the liquid is likely to be stratified by the gravitational force under stationary condition. One of the effects of the additional accelerating force is to changes the liquid stratification, leading to changes in the loop operating temperature. It is cautioned not to apply the results of ground tests directly to a spinning spacecraft. In micro-gravity, the liquid will not stratify. Thus, adding an additional accelerating force to a spacecraft may not produce the same results as in the ground tests because the initial conditions are different.

The LHP operation is also a function of the amount of fluid inventory. Tests should be conducted to study the effect of accelerations on the loop operation for various fluid charges. The transients of temperature oscillation can also be better understood by looking into the pressure drops in the loop. Differential pressure transducers can be added for this purpose. However, adding pressure transducers may cause uncertainties of the fluid inventory in the compensation chamber during operation.

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Table 1. Operating Temperature at Various Spin Rates (Continuous) with Fixed Power and Sink Temperature

Date	Conf	CW/ CCW	Power (W)	TC52 Temp. (°C)	0rpm (°C)	30rpm (°C)	60rpm (°C)	30rpm (°C)	0rpm (°C)
9/21/99 (13:00-17:00)	A	CCW	5	0	22.8	24.3	17.3	ND	ND
9/17/99 (13:30-19:30)	A	CCW	25	0	15.0	ND	21.5	12.7	12.5[a]
9/16/99 (9:50-14:30)	A	CCW	50	10	28.0	26.5	29.2	26.4	27.9
9/30/99 (9:50-15:15)	A	CW	50	10	28.5	26.0	28.4	26.0	28.1
9/15/99 (12:45-15:30)	A	CCW	100	0	38.4	33.0	31.8	34.0	38.8
9/30/99 (15:15-17:15)	A	CW	100	0	39.9	35.8	36.0[b]	ND	ND
9/20/99 (11:30-15:30)	A	CCW	100	-40	7.2	4.1	3.5	ND	8.0
10/19/99 (10:30-14:20)	B	CCW	25	0	10.8	12.5	13.6	12.7	10.9
11/2/99 (8:30-14:45)	B	CCW	50	10	27.6	27.8	29.4	28.4	27.8
3/8/00 (8:00-14:00)	B	CW	50	10	28.8	28.6	30.0	28.4	28.8
3/9/00 (8:30 –12:45)	B	CW	50	10	28.1	28.0	30.0	28.0	28.2
10/19/99	B	CCW	100	0	38.9	40.1	38.0	39.5	38.8
3/8/00 (14:15-19:00)	B	CW	100	0	40.8	41.3	41.0	41.5	40.2
3/9/00 (14:15-18:00)	B	CW	100	0	39.1	41.3	39.7	41.5	40.2
10/25/99 (10:30-14:15)	B	CCW	100	-40	8.1	10.1	8.9	9.0	8.0

*ND – No data; test was not conducted under such condition.
(a) temperature hysteresis
(b) The loop had not reached a steady state before the test ended.

Table 2. Operating Temperatures in Model Profile Tests with Continuous Accelerations

Date	Configuration	CW/CCW	Spin rate (rpm)	TC52 Temp (°C)	25W/0°C	100W/0°C	25W/0°C	100W/0°C	100W/-40°C	100W/0°C
8/23/99	E	-	0	0.9	12.8	39.5	14.9	38.6	8.0	37.5
8/18/99	A	CW	30	1.0	13.2	32.3	13.0	32.5	3.2	33.0
8/20/99	A	CW	60	0.9	19.2	33.2	18.6	33.5	2.6	33.1
10/14/99	C(Evap > CC)		0	0.9	12.7	41.5	12.7	41.8	9.4	41.2
10/20/99	B	CCW	30	1.0	12.7	39.1	12.3	39.2	9.6	39.0
11/1/99	B	CW	30	1.4	12.0	40.6	12.9	40.0	9.3	38.9
10/26/99	B	CCW	60	-0.1	13.3	38.5	14.0	38.4	8.5	38.7
10/13/99	D(CC > Evap)	-	0	1.1	13.0	46.1	12.3	45.0	15.0	45.4
The following test was conducted with sink temperature varying between +15 °C and –25 °C										
11/22/99	B	CW	30	15.5	26.5	53.8	23.5	53.9	20.9	53.7
11/30/99	E	-	0	18.0	23.5	52.6	23.7	52.6	19.9	53.8

*ND – No data; test was not conducted under such condition.

Table 3. Operating Temperatures in Model Profile Tests with Periodic Spin Patterns

Date	Conf.	CW/CCW	Spin Pattern/ Periodic (rpm)	TC52 Temp (°C)	25W/0°C	100W/0°C	25W/0°C	100W/0°C	100W/-40°C	100W/0°C
9/24/99	A	CCW	30/0		15	38.0	13.2	38.8	9.4	38.0
10/1/99	A	CW	30/0	1.1	14.8	38.8	13.6	38.6	9.4	38.0
9/28/99	A	CCW	60/0		14.6	37.9	14.0	37.8	7.4	38.0
10/4/99	A	CW	30/0/60/0	1.1	14.0	38.0	13.8	38.0	8.2	38.1
10/6/99	A	CCW	30/0/60/0	1.3	14.5	38.9	14.3	38.7	9.7	38.6
10/27/99	B	CCW	30/0	1.8	10.0	38.1	10.1	38.0	5.1	38.1
10/28/99	B	CCW	60/0	1.8	14.5	38.0	14.0	38.1	7.0	38.0
10/29/99	B	CCW	30/0/60/0	1.6	14.5	39.0	16.5	38.5	7.8	38.5
The following test was conducted with the sink temperature varying between +15 °C and –25 °C										
11/23/99	B	CW	30/0	15.7	26.0	52.9	24.1	53.3	20.1	53.6

(a)

9/16/99 (9:30-14:30)—Both figures

Figure 4. Loop Temperatures as a Function of Spin Rate in the 50W/10 °C Test

(b)

Figure 4

9/15/99 (12:30-15:30)

Figure 5. Loop Temperatures as a Function of Spin Rate in the 100W/0 °C Test

8/23/99

Figure 6. Loop Temperature in the Model Profile Test at 0 rpm Under Configuration E

SPIN TABLE TESTS - August 18, 99 - 30 RPM

8/18/99

Figure 7. Loop Temperature in the Model Profile Test at 30 rpm Under Configuration A

SPIN TABLE TESTS - August 20, 99 - 60 RPM

8/20/99

Figure 8. Loop Temperature in the Model Profile Test at 60 rpm Under Configuration A

10/19/99 (10:30-14:20)

Figure 9. Loop Temperatures as a Function of Spin Rate in the 25W/0 °C Test Under Configuration B

10/19/99 (14:30 –17:00)

Figure 10. Loop Temperatures as a Function of Spin Rate in the 100W/0 °C Test Under Configuration B

11/22/99 (9:00 –17:00)

Figure 11. Loop Temperature in the Model Profile Test at 60 rpm Under Configuration B

9/15/99 (15:00-17:00)

Figure 12 Loop Temperatures in the 100W/0 °C Test with Periodic Spins Under Configuration A

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3/10/00 (8:45-14:45)

Figure 13. Loop Temperatures in the 5W/0 °C Test With Continuous and Periodic Spins Under Configuration B

9/24/99

Figure 14. Loop Temperatures in Model Profile Test with Spin Pattern 5 Under Configuration A

Mini LHP on Spin Table - 10/06/1999
(Horizontal - CC radially outside)

10/6/99

Figure 15. Loop Temperatures in Model Profile Test with Spin Pattern 7 Under Configuration A

Mini LHP on Spin Table - 10/07/1999
(Horizontal - CC radially outside)

10/7/99 (10:00-16:30)

Figure 16. Loop Temperatures for 100W/5W/100W/5W/100W Power Cycle Test Under Configuration A

Mini LHP on Spin Table - 11/08/1999
(Horizontal - CC radially inside)

TC41 — TC8 — TC26 — TC30 — TC36 — POWER — RPM

SPIN CW

11/8/99 (8:00-17:00)

Figure 17. Loop Temperatures at Low Power 5W/0 °C Test Under Configuration B

Mini HTS on Spin Table - 12/02/1999
(Horizontal - CC radially inside)

TC41 — TC26 — TC30 — TC36 — TC52

NO SPIN

12/2/99 (9:30-15:30) TC 41, 26, 30, 36, 52

Figure 18. Loop Temperatures versus Sink Temperature at 25W Under Configuration E

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