THERMAL PERFORMANCE OF A LOW-COST LOOP HEAT PIPE

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Abstract

This paper presents the thermal performance of a low-cost loop heat pipe (LHP) consisting of a single evaporator and a single condenser. The evaporator has an outer diameter of 14mm and a length of 50mm. An organic solvent was used as the working fluid. The low-cost LHP was made possible through a new manufacturing process. The LHP demonstrated excellent performance over heat loads ranging from 1W to 150W and sink temperatures between 253K and 293K. Tests performed included start-up, power cycle, sink temperature cycle, high power and low power operations. No performance anomalies were seen.

1. Introduction

A loop heat pipe (LHP) is a versatile two-phase heat transfer device that can transport large heat loads over long distances with small temperature differences [1, 2]. LHPs have been used for thermal control of several commercial communications satellites and NASA spacecraft including ICESAT, SWIFT, AURA and GOES [3-6]. The application of LHPs is currently restricted to space and some special areas due to their high manufacturing costs. Recently, NASA Goddard Space Flight Center and the U.S. Army have purchased a low-cost LHP and jointly conducted a test program. The LHP demonstrated excellent performance over heat loads ranging from 1W to 150W and sink temperatures between 243K and 293K. Tests performed included start-up, power cycle, sink temperature cycle, high power and low power operations. No performance anomalies were seen. The low-cost LHP was made possible because of a new manufacturing process employed by the vendor. Thus, the LHP has the potential to become the next-generation heat transfer device to cool terrestrial devices such as advanced electronics which have high power dissipations.

In this paper, important design parameters of the LHP, and the test set-up for performance testing will be described first. This will be followed by detailed descriptions of the tests conducted and the experimental results.

2. Test Article and Test Set-up

The low-cost LHP that was tested has a single evaporator and a single condenser. The evaporator and its integral compensation chamber (CC) have an outer diameter (O.D.) of 14mm and lengths of 50mm and 40mm, respectively. The primary wick has a pore radius of 2.5 μm. The vapor line, liquid line, and condenser have an O.D. of 4mm and lengths of 100mm, 233mm and 625mm, respectively. An organic solvent is used as the working fluid. Additional design parameters can be found in Table 1. A picture of the test article is shown in Figure 1.

An aluminium saddle was attached to the evaporator and a cartridge heater was inserted into the aluminium saddle to provide heat loads up to 150W. The condenser was attached to a cold plate that was cooled by a circulating coolant provided by a refrigerator. Forty type-T thermocouples were used to monitor the temperatures. A data acquisition system consisting of a data logger, a personal computer, and a monitor was used to display and store the temperature data as frequently as every second. A schematic of the test article with thermocouple locations is given in Figure 2.

Table 1. Low-Cost LHP Design Parameters

Design Parameter		Value
Evaporator	O. D.	14.0 mm
	I. D.	13.0 mm
	Length	50.0 mm
Primary Wick	O. D.	13.0mm
	I. D.	5.0 mm
	Length	40.0 mm
	Pore Radius	2.5 μm
	Permeability	4.5×10^{-13} m^2
CC	O. D.	14.0 mm
	I...D.	13.0 mm
	Length	40.0mm
Vapor line	O. D.	4.0 mm
	I.D.	2.8 mm
	Length	100 mm
Liquid line	O. D.	4.0 mm
	I.. D.	2.8 mm
	Length	233 mm
Condenser	O. D.	4.0 mm
	I. D.	2.8 mm
	Length	625 mm
Working fluid	Material	Organic solvent
	Inventory	11 grams

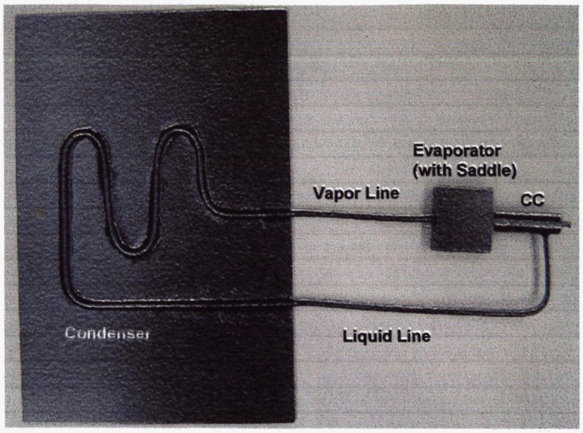

Figure 1 Picture of Low-Cost LHP

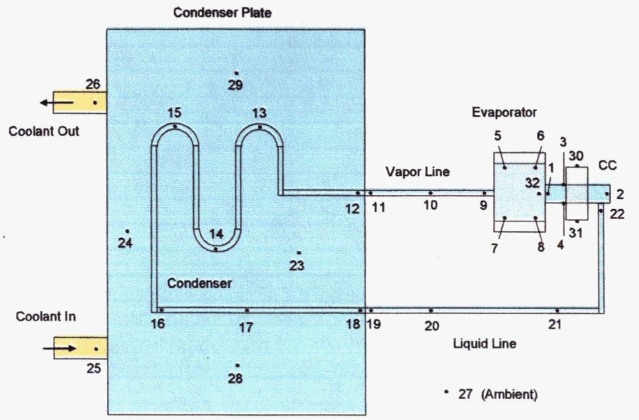

Figure 2 Schematic of Low-Cost LHP with Thermocouple Locations

3. Tests and Results

The purpose of this test program was to characterize the performance of the low-cost LHP under various operating conditions. Characterization tests conducted included start-up, power cycle, sink temperature cycle, high power, and low power operations. All tests were conducted with the LHP in a horizontal plane. Descriptions of each test follow.

Start-up Test

An LHP must start successfully before it can transport a heat load. Start-up can be problematic in some cases and may require pre-conditioning, especially at low heat loads [1, 2]. Start-up tests for the low-cost LHP were conducted under various heat loads and sink temperatures. The LHP started successfully in all cases by simply applying a heat load to the evaporator without any pre-conditioning. The evaporator heat load ranged from 1W to 50W, and the condenser sink temperature varied between 243K and 293K. The start-up is characterized by an increase of the vapor line temperature to the CC saturation temperature and a decrease of the liquid line temperature, indicating that a flow circulation has been established. Start-up is successful if the flow circulation continues and the CC and the evaporator temperatures are steady, with the evaporator temperature slightly higher than that of the CC.

Thirty-two start-up testes were conducted and all were successful. Figures 3 shows the temperature profiles during the start-up where 5W was applied to the evaporator at a condenser sink temperature of 253K. The vapour line temperature rose to the saturation temperature minutes after 5W was applied, and the loop reached a steady state quickly. At 10:05, the heat load increased to 100W, and the loop operated at a different temperature.

Figure 4 shows the temperature profiles for a start-up with 50W to the evaporator and the condenser temperature was maintained at 263K. At such a high power, the loop started almost immediately. The loop reached a steady state after a very short transient period.

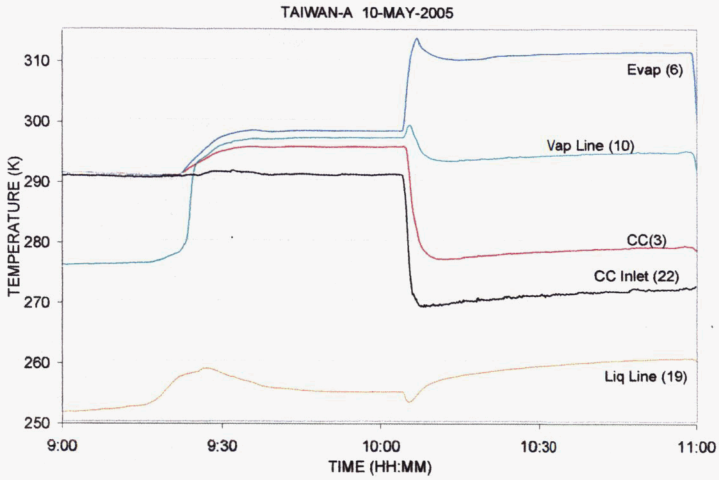

Figure 3. Start-up with 5W at Condenser Sink of 253K (need to add power)

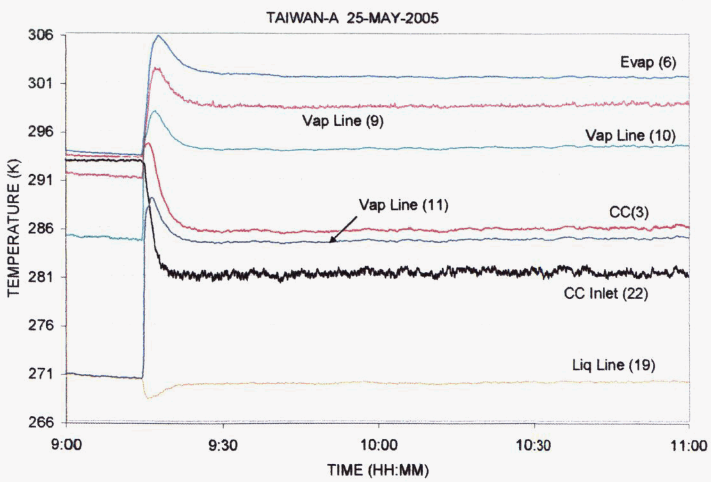

Figure 4. Start-up with 50W at Condenser Sink of 263K

Power Cycle Test

The power cycle test was performed by imposing a sudden, large step change in the evaporator heat load. The purpose of this test was to verify that the LHP could adapt to a rapid change in the heat load, especially during the power step down. Typical power cycle tests performed included power profiles of 5W/100W/5W, 50W/2.5W/50W, and 100W/2.5W/25W at sink temperatures ranging from 253K to 293K.

Figure 5 shows the temperature profiles during a power cycle test where the heat load varied between 100W and 5W at a sink temperature of 263K. The corresponding power turn down ration was 20. The CC temperature varied with the heat load as expected. Also note that the loop reached a steady state much quicker at 100W than at 5W. Figure 6 shows the temperature profiles in another power cycle test with heat load varying between 25W and 2.5W while the sink temperature was kept constant at 273K.

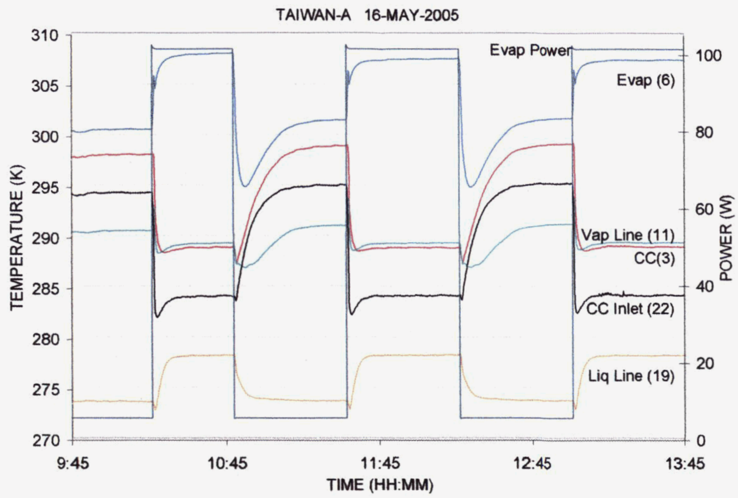

Figure 5. Power Cycle Test of 5W/100W/5W at Condenser Sink of 263K

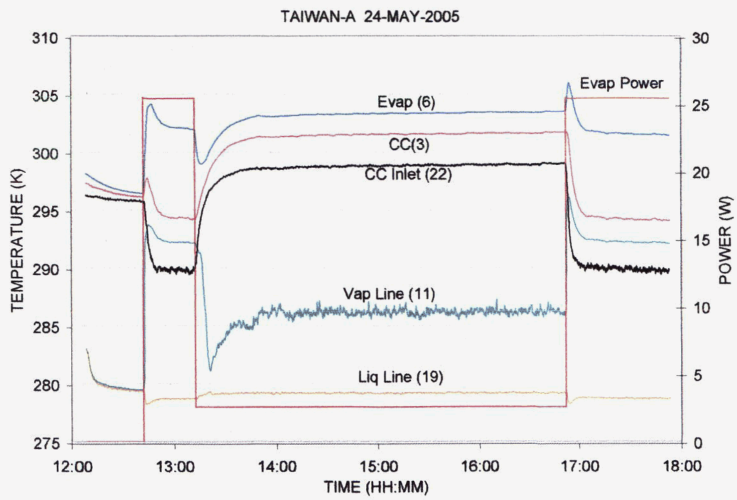

Figure 6. Power Cycle Test of 2.5W/25W/2.5W at Condenser Sink of 273K

Sink Temperature Cycle Test

The sink temperature cycle test was conducted by making a sudden and large change in the condenser sink temperature. The purpose of this test was to verify that the LHP could adapt to a rapid sink temperature change. A typical sink temperature cycle test included a sink temperature profile such as 243K/273K/293K/243K293K/273K, and the evaporator heat load was kept constant at 5W, 25W or 50W. The LHP demonstrated successful operation in all tests, i.e. the loop reached a new steady state after a short period of transient following the sink temperature change.

Figure 7 shows the temperature profile in a sink temperature cycle test where the evaporator heat load was kept constant at 50W and the condenser sink temperature varied between 243K and 293K. The loop operating temperature varied with the sink temperature as expected. Figure 8 illustrates another sink temperature cycle test at a heat load of 5W. Note that at low heat loads, the condenser was hardly utilized and the CC temperature was dependent more upon the ambient temperature than the sink temperature.

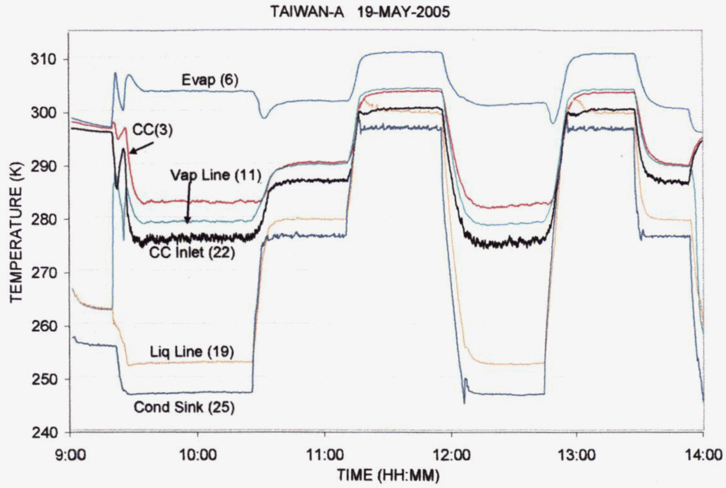

Figure 7. Sink Temperature Cycle Test at 50W

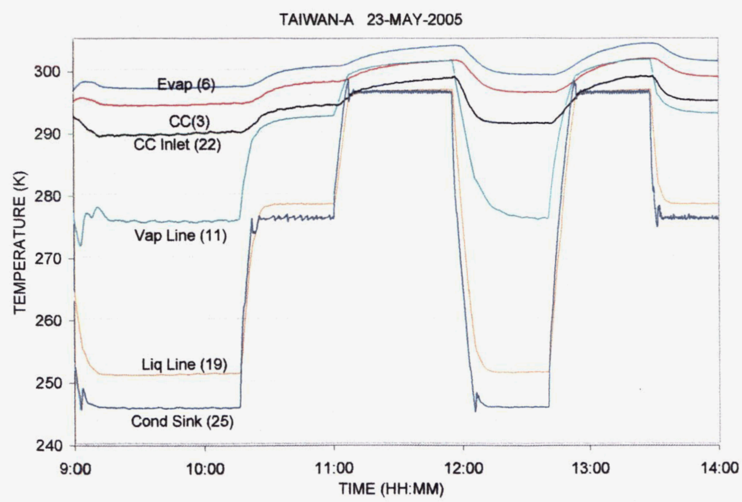

Figure 8. Sink Temperature Cycle Test at 5W

Figure 9 shows the loop temperature profiles in a test where an evaporator heat load change was superimposed upon the sink temperature change, i.e. the power was varied between 25W and 100W while the sink temperature changed between 253K and 293K. Again, the loop demonstrated its ability to adopt to simultaneous changes of the heat load and the condenser sink temperature and operated successfully.

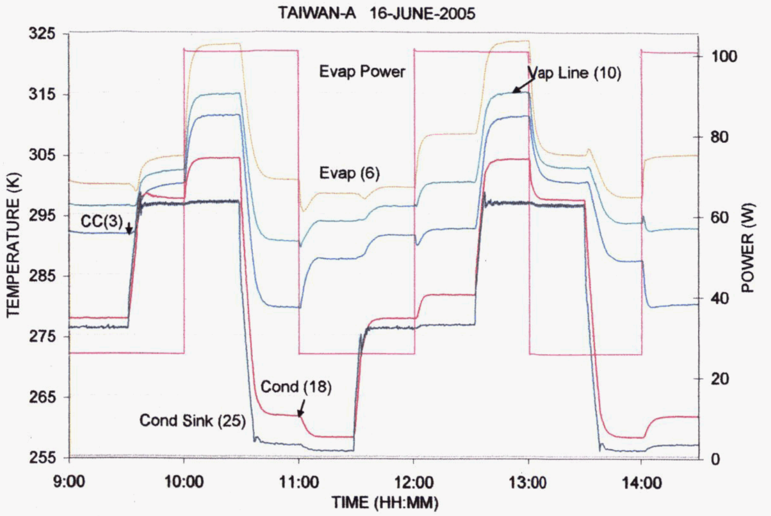

Figure 9. Power Cycle and Sink Temperature Cycle Test

High Power Test

The high power test was conducted following a successful start-up by gradually increasing the heat load in steps until the evaporator capillary limit was reached. When the evaporator capillary limit is reached, the CC temperature will increase sharply, and so does the difference between the evaporator temperature and the CC temperature due to a penetration of the vapor through the primary wick. Under most circumstances, the loop will reach a new steady state at a higher CC temperature, and the loop will return to normal operation as the heat load is reduced. However, a temperature excursion may result when the applied heat far exceed the loop's heat transport limit.

Figure 10 shows that the loop reached the capillary limit at 140W. Nevertheless, the loop reached a new steady state even when the heat load was further increased to 150W. The evaporator recovered from a dry-out as soon as the heat load was reduced to 70W.

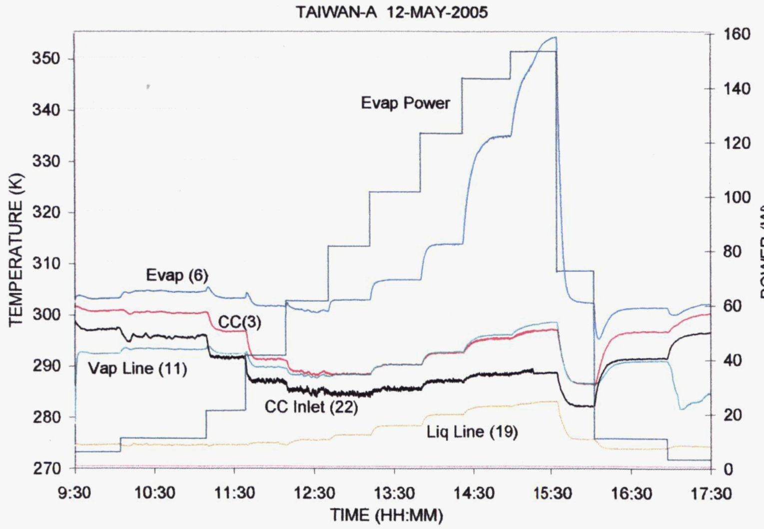

Figure 10 Temperature Profiles During a High Power Test at 273K Sink

Figure 11 shows another high power test at a sink temperature of 293K. The evaporator and the CC temperatures rose sharply as the heat load exceeded 150W, but recovered as the heat load was decreased to 100W.

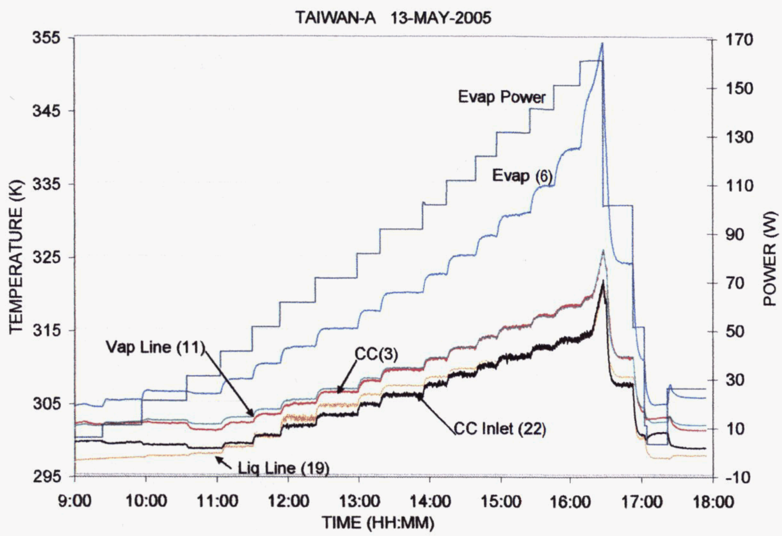

Figure 11 Temperature Profiles During a High Power Test at 293K Sink

<u>Low Power Test</u>

The flow circulation in an LHP is very slow at low powers, and is near stagnation at extreme low powers. The low heat load represents another challenge on the LHP operation. In the low power range, the operating temperature tends to increase with a decreasing heat load in order for the returning liquid to provide enough subcooling to compensate for the heat leak from the evaporator to the CC.

Figure 12 shows the loop operated at 5W for 8 hours. At this low power, the CC temperature was mainly a function of the ambient temperature. Test results show that the CC temperature increased by 0.5K over the test period. This was caused by a steady increase of the ambient temperature from 298K to 299K over the same period. Figure 13 shows that the loop could operate at heat loads as low as 1W and 0.5W. The loop operation at these low powers was evidenced by the fact that the CC temperature varied with the heat load and that the vapor line temperature rose and fell in tandem with the CC temperature.

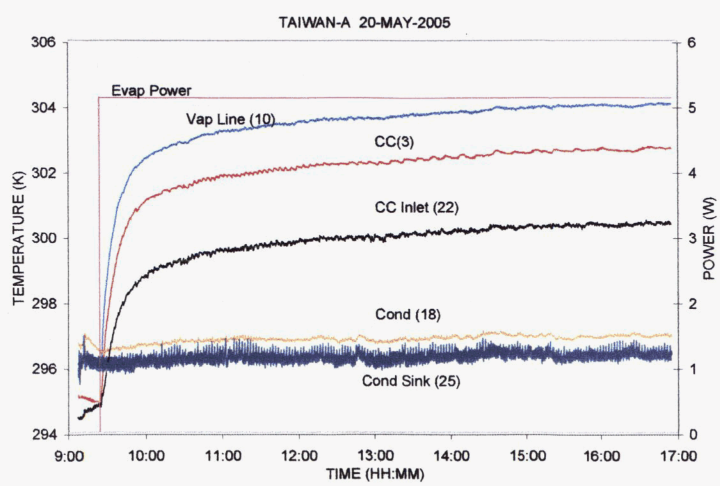

Figure 12 Temperature Profile During a Low Power Test

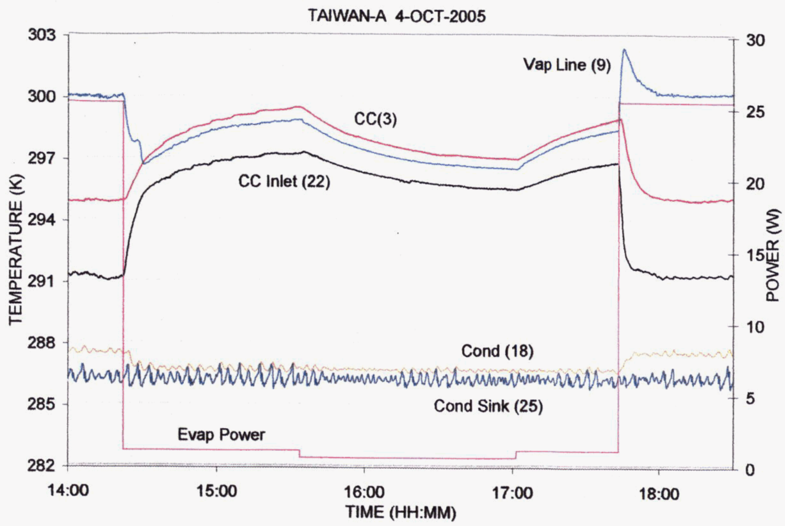

Figure 13 Temperature Profile during a Low Power Test

Characteristic Operating Temperature Curve

Figure 10 shows that the CC temperature decreased with an increasing heat load, reached a minimum and then increased with an increasing heat load. This is characteristic of the LHP operation when the ambient temperature is higher than the condenser sink temperature. The ambient temperature for all tests was between 292K and 298K. For all heat transport tests performed at sink temperatures of 253K, 273K and 283K, the same operating characteristics were seen. Figure 11, on the other hand, shows that the CC temperature increased with the heat load at all powers. This was because the sink temperature was at 293K, the same as the ambient temperature.

Figure 14 depicts the CC temperature as a function of the heat load at various sink temperatures. The plots yield the well known "V-shaped" curves. The minimum CC temperature in Figure 14 corresponds to the minimum heat load at which the condenser is fully utilized for vapor condensation. The heat load at which the minimum CC temperature occurred increased with a decreasing sink temperature, i.e. the condenser could accommodate a higher heat load at a lower sink temperature before it was fully utilized.

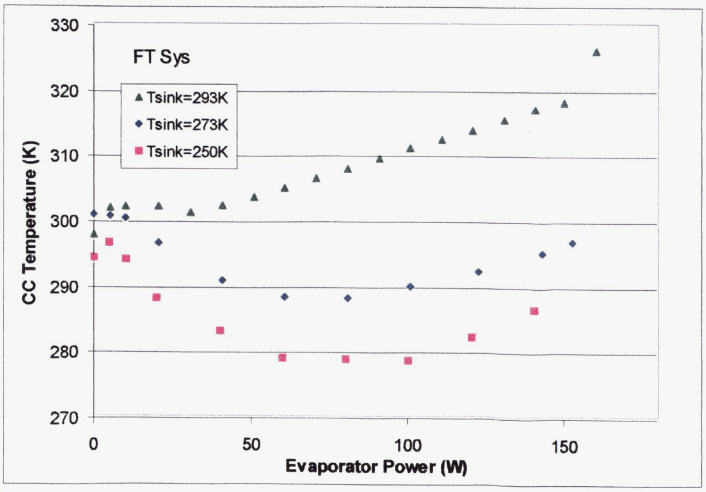

Figure 14 Loop Operating Temperature versus Heat Load

The CC temperature is directly affected by the condenser temperature, which in turn is a function of the condenser sink environment. As the condenser environment changes, e.g. from a convective environment to a radiative environment, the condenser temperature will be different, and so will the CC temperature. For the same reason, when the chiller which provides the circulating coolant to the condenser changes, the CC temperature could be affected. During the course of this test, two chillers were used because the first chiller malfunctioned shortly after test program began. Figure 15 shows how the loop operating temperature changed with the chiller at all power levels.

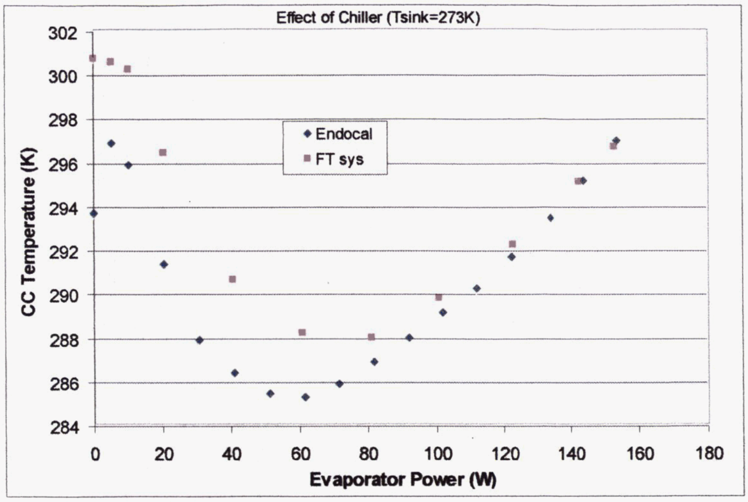

Figure 15 Effect of Different Sinks on the Loop Operating Temperature

4. Summary and Conclusion

A low-cost LHP was tested for performance characterization. The LHP demonstrated excellent performance over a wide range of operating conditions. Tests conducted included start-up, high power, low power, rapid power change and rapid sink temperature change. The loop could start with heat loads between 1W and 50W. It demonstrated stable operation with the heat load ranging from 1W to 150W, and the condenser sink temperature from 243K to 293K. The loop could adapt to step changes of the evaporator heat load from 5W to 100W to 2.5W, and step changes of the sink temperature between 243K and 293K. The loop operating temperature versus the heat load followed the typical "V-shaped" curve for a given condenser sink temperature. No performance anomalies were seen. Thus, the low-cost LHP has the potential to become the next-generation heat transfer device to cool terrestrial devices such as advanced electronics which have high power dissipations.

References

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