Testing of a Miniature Loop Heat Pipe Using a Thermal Electrical Cooler for Temperature Control

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Abstract

This paper describes the design and testing of a miniature LHP having a 7 mm O.D. evaporator with an integral CC. The vapor line and liquid line are made of 1.6mm stainless steel tubing. The evaporator and the CC are connected on the outer surface by a copper strap and a thermoelectric (TEC) is installed on the strap. The TEC is used to control the CC temperature by applying an electrical current for heating or cooling. Tests performed in ambient included start-up, power cycle, sink temperature cycle, and CC temperature control using TEC. The LHP demonstrated very robust operation in all tests where the heat load varied between 0.5W and 100W, and the sink temperature varied between 243K and 293K. The heat leak from the evaporator to the CC was extremely small. The TEC was able to control the CC temperature within ± 0.3K under all test conditions, and the required control heater power was less than 1W.

1.0 Introduction

Loop Heat Pipes (LHPs) are versatile two-phase heat transport devices capable of transferring large heat loads over long distances with small temperature differences [1,2]. After extensive developments over the last two decades, LHPs are being used on many NASA spacecraft including ICESAT, EOS-AURA, GOES and SWIFT, and commercial communications satellites. These "standard" LHPs have a single evaporator with an outer diameter (O.D.) of approximately 25mm. They can transport more than 1 kW of heat load using ammonia as the working fluid.

The advent of small spacecraft requires all subsystems to downsize. To meet such requirements, the LHP must reduce its evaporator to less than 15mm O.D. Under NASA's Cross Enterprise Technology Program, a project was implemented to develop miniature LHPs for future small spacecraft missions. Miniaturization of the evaporator faces several challenges. First, the manufacturability of a small metal wick must be demonstrated. Second, the ability to insert a small hollow wick with a thin wall into the evaporator body must be demonstrated. Third, as the wick thickness decreases, the heat leak from the evaporator to the compensation chamber (CC) as a percentage of the evaporator heat load may increase. Ways to design an evaporator with minimal heat leaks must be demonstrated.

This paper describes the design and testing of a miniature LHP having a 7 mm O.D. evaporator with an integral CC. The vapor line and liquid line are made of 1.6mm stainless steel tube. It has a transport capability of about 100W using ammonia as the working fluid. Details of the test article design, test set-up, and test results are discussed in the following sections.

2.0 Test Article

The miniature LHP, made by the Thermacore Inc., consists of an evaporator with an integral compensation chamber (CC), a vapor line, a liquid line and a condenser [10]. Main features of this miniature LHP include: 1) a 7-mm O.D. evaporator, 2) a stainless steel (SS) primary wick with 1.2 μm pore size, 3) SS vapor and liquid transport lines with 1.59 mm O.D., 4) aluminum condenser line with 2.39 mm O.D., and 5) a thermoelectric cooler (TEC) attached to the CC. Other design parameters are shown in Table 1. The design goal is to demonstrate miniature LHP operation between 2W and 20W in the temperature range of 263K and 303K.

Figure 1 show a picture of the test article where pert of the transport lines has been omitted for clarity. Figure 2 shows a close-up view of the evaporator and CC. A TEC is attached to the CC for temperature control. A copper strap connects the hot side of the TEC to the evaporator. Figure 3 shows that the condenser is serpentined for four passes and is mount to an aluminum cold plate.

Table 1. Summary of Design Parameters

Item	Description
Evaporator	Aluminum shell 7 mm O.D. x 51 mm L
Primary Wick	SS, 5.6 mm O.D. x 2.4mm I.D. 1.2 μm pore size 1.0×10^{-14} m^2 permeability
Secondary Wick	SS screen, 400 x 400 mesh
Compensation Chamber	SS 9.52 mm O.D. x 25.5 mm L
Vapor Line	SS, 1.59mm O.D. x 560 mm L
Liquid Line	SS, 1.59 mm O.D. x 635 mm L
Condenser	Aluminum 2.39mm O.D. x 200 mm L
Working Fluid	Ammonia, 1.5 grams
Total mass	79 grams

3.0 Test Program

3.1 Test Objectives

The objectives of the test programs are: 1) to verify that the miniature LHP can provide robust operation as the standard LHPs; 2) to verify that the loop can operate between 2W and 20W of evaporator heat load; 3) to verify that the loop can adapt quickly when subjected to rapid changes in the evaporator power and sink temperature; 4) to verify that the TEC can be used to control the CC temperature; 5) investigate the start-up transients, and 6) to investigate the effect of thermal masses on the loop operation.

3.2 Test Set-up

The miniature LHP was mounted to a thick oak board, and was insulated from all sides. A cartridge heater was attached to the evaporator through an aluminum saddle. Two aluminum thermal masses, 117 grams and 233 grams, were available to be attached to the aluminum saddle to simulate the instrument mass. A bipolar power supply was used for TEC operation. By changing the polarity of the power supply, the TEC could heat or cool the CC. Thermostats were used for all heaters for over temperature protection. The condenser plate was cooled by a chiller, which provided a coolant flow through copper tubing that was attached to the bottom side of the condenser plate.

The loop temperatures were measured by thirty-six type-T thermocouples. All power inputs were measured by wattmeters. A data acquisition system consisting of a personal computer, a CRT monitor, an HP datalogger, and Labview software was used to display and store data every two seconds.

3.3 Tests Performed

The test article was placed in a horizontal plane with the evaporator/CC slightly higher than the condenser (6.35mm). Tests were conducted with and without using the TEC, and with and without using the aluminum thermal masses. Without TEC, the loop would reach a natural equilibrium temperature according to the heat load and sink temperature. With TEC, the reservoir temperature was controlled at a desired set point through heating and cooling that was provided by the TEC. Two aluminum thermal masses (117 grams and 233 grams) were used. Each thermal mass has a hole to accommodate the cartridge heater. The two thermal masses could be used individually or together. Without thermal masses, the cartridge heater was attached to the evaporator through an aluminum bracket.

More than 500 hours of experimental data have been collected. Tests were performed with 0 gram, 117 gram, and 350 grams of thermal masses attached to the evaporator. The power to the evaporator varied between 0.5W and 100W, and the condenser sink temperature varied between 243K and 293 K. Tests conducted included start-up, power ramp-up, power cycle, low power, sink temperature cycle, and CC temperature control tests. Tests with 0 gram and 117 grams of thermal mass were conducted with the same chiller. Tests with a 350-gram thermal mass were conducted with a different chiller because the original chiller malfunctioned. To investigate the effects of different chillers on the loop operation, some tests without the thermal mass were repeated using the new chiller. Details of the results are discussion in the next section. Some highlights of the loop performance are given below:

- The loop could start and operate steadily with heat loads ranging from 0.5W to 100W and sink temperatures ranging from 243K to 293K.
- The TEC could control the CC temperature within ± 0.3K under all test conditions. The control heater power for TEC was less than 1W.
- The loop can adapt to rapid power changes (e.g. 5W/50W/5W, 1W/10W/1W, 25W/100W/25W) and rapid sink temperature changes (273K/293K/253K/273K) without any problems.
- The thermal masses had negligible effects on the loop operation.
- The loop operating temperature was affected by the chillers used under otherwise the same test condition.

4.0 Discussion of Test Results

4.1 Start-up

There are four start-up scenarios for LHPs, depending on the status of liquid and vapor in the evaporator core and the vapor grooves [2, 3]. Suffice it to say that the loop can start successfully if a high power (high heat flux) is applied to the evaporator. On the other hand, start-up with low heat loads (low heat fluxes) could be problematic, especially if the vapor grooves in the evaporator are filled with liquid and the evaporator core has a high vapor void fraction [4]. One objective of this test program is to study the minimum heat load that is required to start the loop successfully.

Figure 5 shows the loop temperatures during the start-up with 50W to the evaporator. The condenser sink was kept at 293K. With such a high heat load to the small evaporator, the loop started immediately as evidenced by the rise of the vapor line temperature and the decrease of the liquid line temperature. A power cycle test was subsequently conducted. Figure 6 shows the loop temperatures during start-up with a heat load of 5W and a sink temperature of 253K. The LHP also started almost immediately. After start-up, a rapid power cycle test was conducted. In both start-ups, no thermal masses were attached to the evaporator.

Adding a thermal mass to the evaporator has the same effect as reducing the net heat load to the evaporator during the start-up transient, and may adversely affect the success of the loop start-up. Figure 7 illustrates the start-up with a 117-gram aluminum block attached to the evaporator. A heat load of 1W was applied to the aluminum block and the sink was kept at 253K. Surprisingly, the loop started immediately as evidenced by the rise o the vapor line temperatures TC10 and TC13. The 117-gram thermal mass did not appear to have any effect on the start-up. The loop continued to operate for about 7 hours. The difference between TC10 and TC13 temperatures indicates that the vapor front hardly reached the condenser and vapor condensed in the vapor line. The heat load was then increased to 2.5W.

In summary, the loop demonstrated successful start-ups, with and without thermal masses, for heat loads of 1W, 2.5W, 5W, 10W, 20W, 40W, 50W and 80W, and sink temperatures of 243K, 253K, 273K and 293K. The fact that the loop could start with a low heat load and with a thermal mass is a good indication that the heat leak from the evaporator to the CC was very small.

4.2 Power Ramp-up and Power Cycle

The objectives of the power ramp-up and power cycle tests were to verify that the LHP can adapt to a sudden change in the evaporator heat load, and to study the effect of the thermal mass on the loop operation during the power transient. A typical power ramp-up test had a power profile of 20W/40W/60W/80W/100W. In most cases, the test was followed by a power cycle test. Figure 8 shows the power ramp-up test with 117 grams of thermal mass at a sink temperature of 273K. A power cycle test of 100W/25W/100W/25W was conducted following the power ramp-up test.

Figure 9 shows the power cycle test with 117 grams of thermal mass at a sink temperature of 273K. After the loop had successfully started with 1W, the evaporator power cycled between 1W and 10W several times. The loop operating temperature changed accordingly.

Many power cycle tests were performed throughout this test program. Two more examples can be seen in Figures 5 and 6 following the loop start-up. Test results indicate that the loop can adapt to the power change very quickly and, if necessary, adjust its operating temperature to reach a new steady state. The thermal masses attached to the evaporator had negligible effects on the loop operation during transients.

In addition to power cycle tests, many tests were performed with a constant power of 1W, 10W, 20W or 40W and lasted for more than 8 hours. Figure 10 shows the performance curves of the loop where the operating temperature is plotted as a function of evaporator heat load for three different sink temperatures. The performance curves with a 117-gram thermal mass are also included. As mentioned before, tests with 350-gram thermal mass were conducted with a different chiller. To verify the effect of the thermal mass on the loop operation, some tests without the thermal mass were repeated using the new chiller. The performance curves are illustrated in Figure 11.

Several features are worth mentioning regarding Figures 10 and 11. First, the performance curves follow the well-known V-shaped curve for LHP operation. Second, the operating temperature at the low end of the power spectrum is very close to the ambient temperature, deviating from the high operating temperatures as seen in many other LHPs. This is another indication that this loop has a very small heat leak from the evaporator to the CC. Third, the thermal masses, 117 grams and 350 grams, had little effects on the loop operating during steady state. This was expected. What was not expected, as mentioned previously, was that they also had little effects during the transients. Fourth, the new chiller yielded a lower operating temperature for the same heat load and sink temperature. The reason is that the new chiller provided a higher coolant flow rate. Therefore, the condenser was less utilized for the same hat load and the liquid exiting the condenser was more subcooled. Because the heat leak from the evaporator to the CC was the same, the CC naturally reached a lower equilibrium temperature.

4.3 Temperature Hysteresis

Under certain circumstances, the LHP can operate at different temperatures at different times even if the heat load and the sink temperature are the same. This is referred to as temperature hysteresis [2, 5-6]. A temperature hysteresis occurs because the vapor void fraction inside the evaporator core changes, resulting in a change in the heat leak from the evaporator to the CC. As long as the energy balance requirements are satisfied in the CC and the condenser, the loop can operate steadily at a different state.

The temperature hysteresis usually occurs at the low end of the evaporator power spectrum where the heat leak dominates the CC temperature. At higher heat loads, the mass flow rate (heat load) dominates the CC temperature and the temperature hysteresis is hardly noticeable even when it is present. In Figure 9, the loop operated at 302K right after the loop started with 1W. After a power cycle of 1W/10W/1W, the loop operated at 297K, i.e. a drop of 5K in the operating temperature. This can be explained as follows. The evaporator core had a higher void fraction right after start-up. When the loop operated at a higher power of 10W, the void fraction reduced due to the higher mass flow rate of cold liquid which caused some vapor to condense. When the power was decreased to 1W, the void fraction did not change from what it was at 10W. This is further evidenced in the second power cycle of 1W/10W/1W, where no temperature hysteresis is seen. Another example of the temperature hysteresis is seen in Figure 6 at 5W when the loop started and after a power cycle of 5W/50W/5W. For this loop, temperature hysterees only occurred when the heat load was less than 10W. Temperature hystereses were also absent for all tests where the CC temperature was actively controlled by the TEC.

4.4 Sink Temperature Cycle

The objective of the sink temperature cycle test was to verify that the miniature LHP can adapt to rapid changes in the sink temperature as standard LHPs will. Tests were conducted by cycling the sink temperature between 253K and 293K (273K/293K /253K/273K) while keeping the heat load constant at 2.5W, 10W, 20W, or 40W. Test conditions also included no thermal mass and 117 grams of thermal mass.

Figures 12 and 13 depict the loop temperature during the sink temperature cycle tests with an evaporator power of 40W and 2.5W, respectively. At 40W evaporator power, the CC temperature changed significantly with the change of the sink temperature. At 2.5W, the CC temperature was much less affected by the sink temperature because the ambient temperature dominated the CC temperature at low powers.

4.5 Low Power Operation

For LHPs and capillary pumped loops, operation at low powers represents a major challenge because the loops are more susceptible to failure due to the extremely low mass flow rates. This miniature LHP has demonstrated stable operations for heat loads less than 10W. Figure 7 shows the loop operated steadily for many hours with 1W applied to the 117-gram thermal mass. Figure 13 shows that the loop operated steadily at 2.5W even when subjected to varying sink temperatures.

Figure 14 shows that loop operation with 350 grams of mass at a sink temperature of 243K. After a successful start-up with 20W, the loop demonstrated steady operation at 5W, 1W and 0.5W. The result indicates that loop may be able to operate with parasitic heat gains alone.

4.6 Temperature Control with TEC

The CC temperature can be controlled at a desired set point temperature so that the loop operating temperature will not vary with the heat load and/or the sink temperature. There are several methods to control the CC temperature [2, 8, 9]; all are based on the same principle of cold-biasing the CC and providing external heat to maintain the CC at the desired set point temperature. The required control heater power is a function of the heat load and the sink temperature. One deficiency of this type of control method is that no active cooling of the CC is available. At low powers, the CC will reach a natural equilibrium temperature that is higher than the ambient temperature. In order for the loop to operate at lower temperatures, cooling of the CC is required. The use of TEC can accomplish both heating and cooling with a single device.

Figure 15 shows the loop operating temperature at a sink temperature of 273K when 1W was applied to the 117-gram thermal mass. Without active control, the CC reached an equilibrium temperature of 300.5K. Using a TEC, the loop temperature was controlled at 288K and the required power for the TEC was only 0.05W.

Figure 16 shows that the CC temperature was controlled at 293K over the power range of 1W to 100W at a sink temperature of 253K. Heating was required for heat loads of 20W and higher, while cooling was required for heat loads of 10W or lower. The required TEC power for heating or cooling the CC was less than 1W.

In Figure 12, the CC temperature varied between 281K and 301K as the sink temperature changed. Figure 17 shows that the CC temperature can be controlled at 300K using a TEC under the same heat load and sink temperatures. The required TEC power for heating or cooling was again less than 1W. Note that cooling of the CC after the condenser has been fully utilized is usually not practical because the CC has to dissipate the excess heat load that the condenser is not able to, and the excess heat load removed by the TEC is put right back into the evaporator and ultimately into the condenser. In Figure 17, the desired CC set point temperature of 300K was only 1K lower than the natural equilibrium temperature, it took the TEC less than 1W to cool the CC and the additional 1W was dissipated somewhere in the loop.

5.0 Conclusions

A miniature LHP with a 7mm O.D. evaporator and 1.6mm O.D. transport lines has been designed, fabricated, and tested. In ambient tests, the loop demonstrated robust operation and excellent performance for evaporator powers between 0.5W and 100W, sink temperatures between 243K and 293K, and thermal masses of 0 gram, 117 grams and 350 grams. The evaporator/CC design yielded a very small heat leak judging from the loop start-up and its normal operation. The loop could adapt to rapid changes in evaporator power and/or sink temperature. A single TEC was used for hating and cooling the CC and the CC temperature could be controlled within ± 0.3K under all test conditions. The TEC required less than 1W for its operation. The success of this miniature LHP development program represents a significant advance in LHP technology. Such miniature LHPs are particularly suited for future space missions requiring micro-satellites.

References

1. Maidanik
2. Ku, J, "Operating Characteristics of Loop Heat Pipes," SAE Paper No. 1999-01-2007, 29th International Conference on Environmental Systems, July 12-15, 1999, Denver Colorado.
3. Maidanik, Y.F., Solodovnik, N.N., and Y.G. Fershtater, "Investigation of Dynamic and Stationary Characteristics of a Loop Heat Pipe," IX International Heat Pipe Conference, May 1-5, 1995, Albuquerque, New Mexico.
4. Ku, J., Ottenstein, L., Rogers, P. and K. Cheung, "Low Power Operation of a Loop Heat Pipe," 31st International Conference on Environmental Systems, July 9-12, 2001, Orlando, Florida.
5. Cheung, M., Hoang, T., Ku, J., and Kaya, T, "Thermal Performance and Operational Characteristics of Loop Heat Pipe (NRL LHP), " SAE Paper No. 981813, *28th International Conference on Environmental Systems*, July 13-16, 1998, Danvers, Massachusetts.
6. Kaya, T., and Ku, J., "Investigation of the Temperature Hysteresis Phenomenon of a Loop Heat Pipe," *1999 National Heat Transfer Conference*, August 15-17, 1999, Albuquerque, New Mexico.
7. Wolf, D., and Bienert, W., "Investigation of Temperature Control Characteristics of Loop Heat Pipe," SAE Paper No. 941576, *24th International Conference on Environmental Systems*, July 20-23, 1994, Friedrichshafen, Germany.
8. Nikitkin, M. N., Kotlyarov, E. Y. and G. P. Serov, "Basics of loop Heat Pipe Temperature Control," SAE Paper No. 1999-01-2012.
9. Goncharov, K, "Some Special Features of LHP Designing for Space Applications," International Two-Phase Thermal Control Workshop, June 7-8, 2001, El-Segundo, California.
10. Khrustalev, D. and S. Semenov, "advances in Low-Temperature, Cryogenic, and Miniature Loop Heat Pipes," 14th Spacecraft Thermal Control workshop, March 11-13, 2003, El-Segunda, California.

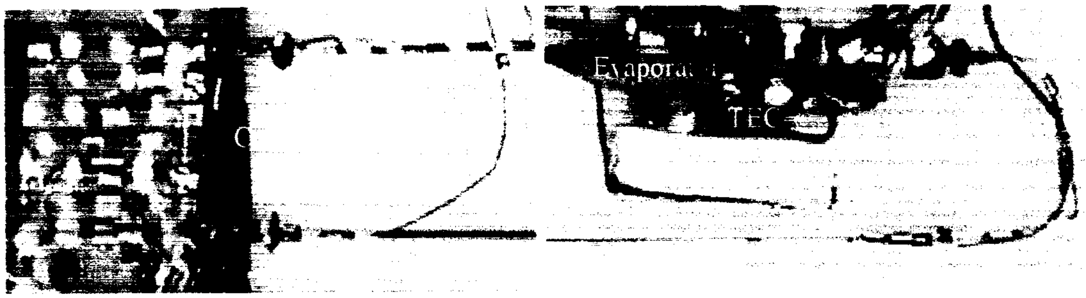
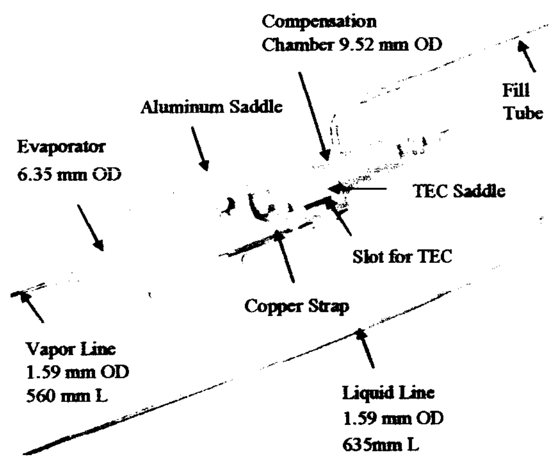


Figure 1



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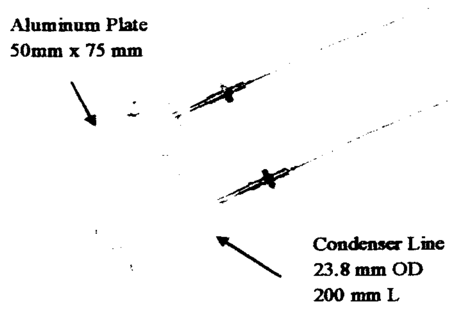

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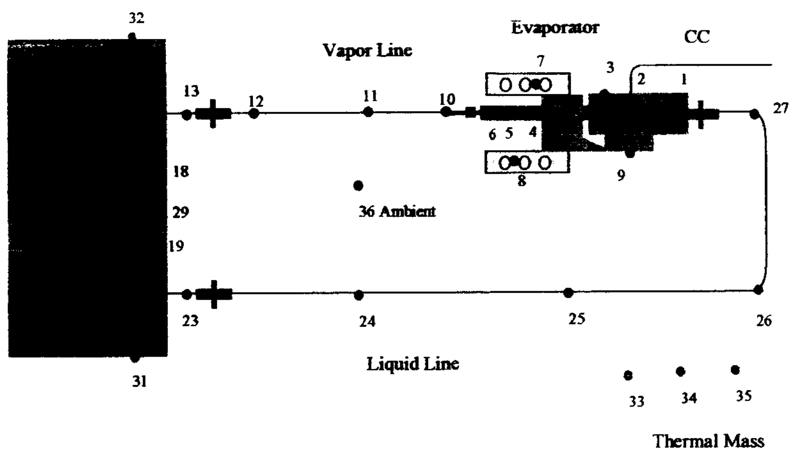

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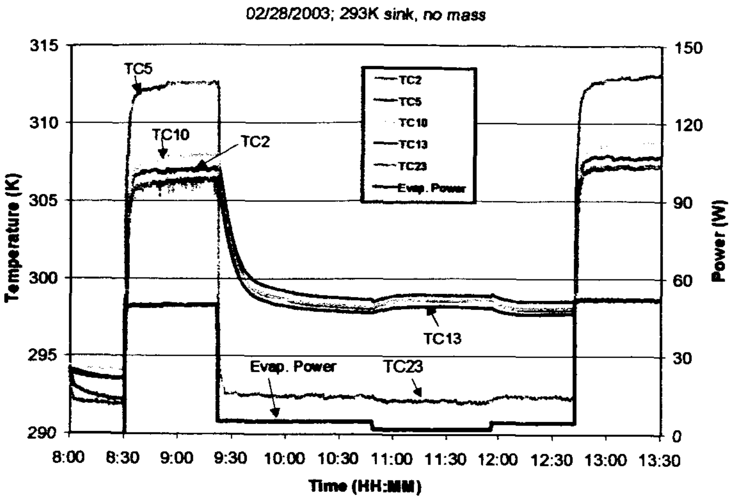

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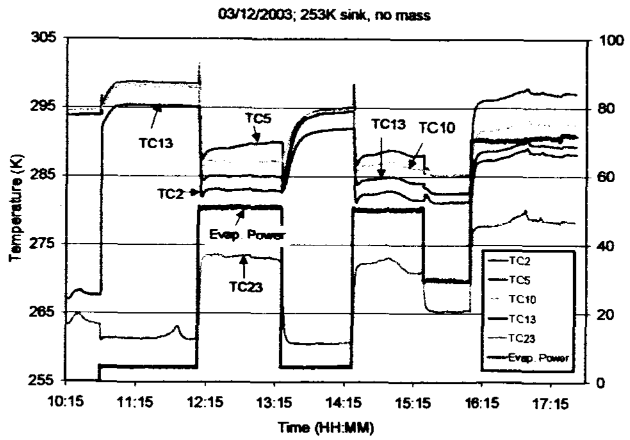

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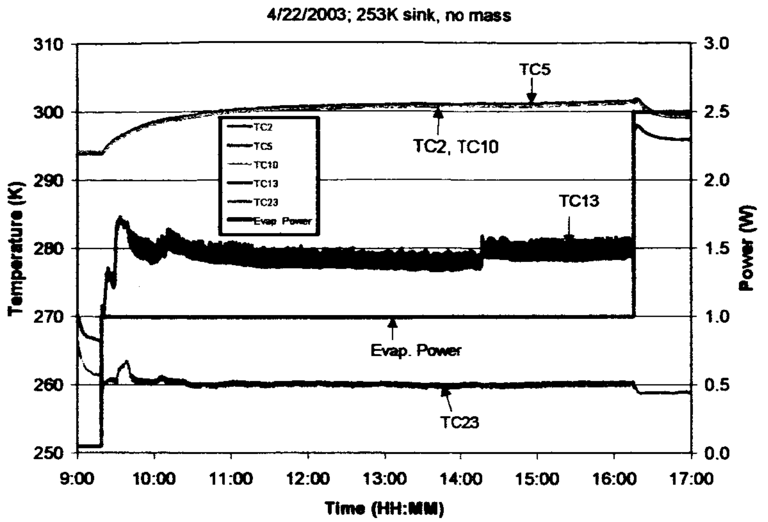

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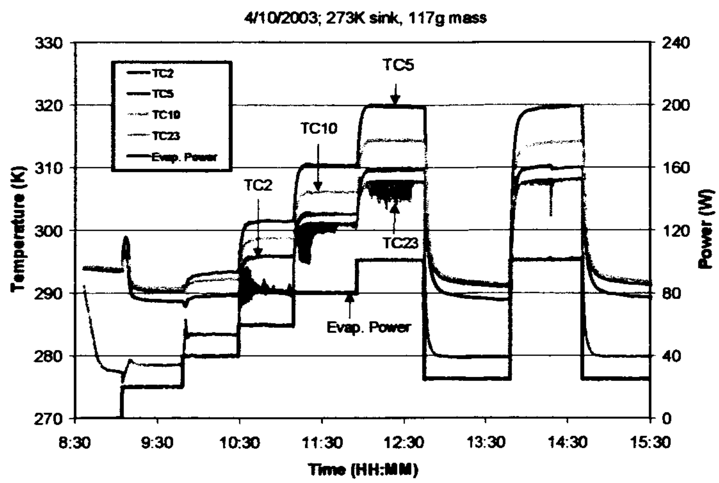

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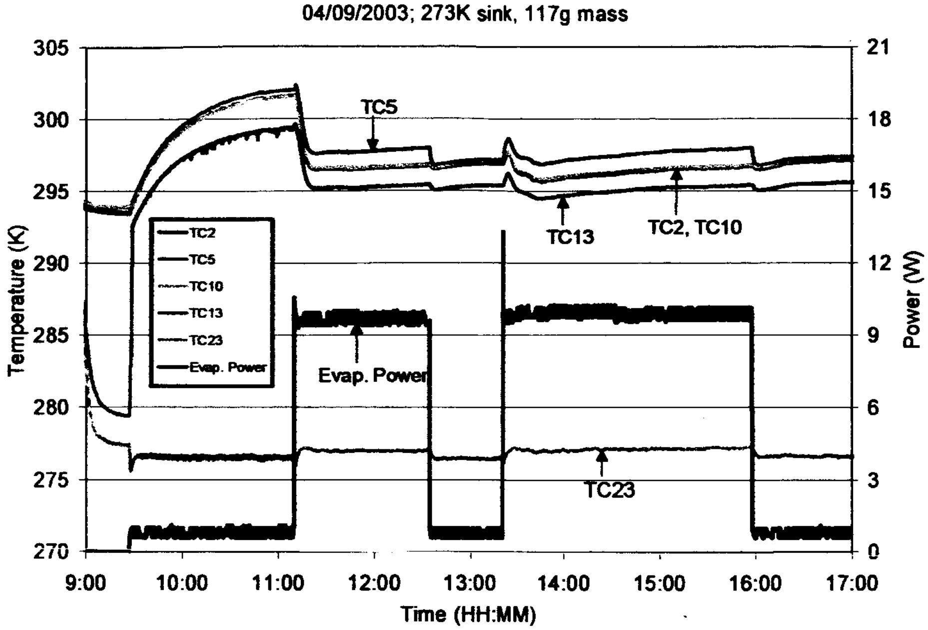


Figure 9

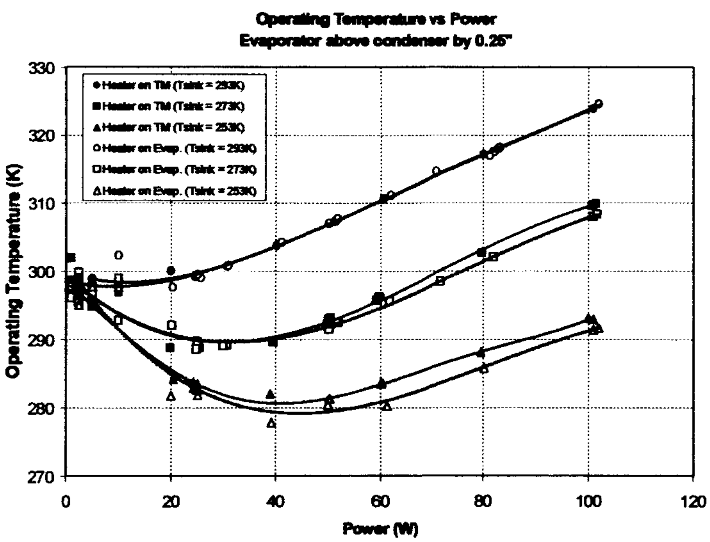
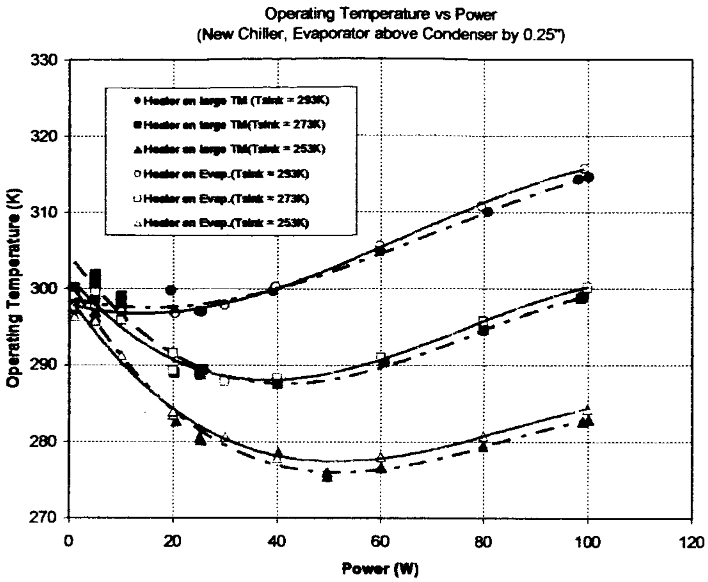


Figure 10



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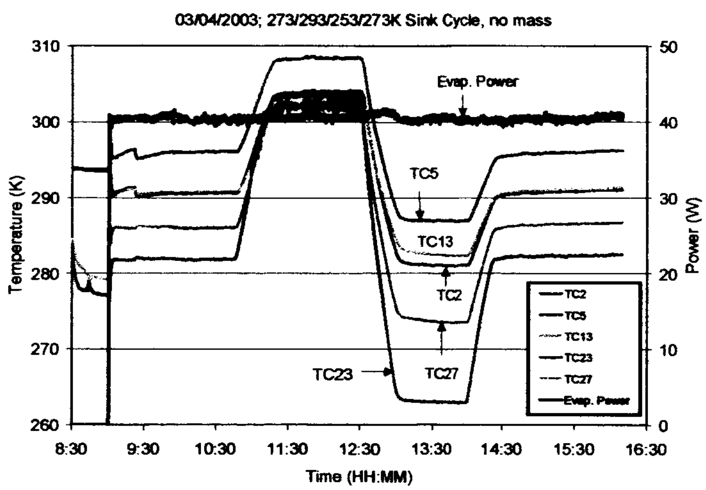

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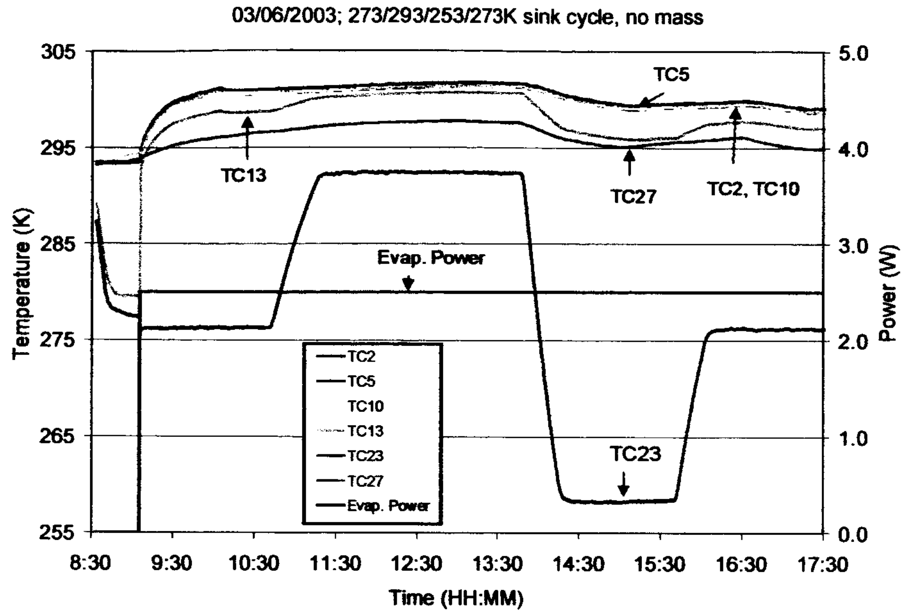

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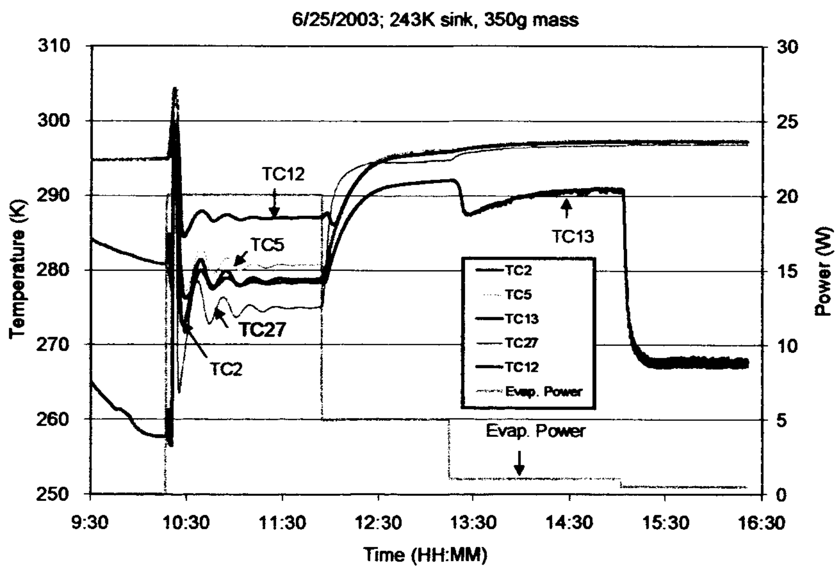

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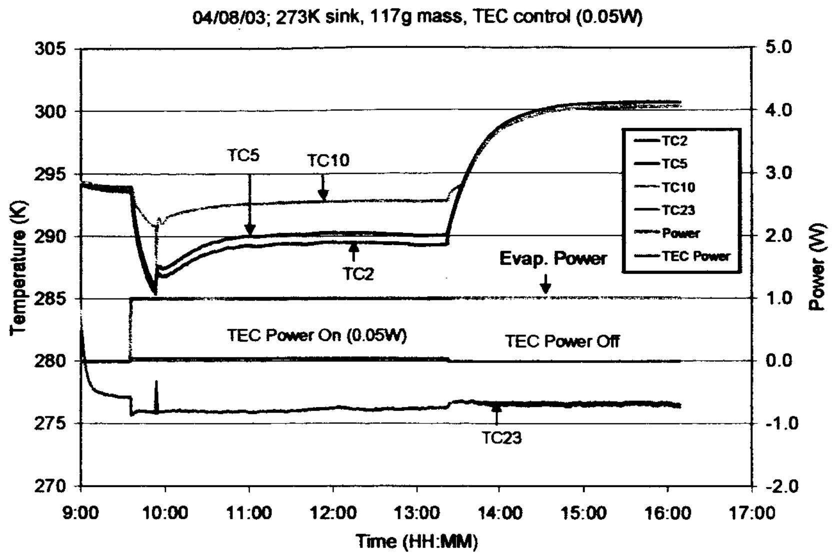
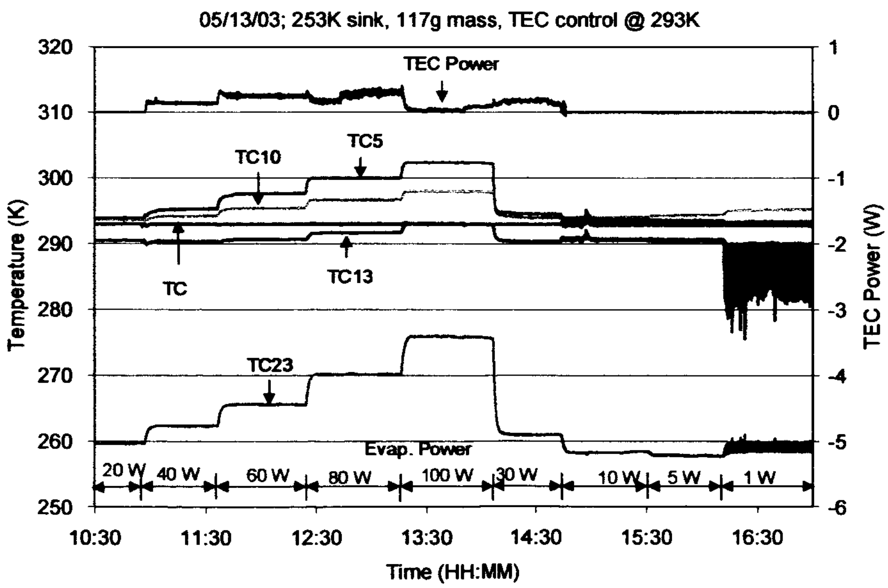


Figure 15



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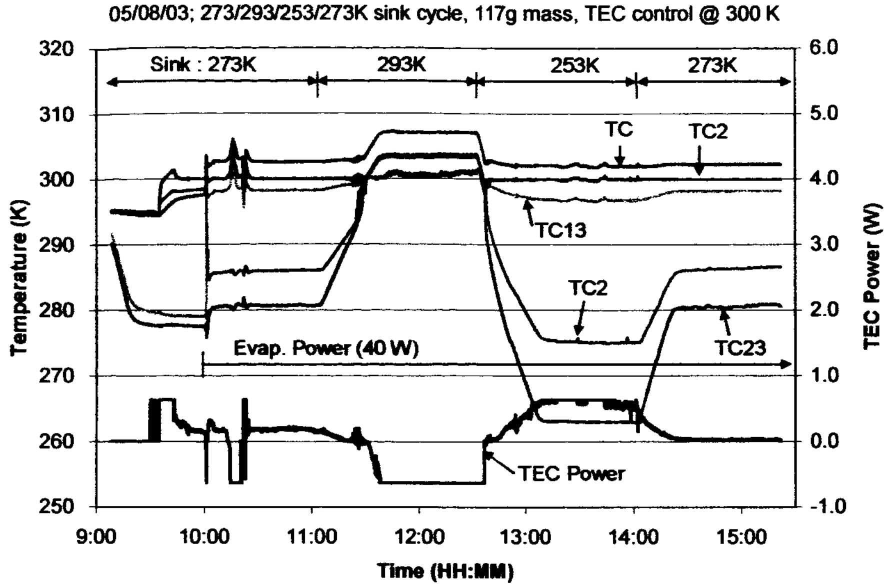

05/08/03; 273/293/253/273K sink cycle, 117g mass, TEC control @ 300 K
Sink : 273K
293K
253K
273K
TC
TC2
TC13
TC2
TC23
Evap. Power (40 W)
TEC Power
Temperature (K)
TEC Power (W)
Time (HH:MM)
320
310
300
290
280
270
260
250
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
9:00
10:00
11:00
12:00
13:00
14:00
15:00

Figure 17