



Two-Phase Loop: Compact Thermosyphon

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Power density of future microprocessors is projected to reach over 100 W/cm². Shrinking system size, the need to integrate more components within limited space, and customer demand to reduce system acoustic noise present significant challenges to the thermal designer. Thermosyphon technology provides a promising solution to these thermal challenges.

Conventional heat sink capability to overcome the new thermal challenges is limited. Refrigeration and spray cooling can provide a solution to the thermal challenges posed by the higher power density, however reliability issues are still unresolved making these solutions impractical for the current challenges. Loop thermosyphon provides the benefits of using liquid cooling for microprocessor. It is a two-phase passive cooling loop that uses liquid as a working fluid. The loop between the evaporator and the condenser results in separate vapor and condensate path. It is considered to be a compact thermal management device due to its flexibility in size and cooling capacity range.

This report presents HP Laboratories loop thermosyphon prototype and the experimental results of its thermal performance.

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CHAPTER 1

INTRODUCTION

1.1 Objective

Heat dissipation from high performance microprocessors is approaching 100 W/cm². At this level, conventional cooling solution cannot match the demand from these high performance components. This report presents a new way to resolve the thermal challenges by developing and implementing an innovative low cost compact loop thermosyphon.

A passive loop thermosyphon cooling system is described in conjunction with a demonstration vehicle built for HP Vectra VL800. The additional goal of the loop thermosyphon in the Vectra VL800 is to reduce acoustic noise in the system by eliminating the existing heat sink fan.

1.2 Background

A loop thermosyphon [1] is a two-phase passive loop that uses liquid as a working fluid for indirect and direct cooling. The loop thermosyphon as shown in Fig. 1.1 consists of an evaporator chamber, a vapor outlet tube called a rising tube exiting the top of the evaporator chamber, a condenser and a falling tube connecting the condenser outlet with the evaporator inlet. The evaporator chamber houses a boiling enhancement structure soldered to the inside surface of the evaporator bottom. It is a closed loop with water at reduced pressure or a dielectric fluid similar to FC72 or PF5060 as its working fluid. Using a dielectric fluid allows one to contemplate direct cooling with the microprocessor. The system removes the heat from the microprocessor by interfacing through the bottom

of the evaporator chamber causing the working fluid to heat up and reach boiling conditions where vapor bubbles start to form. The working fluid vapor then travels to the top of the evaporator chamber and into the condenser via the rising tube where it gets condensed and returns to the evaporator chamber via the falling tube and the cycle continues. The thermosyphon shown in Fig 1.1 is a two-phase loop with a compact evaporator that employs microfabricated boiling enhancement structures made of high thermal conductivity materials. The thermosyphon prototype was developed as a joint effort between Hewlett-Packard Laboratories, Georgia Institute of Technology and Thermacore. The prototype design and project management was performed by Hewlett-Packard Laboratories. The enhanced boiling structure was provided by Georgia Institute of Technology and the fabrication of the thermosyphon units was done by Thermacore.

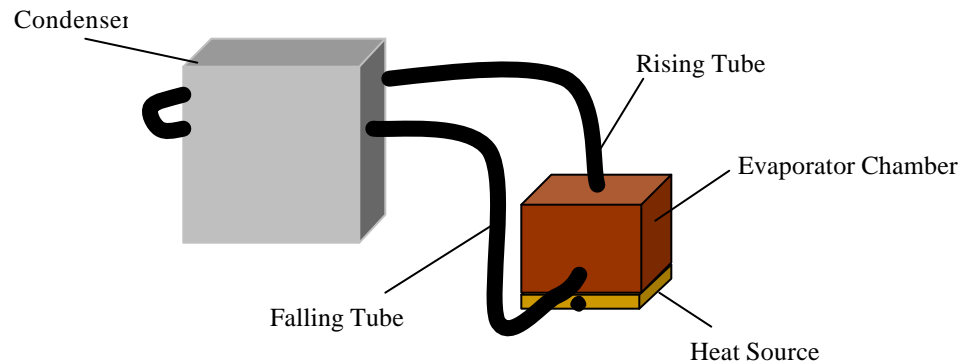


FIG. 1.1
Loop Thermosyphon.

1.3 Micro-Fabricated Boiling Enhanced Structure

Boiling enhancement structures increases vapor bubbles formation and helps the vapor departure from the evaporator chamber. Fig. 1.2 shows a sample of boiling enhancement structure that has been employed at University of Maryland and now at Georgia Institute of Technology to promote boiling of dielectric liquids similar to PF5060 [3].

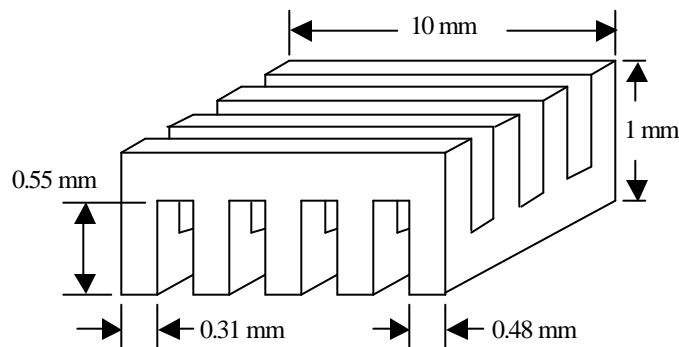


FIG. 1.2
Micro-fabricated boiling enhancement structure typical dimensions.

The fabrication of copper boiling enhancement structures uses wire electro-discharge machining (EDM). Figure 1.3 shows a 100 μm brass wire was used to cut these channels in a 1 mm thick copper plate where layers are bonded using 63Pb-37Sn solder.

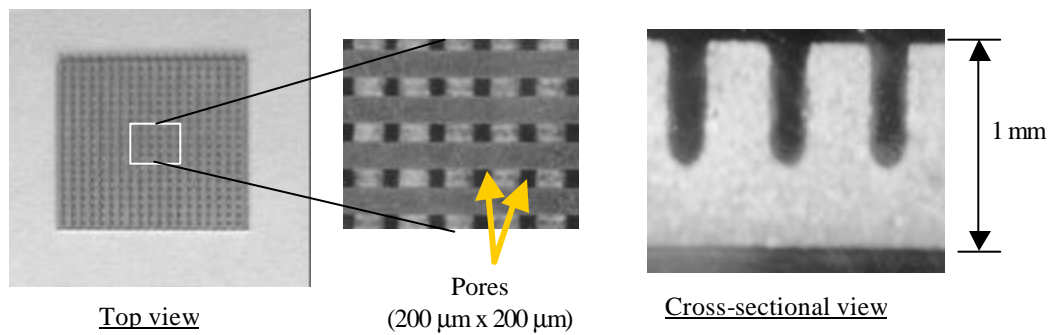


FIG. 1.3
Fabrication of copper boiling enhancement structures uses wire electro-discharge machining.

The structure is usually fabricated of copper and silicon and composed of an interconnected network of micro-channels that can be stacked to optimize space available as shown in Fig. 1.4.

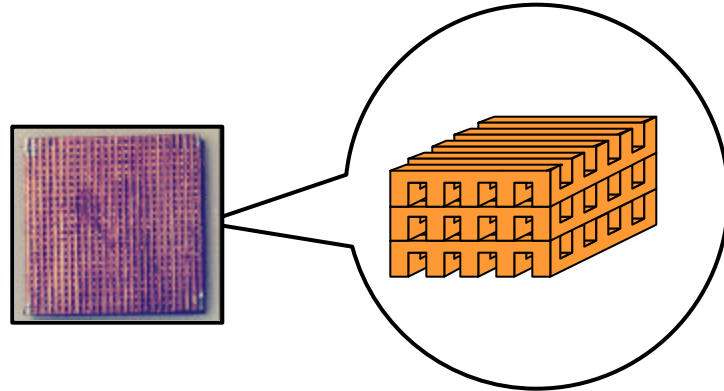


FIG. 1.4
A stacked boiling structure formed by joining multiple layers.

This structure is attached to the evaporator bottom as shown in Fig. 1.5. The heat is transferred from the processor lid to the evaporator and into the working fluid with the help of the enhanced structure.

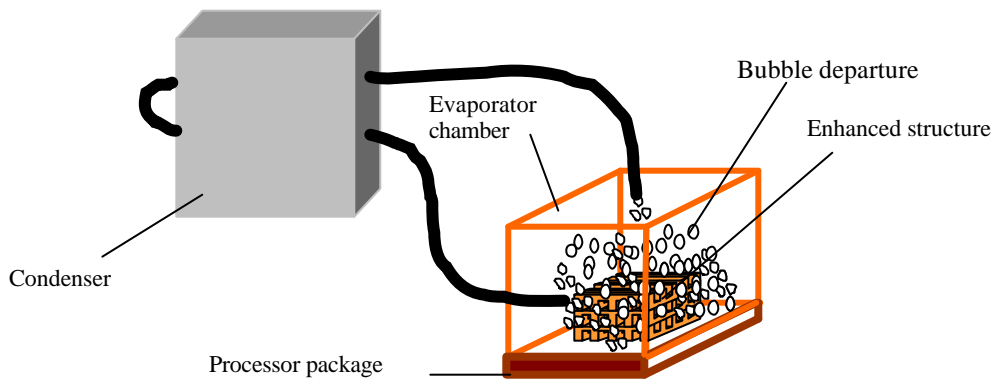


FIG. 1.5
Copper boiling enhancement structures fabricated using wire electro-discharge machining.

Georgia Institute of Technology, under DARPA (The Defense Advanced Research Projects Agency) HERETIC program, is working on developing an enhanced structure capable of removing heat flux up to 100 W/cm^2 . This is critical as pool boiling limitation of fluorinert fluids, such as PF5060 limit the heat flux removal to 16 W/cm^2 .

CHAPTER 2

COMPACT THERMOSYPHON DEMONSTRATION VEHICLE

2.1 Objective

A thermosyphon prototype was built to verify the performance hypotheses and demonstrate the effectiveness of this system as a passive cooling solution for two HP computer systems. Working jointly with Georgia Tech under the DARPA funded project, HP Laboratories designed and managed the prototype build up. The prototype serves as a demonstration vehicle of a thermal management scheme for Hewlett-Packard Vectra VL800 desktop computer with a 1.5 GHz Pentium-4 processor. The intent was to productize this approach for future systems.

2.2 Prototype Design Specifications

Table 2.1 summarizes the design specifications for the thermosyphon prototype.

CPU	P4
Heat Load	80 W
System Fan Air Flow	8 CFM (3.77 l/sec)
Max. Internal Ambient Temperature	45 C
Working Fluid	PF-5060
Available Condenser Volume	75mm H x 82mm W x 26mm D
Available Evaporator Volume	32mm L x 32mm W x 29mm H
Rise above Ambient	25 C

Table 2.1

2.3 Design Concept

The conceptual design of the prototype had the following:

1. An aluminum finned condenser with the fins oriented vertically.

2. A copper rising tube for vapor outlet exiting the top of the evaporator chamber and entering the side of the condenser.
3. A copper falling tube to return the condensed liquid to the side of the evaporator.
4. An evaporator chamber made of copper that houses the boiling enhancement structure.

Copper was used to fabricate the evaporator chamber and the tube because of its compatibility with the working fluid and ease of manufacturability. Moreover, copper tubing is easily bent making it easy to configure the thermosyphon into the available space inside a given computer system.

2.4 Removing Non-Condensable

Non-condensable such as air degrades thermosyphon performance. Care is required when charging the thermosyphon loop with the working fluid. During charging, the thermosyphon loop is brought to full operation by heating the evaporator chamber. Once the thermosyphon is in full operation, the non-condensable (air) is pushed to the elevated condenser where it is removed through a valve. This process is repeated until all non-condensables are removed from the system. Loss of some of the working fluid occurs during this procedure.

2.5 Working Fluid

The rule of thumb used by Thermacore Inc. requires that the working fluid height is three times the height of the enhanced structure. For the Vectra VL800, the enhanced structure height was 0.2 inch (~ 5mm) and the working fluid level was set at 0.6 inch (~

15mm). The thermosyphon charge amounts to 10 to 15 percent of the total volume available inside the evaporator chamber. That corresponds to about 8 cm³ for the Vectra VL800 PC.

2.6 The Final Prototype

The final thermosyphon prototype for the Vectra VL800 PC is shown in Fig. 2.1. The condenser was made of forty-five 3003-H14-aluminum fins with a surface area of 35 x 80 mm² oriented vertically. The evaporator dimension was 25 x 25 x 25 mm³ with a base of 30 x 30 x 2 mm³. The working fluid used for this prototype was a dielectric coolant PF5060 with a boiling temperature of 56 °C at atmospheric pressure.

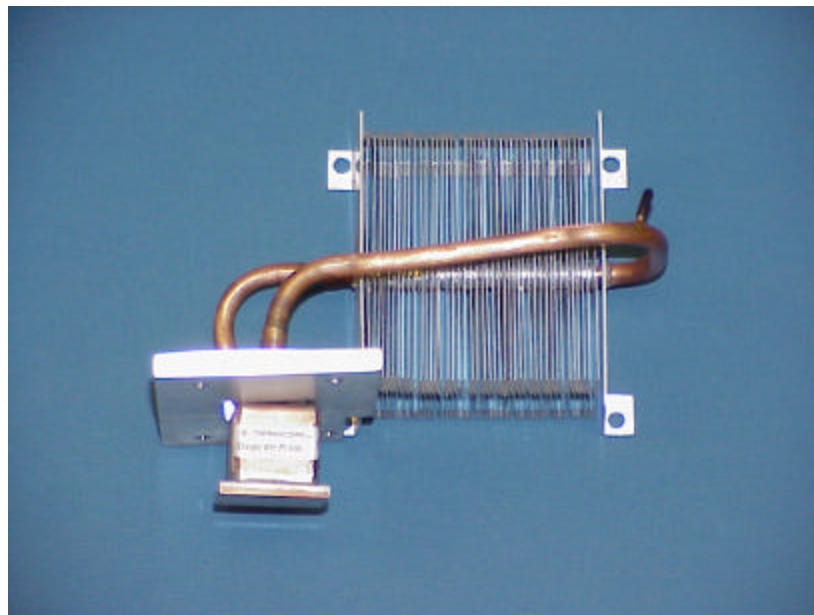


FIG. 2.1
Digital Picture of VL800 Vectra Loop Thermosyphon

This prototype was developed to replace the existing thermal management scheme of a heat sink with an integral fan as shown in Fig. 2.2.



FIG. 2.2
The existing thermal management scheme utilized in the HP Vectra desktop computer.

Figure 2.3 shows the new thermosyphon prototype integrated inside the 1.5 GHz Pentium 4 in Hewlett-Packard Vectra VL800 PC.

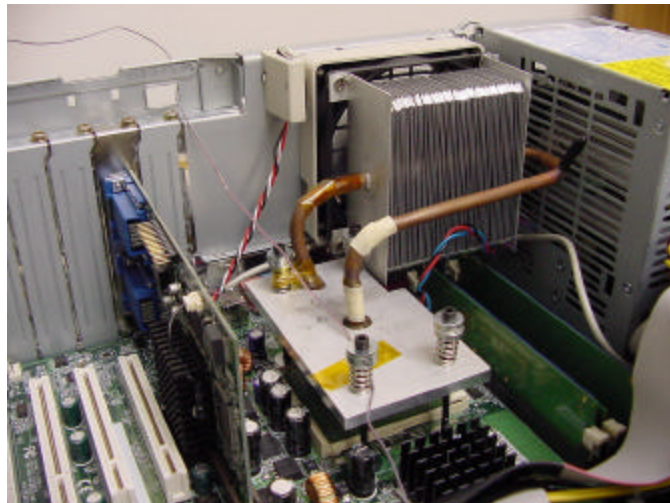


FIG. 2.3
Hewlett-Packard Vectra desktop retrofitted with a two-phase thermosyphon. The aluminum plate clamps the evaporator on the processor case.

CHAPTER 3

INVESTIGATION ON THE PERFORMANCE OF THE LOOP THERMOSYPHON

3.1 Inclination Effects

The performance of loop thermosyphon demonstration vehicle as a function of tilting angle was examined. Experiments were performed using a HP custom design protractor assembly to tilt the loop thermosyphon under a controlled condition. The tests were performed at a constant heat dissipation of 60 Watts for different tilting angles at an increment of 2° in both positive and negative direction from the horizontal position of the loop thermosyphon system.

3.1.1 Experimental Method and Apparatus

A schematic of the experimental apparatus is shown in Fig. 3.1. The evaporator chamber is attached to the top surface of a copper heater block. The bottom surface of the evaporator chamber is attached to the top surface of the heater block with thermal compound interface material (thermal conductivity = 0.39 W/(m-K)). Both the evaporator chamber and the heater block assembly are centered inside a bolted Plexiglas/Ultem enclosure to ensure a firm attachment between the evaporator and the surface of the heat source to minimize the interface resistance and to reduce heat lose to the environment. The heat source dimension is $30 \times 30 \times 10 \text{ mm}^3$. A cartridge heater inserted into the cooper block to provide 60 Watts of total power. The heat is provided by a variable power supply monitored by a digital wattmeter. The condenser is cooled by a fan powered by an HP E3616A DC power supply.

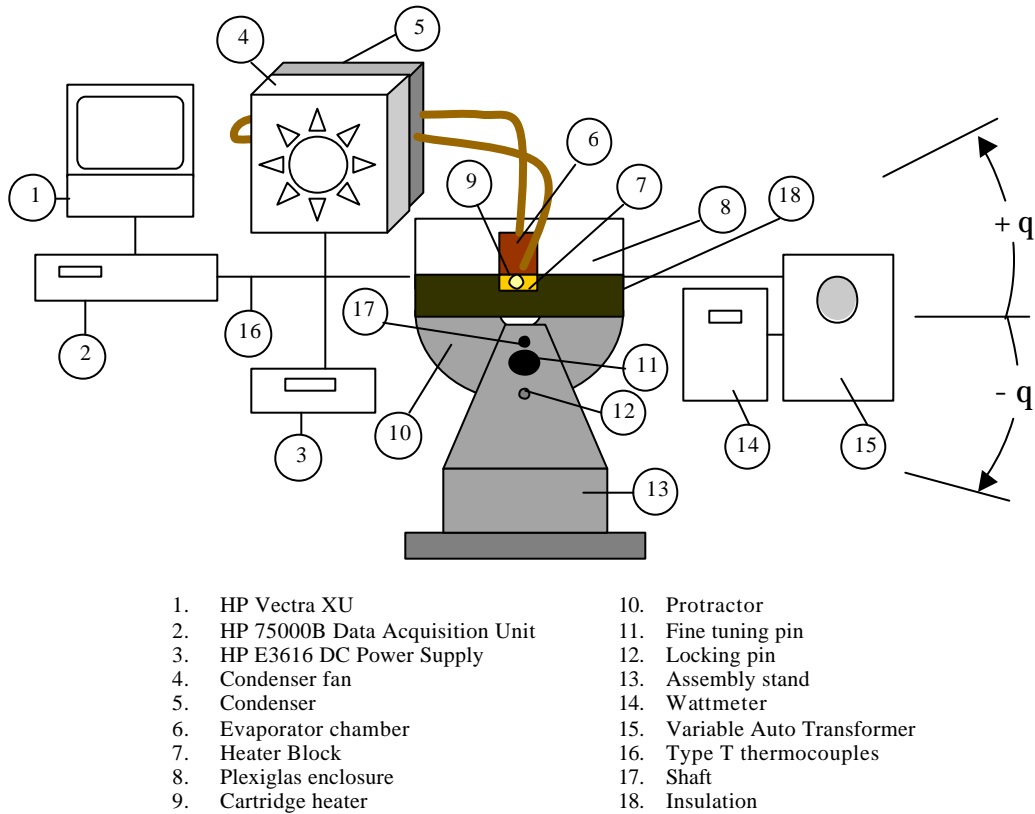


FIG. 3.1
Thermosyphon Test Assembly

The protractor assembly, as shown in Fig. 3.2, allows the tilting of the loop thermosyphon in increments of 2° from the horizontal position in both the positive and negative direction with a $\pm 0.2^\circ$. Temperatures of the evaporator, the condenser, the heat source and the inlet air to the condenser were measured using nine type T thermocouples. Steady-state temperature measurements were collected and recorded using an HP75000B data acquisition unit and an HP Vectra XU 6/200 utilizing HP Visual Engineering Environment (HPVEE) software program.

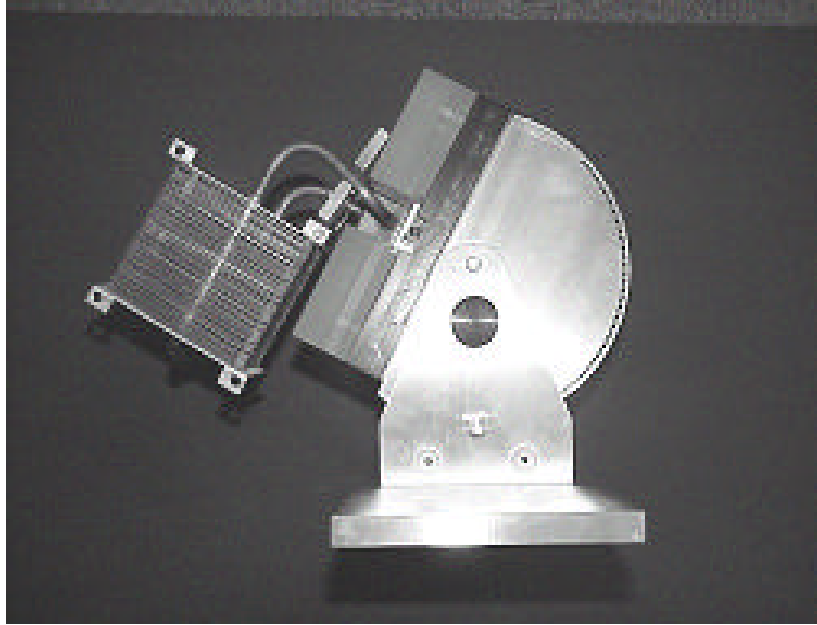


FIG. 3.2
Protractor Assembly Fixture.

3.1.2 Results and Discussion

The focus of the investigation is to examine the effect of the tilting angle on the performance of the loop thermosyphon. The heat removal takes place by forced convection from the surface of the condenser. Radiation heat loss is assumed to be small and negligible.

The temperature measurements showed that the evaporator maintains a uniform temperature reading for tilting angle up to -58° and that is the maximum tilting angle possible with the current fixture in the negative direction. However, in the positive direction, as shown in Fig. 3.3, the evaporator maintained a temperature between $66-71^\circ\text{C}$ for tilting angles up to 36° after which the evaporator temperature shot up to over 120°C . At this point the inclination is severe enough to prevent the return of sufficient

amount of liquid into the evaporator to replace the vapor leaving the chamber leading to dry out.

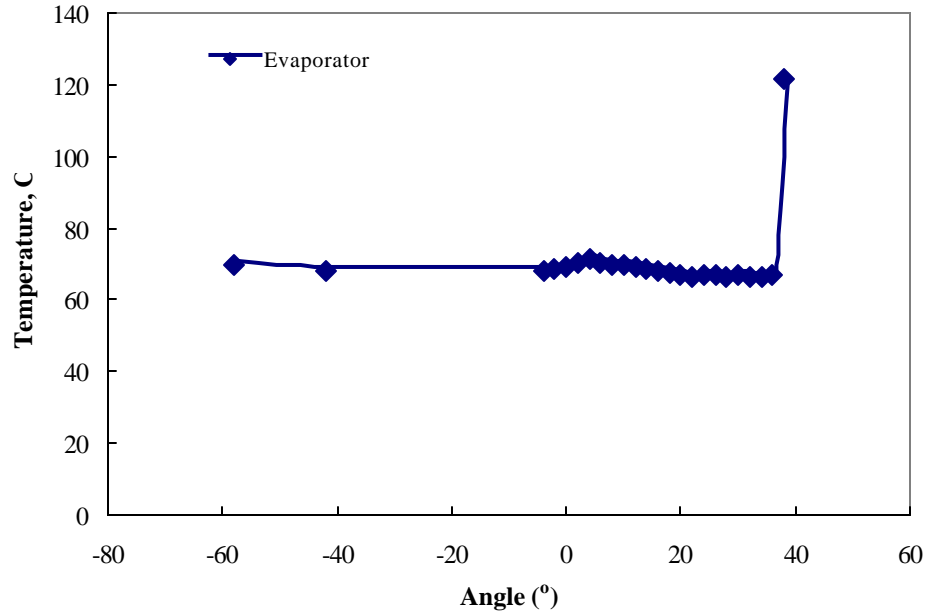


FIG. 3.3
Evaporator temperature vs. tilting angle.

Dry out makes the evaporator temperature rise suddenly due to the lack of cooling liquid present inside the evaporator chamber. The process takes place suddenly and with no advance notice causing a discontinuity in temperature. It is observed that the dry out angle occurs when the condenser outlet is at about the same level as the evaporator inlet. This was expected since this loop is gravity aided for liquid to return to the evaporator chamber. A positive gravity level has to be present between the condenser outlet and the evaporator chamber inlet.

Figure 3.4 shows temperature difference between the condenser and the evaporator versus the tilting angle.

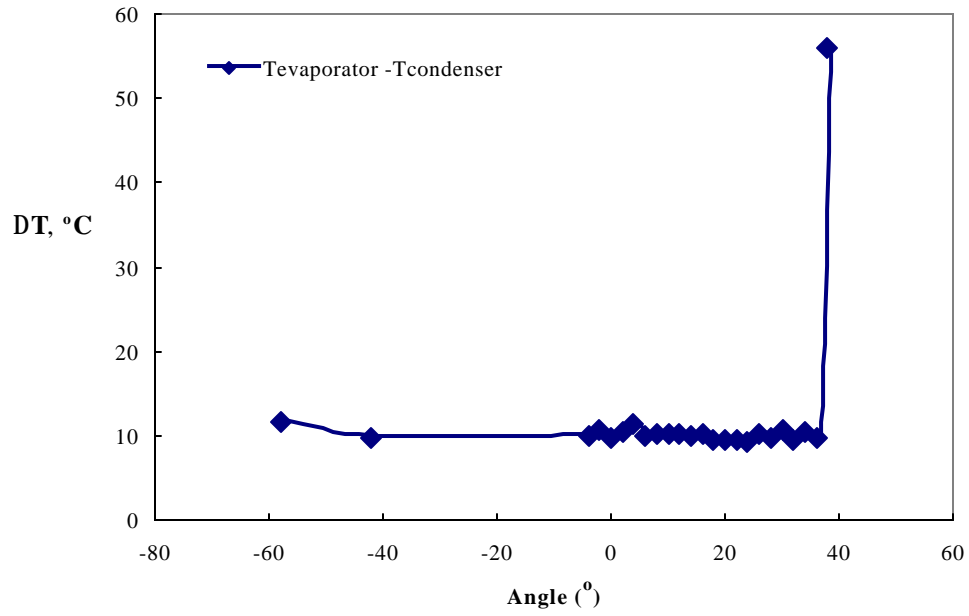


FIG. 3.4
 $(T_{\text{evaporator}} - T_{\text{condenser}})$ vs. tilting angle.

Figure 3.5 shows the thermal resistance between the heat source (chip) and the surrounding air temperature.

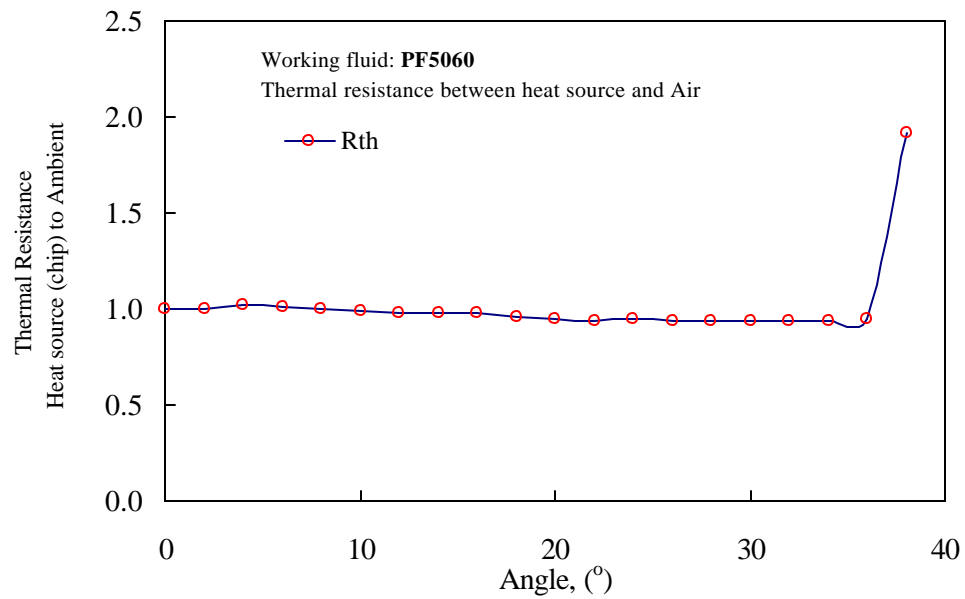


FIG. 3.5
 Thermal Resistance vs. Inclination Angle

The thermal resistance maintains a constant value up until reaching dry out temperature where the thermal resistance jumps to close the value of 2. A key finding is the thermal performance of the loop thermosyphon remained almost unaltered for a very large tilting angle. The results in this report represent preliminary findings and further testing will be performed on the general performance of the loop thermosyphon using water at a reduced pressure as the working fluid.

3.2 HP Vectra VL800 System Test

The objective was to test the system by exercising the processor using a program called p4maxpowerver5.exe used by HP to exercise P4 processor between 70 to 100 percent. A wattmeter connected between the main power outlet and the system provided the amount of power used to run the system. The test was performed by running the power level exercise program between 70 and 100 percent and recording the temperature of the evaporator chamber and the power consumed from the wattmeter.



FIG. 3.6
A digital photo of processor power exercise setup.

Table 3.1 shows the performance for different processor exercise level between 70 and 100 percent.

System: HP Vectra VL800 PC
 Inlet air temperature: 22 °C

Processor Exercise Level (%)	Evaporator Temperature (°C)	System Power Usage (Watt)	Comments
70	63	98	
75	65	102	
80	64	108	Fan speed increases
85	66	111	
90	68	116	
100	73	128	

Notice: The system equipped with a two-speed fan. The increase in the fan speed causes an increase of about 4 Watts in system power consumption.

Table 3.1
 Processor exercise test results.

The power consumption exhibits a linear increase with processor exercise level as shown in Fig. 3.7.

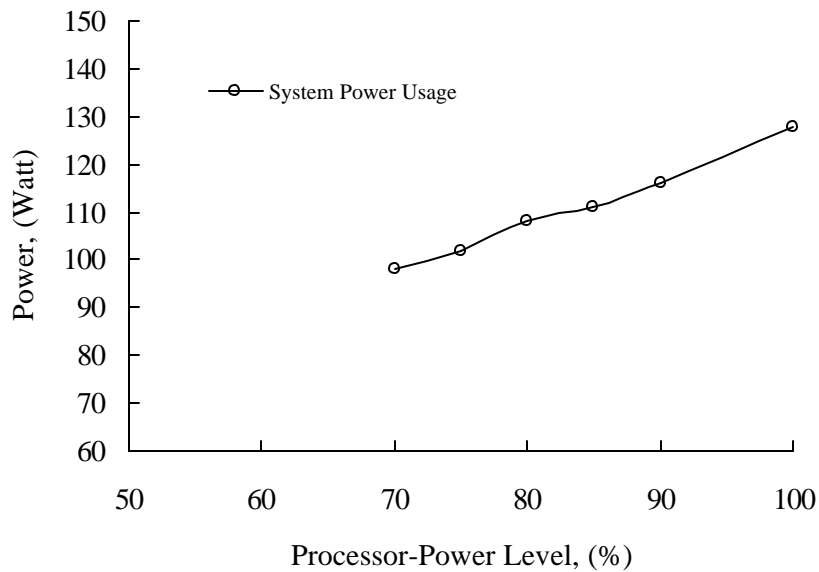


FIG. 3.7
 System power trend

Figure 3.8 shows the evaporator temperature response to the increase of the processor exercise level. The temperature of the evaporator follows more less a linear scale and the decrease in temperature at the 80 percent level of the processor's power was due to the increase in the system fan speed causing the evaporator temperature to drop down a little. The system fan has a two speed options depending on the processor's temperature.

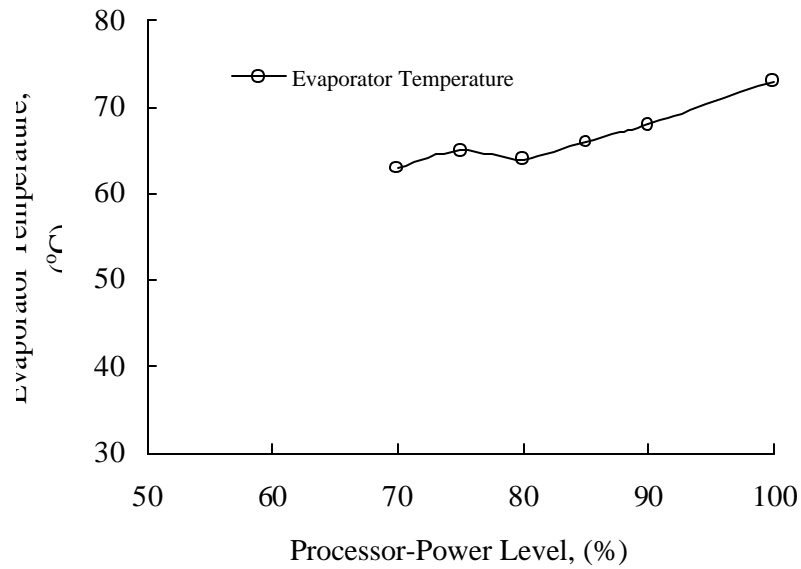


FIG. 3.8
System Power Trend

3.3 Vertical Arrangement (Right Angle) Test

For this technology to be useful to both desktop and mini-tower computers, thermosyphon system has to work in both horizontal and vertical arrangement. A right angle test was performed to investigate the effects of inclination on the performance of the thermosyphon. Table 3.2 display the test results for the VL800 Vectra system running at both the desktop (horizontal) position and the minitower (vertical) position. The

maximum deviation in temperature was about 9% where the average deviation was less than 5%. The test also included the minitower (vertical) position while having the system fan speed running at half the voltage (6 volts). Further tests should be done to analyze the performance of the thermosyphon as a function of the system fan voltage or system power consumption.

TC #	Description	Temperature				
		Horizontal (12V)	Vertical (12V)	% Diff.	Vertical (6V)	% Diff.
1	Evaporator Inlet	69.3	71	2%	79	14%
2	Evaporator Top	71.6	72	1%	79	10%
3	Condenser Outlet	58.6	58	-1%	65	11%
4	Heat Source	81.9	86	5%	93	14%
5	Evaporator Outlet	69.4	75.5	9%	82	18%
6	Fin Surface	29.7	28	-6%	33	11%
7	Condenser Inlet	60.5	60	-1%	66	9%
8	Inlet Air	22.2	22.5	1%	22.8	3%

Table 3.2
Right angle and fan power test results

3.4 Summary and Conclusions

A loop thermosyphon prototype was developed for Hewlett-Packard VL800 Vectra PC and its performance was evaluated as a function of tilting angle. System level analysis was also performed. The authors believe the thermosyphon device to be a very promising thermal management solution for the following reasons:

1. Thermosyphon is a passive heat transfer device that has no mechanical parts, which significantly reduces its reliability issues.
2. No energy is added to circulate the fluid and transfer the heat to the condenser by virtue of a pump.
3. It has a high heat removal capacity.
4. It has flexibility in design and integration.
5. Its quiet operation, in addition to the reduction in noise by replacing the heat sink fan, is a positive step for consumer and office desktop systems.
6. Eliminates preheated air generated inside the system by processor's heat sink since heat removed from the processor gets transferred to the condenser and into the air leaving the computer system.
7. Cost of producing large quantities for the VL800 PC is estimated to match that of the existing thermal management solution (fan mounted heat sink).

Acknowledgement

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