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Experimental Investigations of an Avionics Cooling System for Aerospace Vehicle

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With extensive use of high-power electronic devices in avionics systems, more effective heat transfer systems must be developed to meet high load heat transfer requirements. In this article, a cooling system in terms of pulsating heat pipe technology is presented and tested for the purpose of heat transfer enhancement in avionics systems. To achieve the enhancement, pulsating heat pipes with 1.65 mm internal diameter are fabricated and mounted with printed circuit boards onto the avionics chassis wall so that a quick heat transfer path is constructed from the electronic devices to the external heat sink. Experimental results indicate that pulsating heat pipe is capable of long distance and high-power heat transfer for new generation avionics systems, and temperature differences are significantly reduced compared to traditional thermal systems. Pulsating heat pipe performance characteristics, such as temperature fluctuation and orientation, are explored and discussed in this application as well.

Nomenclature

A	=	PHP cross section area
D	=	PHP tube diameter
g	=	gravity acceleration
h	=	liquid slug moving height
h_{fg}	=	latent heat of operating liquid
k_{eff}	=	effective thermal conductivity
L	=	PHP length
P	=	pressure
R	=	gas constant
T	=	temperature
v	=	average velocity of liquid slug/vapor bubble
Δ	=	difference
ρ	=	liquid density
$\propto$	=	viscosity of operating liquid

Subscripts

c	=	condenser
e	=	evaporator
f	=	friction

Introduction

WITH the introduction of new electronic devices in avionics systems, more waste heat is generated from electronic route and devices. For instance, a new generation avionics system within a chassis would dissipate more than 1 kW waste heat during operation. Even on single electronic modules, the dissipated heat will exceed 100 W. For example, in a traditional heat transfer system shown in Fig. 1, waste heat generated in electronic devices is first transferred to the aluminum chassis wall along printed circuit boards (PCBs), and then sent to an external heat sink by conduction of the chassis wall, and finally removed by gas/liquid convection or a loop heat pipe. As a result of the high waste-heat load, the long heat transfer path along the avionics chassis (approximately 37 cm) and low thermal conductivity of the PCB and chassis wall materials, a large temperature difference is expected between heat sources and the external heat sink. The large temperature difference significantly increases the operating temperature of electronic devices and/or the size of the cooling system. Thus, more effective heat transfer systems must be developed to solve these thermal problems.

Pulsating heat pipe (PHP) is a promising technology in avionics system cooling because it is lightweight, low cost, and capable of high heat load heat transfer. PHP was first invented by Akachi [1] in 1990, and its history can be traced back to Kurzweg and Zhao's [2] investigation of a "dream pipe" in capillary tubes. A PHP is made with a looped or unlooped serpentine capillary tube, as shown in Fig. 2. After vacuuming and filling a certain percentage liquid (volume ratios) in the tube, the atmosphere inside the PHP is set by equilibrium of saturated liquid and vapor slugs. At PHP's steady operation state, heat transfer is achieved by continuous oscillation movements from its evaporator to condenser, which is caused by instant pressure variation among different turns. Both phase change and sensible heat exchanges are thought to participate in the heat transfer. Since the late 1990s, a number of papers on PHP technology have been published. In experimental investigation areas, Akachi et al. [3], Miyazaki and Akachi [4], Maezawa et al. [5], Nishino [6], Gi et al. [7], Lin , and Cai et al. [9] observed liquid/vapor slug oscillation characteristics, explored oscillation mechanisms, and investigated heat transfer performance varying with fill ratios, operating liquid, and orientation. Khandekar et al. [10] conducted detailed reviews on PHP experiments and simulations. Chandratilleke et al. [11], Miyasaki et al. [12], and Katoh et al. [13] introduced PHP technology in the areas of cryogenic, aerospace, and avionics cooling. Zuo et al. [14] combined PHP with wick structure and demonstrated a higher cooling capability. In theoretical investigations, Miyazaki [15], Zuo et al. [14], Ma et al. [16], Wong et al. [17], Shafii et al. [18], and Zhang and Faghri [19] established their correlations to simulate PHP oscillation movements of liquid slugs and vapor bubbles and predicted oscillation relations with different working fluids, operating temperatures, PHP dimensions, and filled liquid ratios.

In the avionics heat transfer area, demonstrations by Katoh et al. [13] exhibit an attractive application potential of PHP technology,

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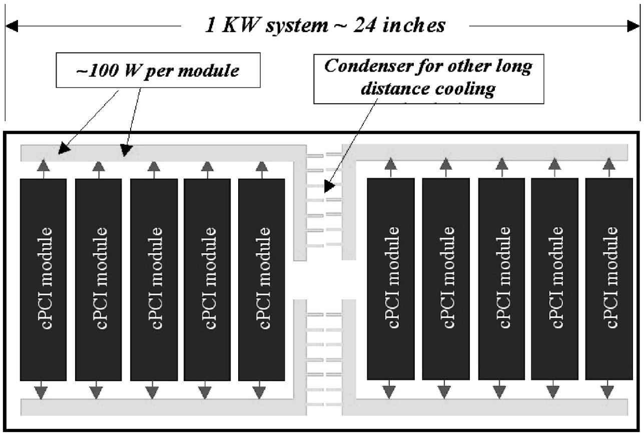

Fig. 1 Traditional avionics chassis cooling.

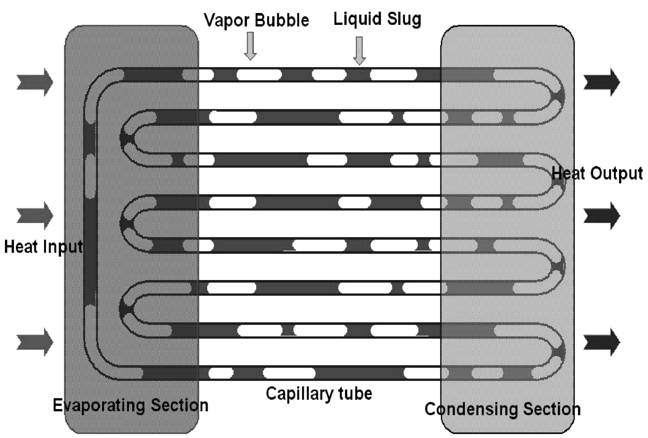

Fig. 2 Operating principle of PHP.

which provides a lightweight, low-cost, and high heat load heat transfer capability approach for modern avionics thermal management issues. In this article, PHP technology is employed to optimize heat transfer of next generation avionics systems. Two sets of PHP are designed to combine with PCB units and the chassis wall to lower temperature differences during system operation. Research attentions are focused on applying PHPs to increase thermal conduction along the heat transfer path, to achieve high heat load and long distance heat transfer along avionics chassis wall, and to investigate PHP operating characteristics, such as orientation effect and the evaporator temperature fluctuations, based on the application requests.

Experimental System Setup and Prototypes

To meet 1 kW and complicated geometry heat transfer requirements for modern avionics systems, a PHP cooling system composed of two sets of PHPs was designed, tested, and shown in Fig. 3. In an operating avionics chassis system, waste-heat is dissipated from electronic devices and mostly transferred down to PCBs. By embedding a PHP between two PCBs, it can provide a quick thermal path to the avionics chassis wall. The PHP section attached with PCBs functions as its evaporator, whereas the other section is bended and mounted on the sidewall of chassis and is used as its condenser. To enhance heat transfer along the chassis wall, another PHP is set. Through the PHP, heat coming from the PCB is quickly transferred in the thin aluminum wall, turns around the 90 deg corner, and reaches its condenser section where a heat sink is mounted. An external cooling system, such as gas/liquid convection or loop heat pipe, will further transport the waste-heat to external heat sinks [20]. In terms of this thermal system design, experimental tests are divided into two sections, which are PHP chassis wall cooling and PHP-PCB cooling, respectively.

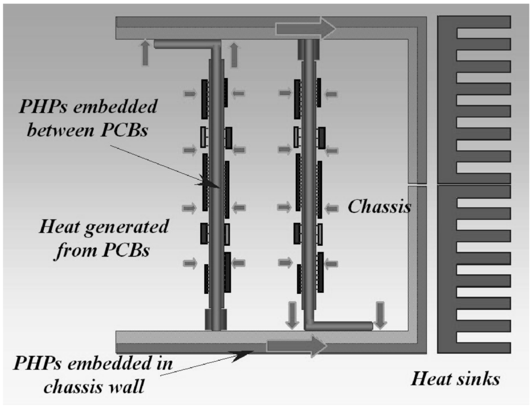

Fig. 3 PHP avionics heat transfer system.

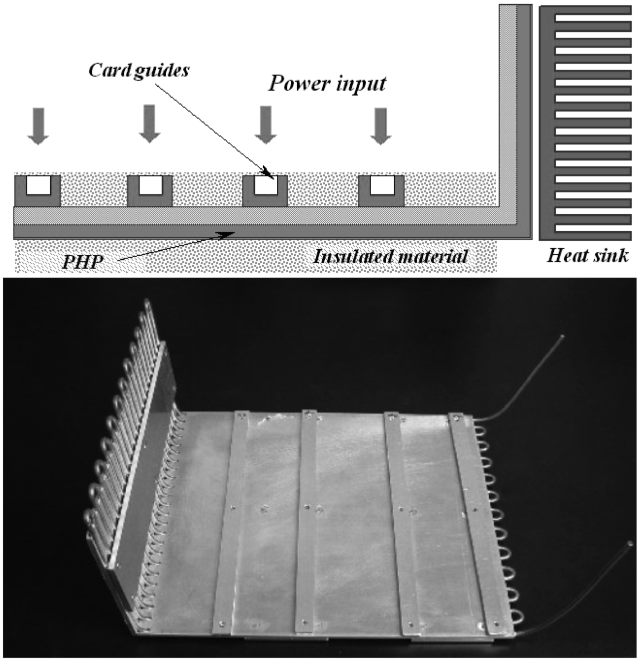

Fig. 4 PHP-chassis combination.

Figure 4 shows PHP design (upper figure) and prototype (bottom figure) for heat transfer enhancement of the chassis wall, which represents a quarter of the actual cooling system. Copper tubes with 3.18 mm outer diameter (OD) sit in serpentine grooves, which are made on the 3 mm aluminum chassis wall. The inner diameter (ID) of the copper tube is 1.65 mm. Because heat enters the PHP from its most horizontal section (24.5 cm), this section acts as the PHP evaporator. An aluminum heat sink is attached to the vertical section and is used as the condenser. It has a length of 12.5 cm. The PHP end-to-end heat transfer distance is around 37.0 cm and is longer than other published applications. In a 25.0 cm width of the aluminum chassis wall, 12 PHP turns are designed and fabricated for the maximum heat transfer of 400 W (250 W plus 60% safety reservation). The same copper tube (3.18 mm OD, 1.65 mm ID) is used to fabricate the PHP attached with PCBs, as shown in Fig. 5. For the maximum heat load of 165 W, eight PHP turns sit in grooves between two thin aluminum plates (2.0 mm) that are mounted on the PCB side opposite to the electronic devices. In experiments, the metal materials of the chassis wall and thin aluminum plates also act as heat collect and share heat transfer. Degassed, deionized water is used as operating liquid for high load heat transfer because of high latent heat, and ethanol and acetone are used as optional operating liquids for freezing environments. Three representative filling ratios, 40, 55, and 70%, are tested in these experiments. To reduce interface resistance, thermal grease is used between PHP tubes and grooves.

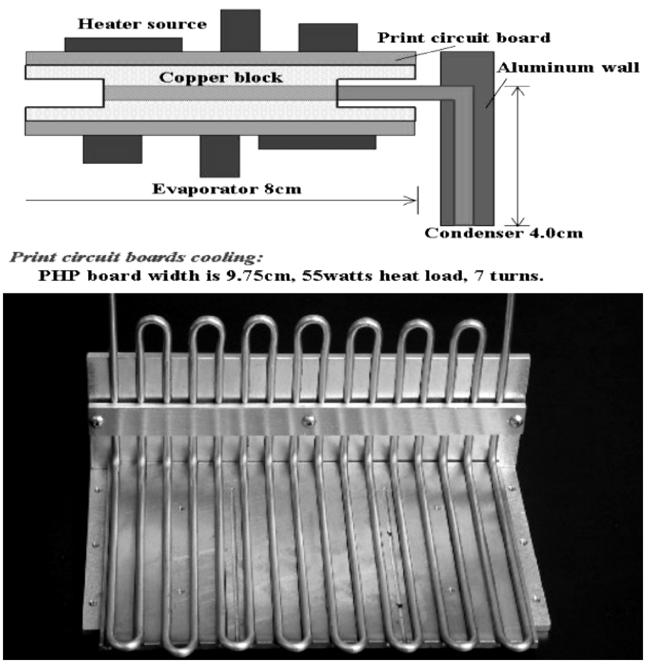

Fig. 5 PHP-PCB combination.

For the PHP prototype in avionics chassis wall cooling, four electrical heaters (1.3 cm long and 25 cm wide) mounted on the upper surface of the evaporator section mimic waste-heat coming from card guides or power modules. Spacing between the two heaters is 4 cm. For the PHP prototype in PCB cooling, uniform heating effect is created by two flat flexible heaters mounted on PCB sides without metal plates attached.

A test bed schematic of the PHP avionics cooling system is shown in Fig. 6. In all of the tests, thermal insulation is achieved by covering 4.0 cm silica fiber blankets on exposed areas of the evaporator sections. Condensers of PHP prototypes are attached with external heat sinks, which are cooled by air convection driven by a cooling fan. A 12-V power supply is used to drive the fan. Two series of thermocouples, which consist of 10 E-type thermocouples from the evaporator to condenser, are set for temperature measurement. The data processing system includes a data acquisition, a power meter, and a computer.

In the following experiments, ΔT is the focal point, which is defined as the temperature difference between the beginning of the evaporator section (right side in Fig. 6) and the end of the condenser section. In the test system described earlier, temperature measurements are conducted at steady states for each input power. The temperature spots drawn in the figures are their average values vs time. Temperature measurement bias of thermocouple is within $\pm 0.2°C$, and input power bias is within ± 2.0 W. The maximum heat loss through natural convection is less than 5% of the total input power while PHP operates at the highest heat load.

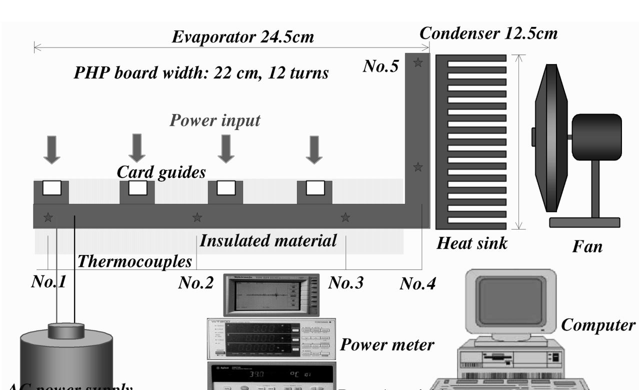

Fig. 6 Schematics of experimental system.

Experimental Results and Analysis

Experimental tests of PHP chassis wall cooling and PHP-PCB cooling are conducted on the test bed shown in Fig. 6. Test results of the avionics chassis wall cooling are plotted from Figs. 7–10, including heat transfer performance of traditional cooling approach by aluminum walls in Fig. 7. A linear increase of temperature difference with input powers indicates that the traditional cooling approach, heat conduction of aluminum wall, is not competent for high load heat transfer. At the lowest input power level of 100 W, the ΔT still exceeds 100°C. Before the maximum ΔT of 275°C at 300 W power level, high operating temperature will ruin most electronic devices. By introducing PHP into chassis wall cooling, heat transfer enhancement is achieved at all input power levels. Figure 8 indicates that temperature difference of water-copper PHP is significantly reduced at all tested filling ratios. Even for increase of input heat loads, heat transfer results of the PHP chassis wall show steady ΔT and high heat transport capability. Filling ratio of operating liquid is the only factor affecting the PHP performance here, and the ΔT varies from 30 to 50°C approximately when more water is filled into the PHP.

Ethanol and acetone are good antifreezing operating liquids and consequently are used in the PHP chassis cooling at potential freezing conditions. For high load heat transfer, their heat transfer performances are plotted in Figs. 9 and 10. A mutual disparity in these figures is the obvious increase of temperature difference vs input power. ΔT becomes three times larger to 57°C when increasing the heat load from 100 to 300 W in the 40% ethanol PHP. However,

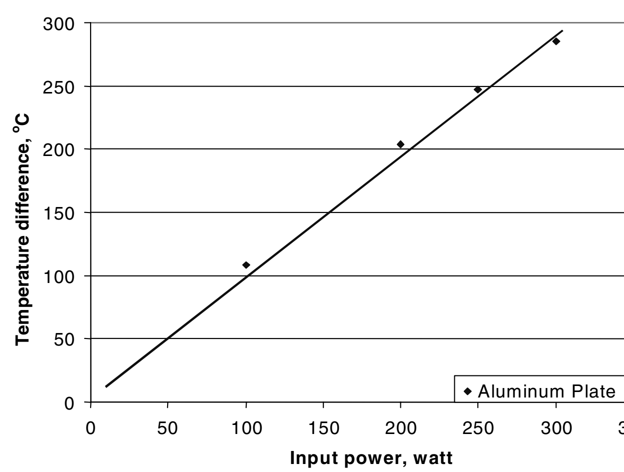

Fig. 7 Cooling effect of aluminum wall.

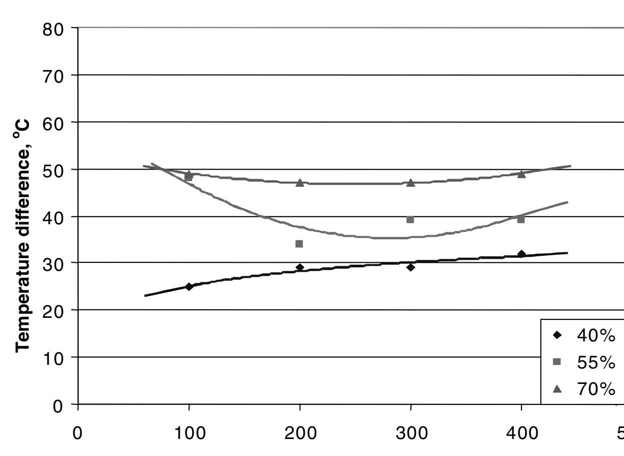

Fig. 8 Cooling effect of the chassis PHP.

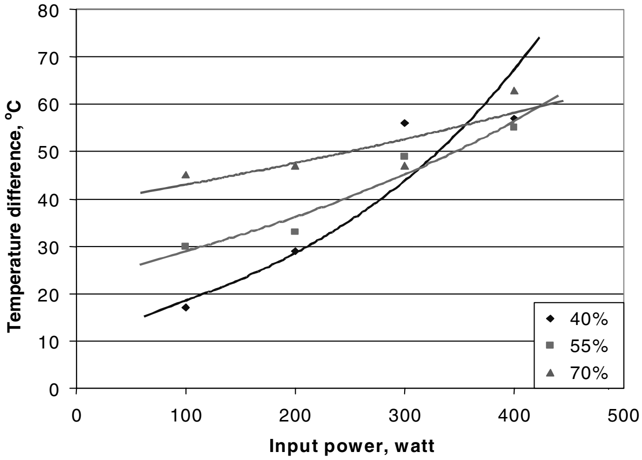

Fig. 9 Cooling effect of the ethanol chassis PHP.

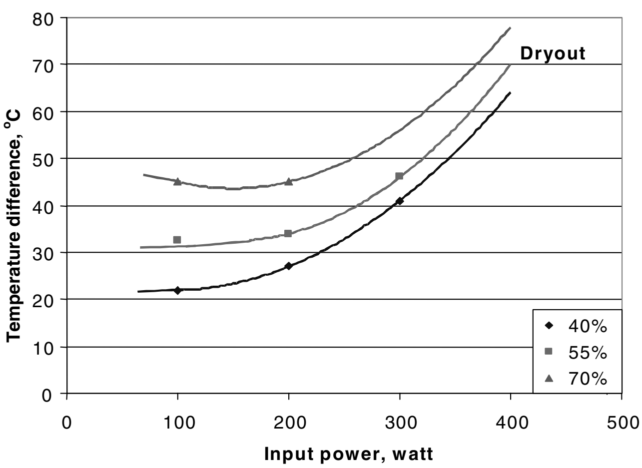

Fig. 10 Cooling effect of the acetone chassis PHP.

higher filling ratios have smaller ΔT increases with heat load, which are shown in tests with 55 and 70% charges. Dryout of the acetone PHP occurs at high heat load, which causes a terrific jump of the evaporator temperature. Except scenarios of dryout, heat transfer of ethanol and acetone PHP chassis cooling still demonstrates better performance than the traditional approach.

In various avionics chassis systems, actual heat dissipation area and load are different. Therefore, a simple theoretical analysis is helpful for system designers to decide proper PHP parameters for each application. In terms of classic heat transfer theory and the previous experimental results, a simplified model based on mechanical balance is established to analyze the PHP functional factors. It is assumed that in the PHP there exists an average transportation velocity v when vapor/liquid slugs are oscillating. It is also assumed that filling ratio of operating liquid is constant and PHP ΔT reflects saturated pressure difference and flow resistance. Starting from the Clausius–Clapeyron equation, vapor pressure in the evaporator section is

$$\Delta P = P_c\left(e^{[h_{\mathrm{fg}}(T_e - T_c)]/(RT_eT_c)} - 1\right) \tag{1}$$

Because the evaporator temperature $T_e = T_c + \Delta T$, using a Taylor series and neglecting high order terms, Eq. (1) can be written as

$$\Delta T = \frac{\Delta P R T_c^2}{h_{\mathrm{fg}} P_c - \Delta P R T_c} \tag{2}$$

Assuming vapor flow resistance can be ignored, liquid flow resistance is

$$\Delta P_f = \Delta P = \frac{32 \propto L v}{D^2} \tag{3}$$

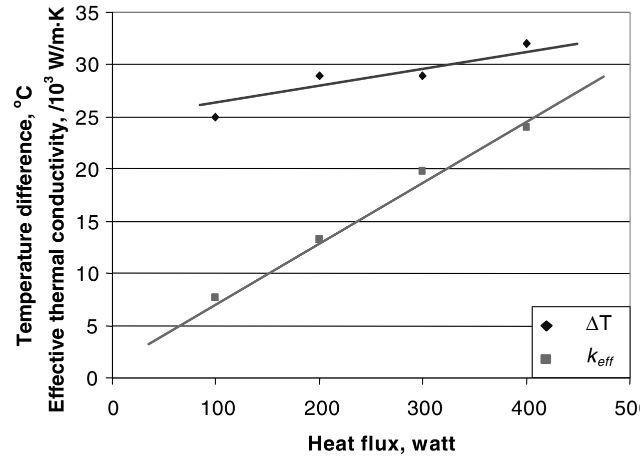

Fig. 11 ΔT and effective thermal conductivity via input power.

Combining Eqs. (3) and (4), the effective thermal conductivity of the PHP is

$$k_{\mathrm{eff}} = \frac{QL}{A\Delta T} = \frac{QL}{A}\left(\frac{h_{\mathrm{fg}} P_c D^2}{32 \propto L v R T_c^2} - \frac{1}{T_c}\right) \tag{4}$$

Equation (4) shows that, if the PHP input power (condenser temperature) and filling ratio are constant, k_{eff} is functions of liquid latent heat h_{fg} (using different liquid), liquid viscosity $\propto$ and flow velocity v. Higher latent heat liquid, lower liquid viscosity, and flow velocity will yield higher effective thermal conductivity. If the sensible heat is most heat transfer mode [18,19] in a PHP, the factor of flow velocity v implies that liquid specific heat C_p will be critical in the PHP performance. For a certain operating liquid, effective thermal conductivity becomes functions of input power Q, saturated temperature T_c and pressure P_c at the condenser, liquid viscosity $\propto$, and flow velocity v. Figure 11 shows the PHP effective thermal conductivities vs input heat loads for 40% water PHP tests. The increase of effective thermal conductivity inhibits ΔT raise.

By changing the PHP condenser temperature at 400 W heat load, temperature differences of the 40% water PHP vs operating temperatures are plotted in Fig. 12. Similar to a conventional heat pipe, the PHP performance also shows a relevance to the system operating temperature. As operating temperature increases, the ΔT first reduces until it reaches the minimum at approximately 120°C, and then rises to higher ΔT.

With the prototype shown in Fig. 5, the PHP-PCB power modules cooling approach is to collect and transport PCB waste-heat to its condenser (aluminum chassis wall). Same operating liquids, water, methanol, and acetone, are tested in the prototype with a filling ratio of 40%. Three levels of input power, 55, 110, and 165 W, are added

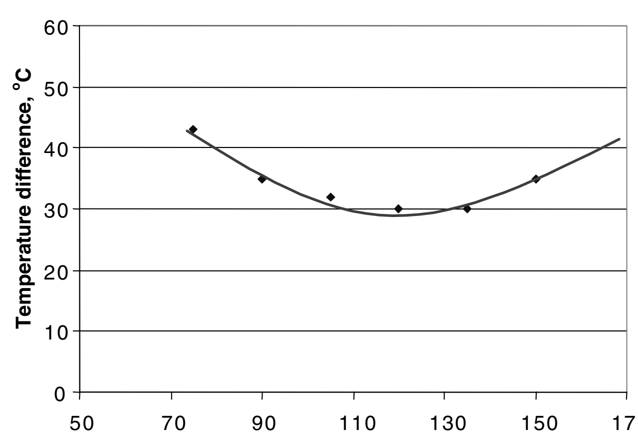

Fig. 12 ΔT variations with operating temperature.

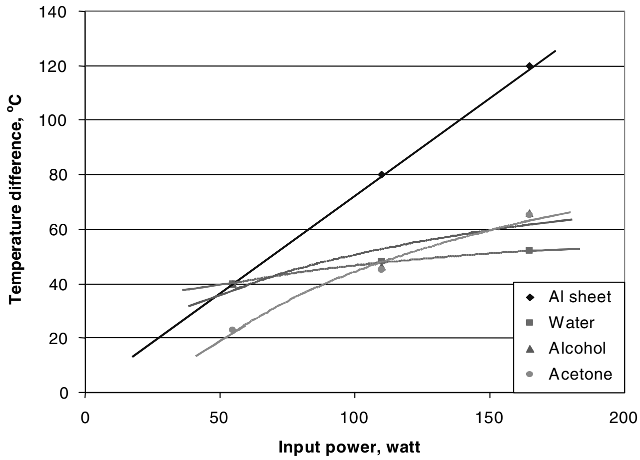

Fig. 13 Test results of PCB cooling.

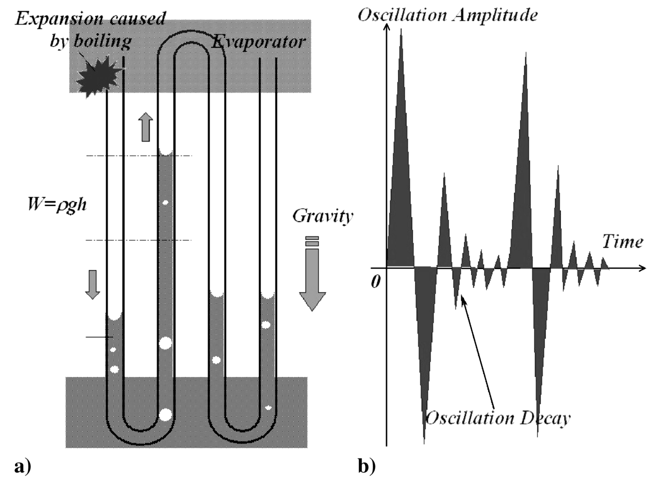

Fig. 15 Analysis of orientation effect.

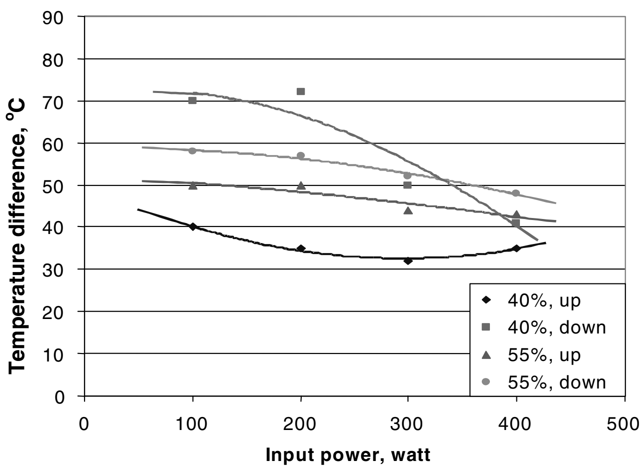

Fig. 14 Test results of orientation effect.

on the system, respectively. For comparison, the heat transfer using aluminum plates is performed.

For the total ΔT shown in Fig. 13, heat transfer across PCB contributes a large proportion due to low thermal conductivity of the PCB material. In aluminum plate tests, temperature difference shows a linear increase with input powers, and the maximum ΔT reaches to 120°C at 165 W input power. Because the PHP needs a minimum input heat to maintain its continuous oscillation movements, at 55 W input heat level, water and ethanol PHPs do not exhibit better heat transfer performance than the metal sheets. The acetone PHP is initiated earlier so it generates better cooling performance than the metal plates at the lowest heat load. With increase of input power, the water and ethanol PHPs start to continuously oscillate and thus yield improved heat transfer performance. The ΔT is reduced to the range of 55–65°C at 165 W heat load, which is only about half of the ΔT with aluminum plates. Similar to previous test results, the acetone PHP shows a faster ΔT increment via heat load (40°C increase from 55 to 165 W).

In actual avionics applications, PHP is involved in various operating orientations. By flipping the prototype, tests of orientation effect are conducted using the PHP prototype of chassis wall cooling. Forty and 50% filling ratios are tested to compare heat transfer performances in the water PHP. Experimental results shown in Fig. 14 indicate that orientation effect is relevant to both heat load and filling ratio. For the lower filling ratio (40%) PHP, heat transfer performance is obviously different at lower heat load. With increase of input heat, orientation effect starts to reduce, and the PHP performance shows only a minor difference at 400 W. On the other hand, orientation effect shows less impact on the higher filling ratio (55%) PHP. Temperature difference slightly reduces from 8 to 5°C with increase of heat load.

Based on the preceding experimental results, an analysis is performed, as shown in Figs. 15a and 15b. It is known that oscillation movements of a PHP are caused by the work of vapor expansion in the evaporator. All of the work will eventually be consumed in flow frictions, including liquid and gas frictions. When the PHP is set up in a gravitational environment as shown in Fig. 15a, gravity should not help or resist the movements due to mechanical energy conservation. However, this scenario is different when the oscillation movement is discontinuous, which corresponds to a lower input power. Because of this discontinuity, vapor expansion work in the previous oscillation is consumed by resistance oscillations before the next vapor expansion could take advantage of it. Shown in Fig. 15b, vapor expansion of later time must start from an inactive state, and push liquid slugs against gravity to reach the evaporator. An additional work, $\rho g h$, must be completed in each new oscillation, which causes worse heat transfer performance against gravity. At a higher input heat, the continuous oscillation is able to use partial kinetic energy

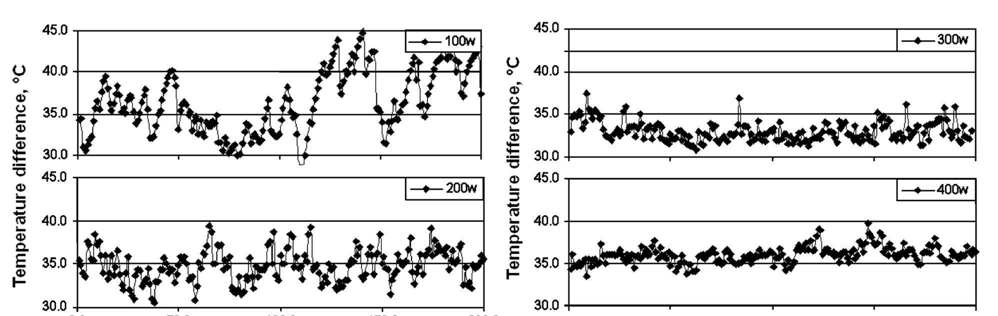

Fig. 16 Temperature fluctuation of water/copper PHP, 40% water, steady state.

from a previous oscillation before it starts to decline, and therefore temperature differences reflecting pressure differences tend to be the same in both along and against gravity tests. Similarly, orientation test results with higher filling ratio can be analyzed with Figs. 15a and 15b. Higher filling ratio means less oscillation amplitude from liquid slug balance position to the evaporator. Therefore, less work is done to break static state and reduces ΔT difference between results of along and against gravity tests.

Because of oscillation motions, the PHP evaporators undergo wet and dry states. Wet state refers to wet evaporator surface and lower evaporator temperature after liquid slug passes. Dry state happens after liquid on the inner surface completely evaporates and before then next liquid slug comes. Evaporator temperature during dry state rapidly increases and temperature fluctuation appears during switch of wet and dry states. In an avionics system, some electronic components are very sensitive to temperature variations so that the PHP evaporator temperature fluctuation becomes a critical factor in the application. Figure 16 shows the evaporator temperature fluctuations vs time. Based on heat load, temperature fluctuations exhibit significant differences. In the chart of 100 W input heat, lower frequency and higher amplitude temperature fluctuations express a discontinuous oscillation statement, and the maximum temperature is 10°C above the average. With increase of heat load, oscillation frequency becomes higher and its amplitude reduces. At 400 W scenario, only 2–3°C average temperature fluctuations (5°C maximum) are observed. Temperature variation plotted for 400 W test describes a statement with steady and continuous oscillations. On the other hand, the temperature/oscillation fluctuation profiles via time also provide evidence for PHP orientation effect analysis, which indicates the continuity of oscillation motions is very important in PHP heat transfer.

Conclusions

In this paper, experimental results and discussions for avionics device cooling lead to the following conclusions:

1) By introducing pulsating heat pipe technology, high load heat transfer performance of avionics chassis wall and PCB systems is significantly improved, and temperature differences/evaporator temperature fluctuations are lowered to a reasonable range for electronic devices.

2) Thermal analysis of PHP performance shows that at same heat load, higher latent heat liquid, lower liquid viscosity and velocity will yield higher effective thermal conductivity; for same operating liquid, effective thermal conductivity is functions of input power, saturated temperature and pressure at the condenser, liquid viscosity, and flow velocity.

3) PHP orientation effect shows that input heat and filling ratio impact PHP performance in gravitational environment. The evaporator temperature fluctuation reduces with increase of heat load. Continuity of PHP oscillation motions is an essential factor.

Acknowledgment

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