Investigation on Pulsating Heat Pipe (PHP) Heat Spreader Plate for Electronics Cooling

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Abstract

A Pulsating Heat Pipe (PHP) plate heat spreader was investigated as a high thermal performance alternative to a conventional conduction plate heat spreader. A 3U form factor card, i.e., 160 mm x 100 mm x 3.38 mm was selected for performance testing. The PHP heat spreader was additively manufactured with aluminum and charged with propylene. From performance analysis, it was determined that the PHP had 100% higher thermal conductance compared to the conduction plate when the condenser (plate heat rejection) temperature was below 0 °C. The maximum variation in thermal conductance observed through repeatable experiments was less than 10% with 95% confidence level. The PHP was capable of transporting more than 220 W of heat without dry-out at these conditions. However, when the condenser was maintained at 20 °C, the thermal performance improvement of PHP was 45% more than the conduction plate.

Keywords

Heat spreader, thermal management, pulsating heat pipe, electronics cooling, two-phase cooling

Nomenclature

C	Thermal conductance (W/°C)
Q	Heat (W)
T	Temperature (°C)

1. Introduction

Rapidly evolving semiconductor technology along with their shrinking footprint has propelled a significant increase in waste heat flux from electronics. High heat flux from electronics results in hot spots which must be avoided for safe and reliable operation. In general, the electronics chips must be maintained below a temperature of 75 °C [1]. In standard electronics enclosures, heat spreaders are used to spread and dissipate localized heat from the electronics to the heat sink. Commercial heat spreaders currently employed are based on conduction plates like aluminum, copper, or graphite. Recently, two phase-heat spreaders based on technologies like Embedded Heat Pipes (EHP) have also been commercially made available. However, the suitability of these heat spreader plates vary based on the application. Aluminum conduction plates have a conductivity of 170 W/m-K, capable of carrying heat fluxes lower than 10 W/cm^2 (~ 127 W as shown in this manuscript). However, they are favored for lightweight applications. Copper heat spreaders with a thermal conductivity of 360 W/m-K can carry about two times more heat flux but are significantly heavier than aluminum. Graphite heat spreaders have a very high thermal conductivity and thus are good solutions for high heat flux applications. Coming to two-phase heat spreaders, EHPs have high thermal conductivity, but the stiffness of the heat pipes limits their application in structures where sharp corners are encountered. As an alternative, recently, another form of two-phase heat spreader solution based on Pulsating Heat Pipes (PHP) is being investigated as a device capable of carrying high-heat flux and also being lightweight. These can be designed to accommodate various form factors including geometries where sharp corners exist.

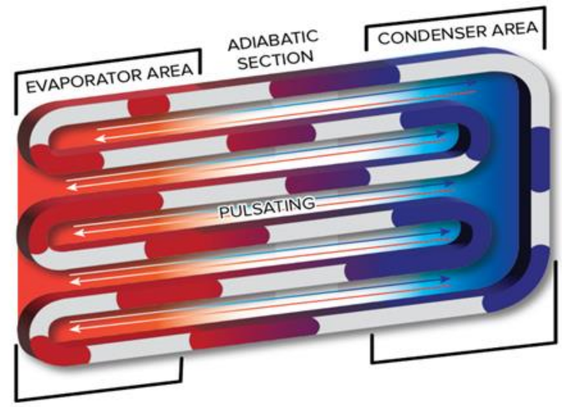

Figure 1. Schematic illustrating the operation of a PHP

A PHP heat spreader is essentially a plate with internal capillary-sized fluid channels in a serpentine layout which is usually connected end-to-end [2]. Since the fluid channels are of capillary size, the working fluid, when introduced into the fluid channels naturally distributes into liquid slugs and vapor plugs. The operation of the PHP, as illustrated in Figure 1, is as follows: [3, 4]: As heat is applied to the PHP (section called evaporator), the working fluid vaporizes, thereby, increasing the fluid pressure. Consequently, as heat is rejected from the other end of the PHP (the section called condenser), the vapor shrinks or condenses, thereby, decreasing the fluid pressure. This dynamic interplay of fluid pressures balanced by thermo-hydraulic forces acting on the fluid results in pulsation of the working fluid. Several studies have indicated the thermal performance of the PHP to be 2 times or more than the conduction plate [2, 5, 6].

In this manuscript, the performance of a PHP plate heat spreader plate in comparison to a conventional conduction plate heat spreader for a standard 3U form factor electronics card [7] is presented.

2. Description of heat spreader and testing methodology

A PHP heat spreader plate was fabricated and tested as a high-performance alternative to a standard aluminum conduction plate. The conduction plate was fabricated by a conventional machining process with a standard surface finish of 3.2 μm. The PHP was fabricated by additive manufacturing with aluminum with particle sizes of 4 μm. As such, the geometric and material influence on thermal performance is minimal. The dimensions of the 3U heat spreader plate are- 160 mm in length, 100 mm in width, and 3.38 mm in thickness. The plate has a depth of 13.39 mm to interface with a card retainer. Further geometric details of the heat spreader plate are shown in Figure 2. These dimensions reference standard 3U form factor electronics cards recommended by the VITA VPX standards [8].

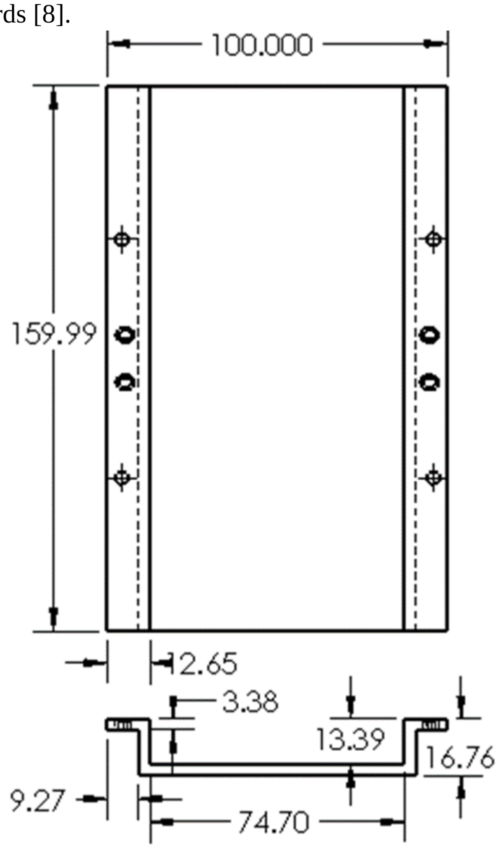

Figure 2. Geometric dimensions of heat spreader plate for electronics cooling. Dimensions are in millimeters (mm).

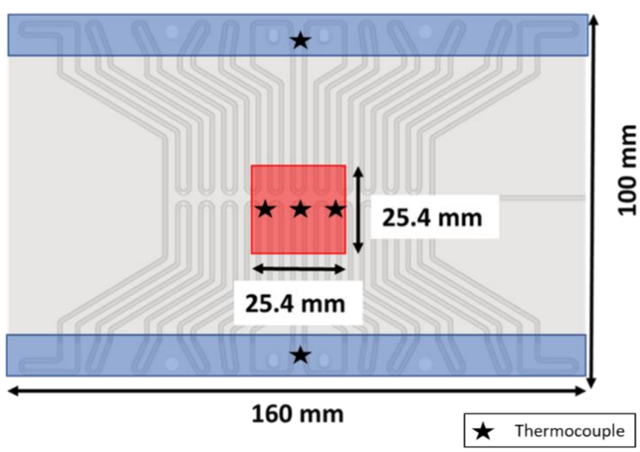

Figure 3. Test methodology for heat spreader plate performance testing. The square box in red represents the heater location, and the blue shaded box at the edges represents heat rejection

Figure 3 shows the test methodology for performance testing of the heat spreader plate. The PHP heat spreader with fluid channels is shown here. The diameter of the fluid channel was 1.52 mm. A central heater (evaporator) and edge heat rejection (condenser) method was adopted for heat spreader plate performance testing. The heater block of size 25.4 mm x 25.4 mm made of aluminum with two cartridge heater inserts was used as the heat source. The evaporator temperature was recorded by using three spring-loaded thermocouples at the heater block and the heat spreader plate interface. The condenser end of the heat spreader was connected to cold plates through Isothermal Card Edge (ICE-Lok®) card retainers [9].

The test methodology is described hereunder:

- Quasi-steady state method was adopted with incremental heater power.
- The condenser of the heat spreader was maintained at a constant temperature and is referred to as the operating temperature in the remainder of the manuscript.
- Testing was performed either until dry-out occurred in the heat spreader plate, or if the evaporator temperature on the heat spreader reached 75±5 °C. Dry-out condition is observed if the evaporator temperature increases sharply resulting in a very low thermal performance of the heat spreader.

The thermal performance of the heat spreader was determined in terms of thermal conductance (C) [W/°C] as:

$$C = \frac{\Delta T}{Q}$$

Where ΔT is the quasi-steady state time-averaged temperature difference between the mean evaporator temperature and the mean condenser temperature; and Q is the applied heater power.

The heat spreader was insulated with an insulation foam. Considering a conservative heat loss coefficient of 5 W/m^2-K [6] from the heat spreader at an average surface temperature of 75 °C, the maximum heat loss is only 8 W. As indicated below, this is less than 3.5% of the applied heater power. To ensure repeatability, the experiments were performed at least three times. The variability in the thermal performance with a 95% confidence interval was found to be less than 10%.

3. Thermal performance of plate heat spreader

3.1 Thermal performance of conduction plate heat spreader

The performance of the PHP heat spreader was investigated and compared to the aluminum conduction plate, which is the baseline heat spreader. To ascertain the two-phase performance improvement, the thermal performance of the empty PHP was also determined.

Figure 4 shows the wall temperature profile and thermal conductance of the aluminum plate heat spreader. The condenser was maintained at a constant set point temperature of 20 °C. The evaporator temperature increased almost proportionally with increasing heater power. When the heater power was 127 W, the evaporator temperature reached a maximum value of 72.5 °C. Based on the test results, the thermal conductance of the aluminum plate was computed to be 1.09 W/°C. The variability in thermal conductance within a 95% confidence level was 0.1 W/°C (less than 10%).

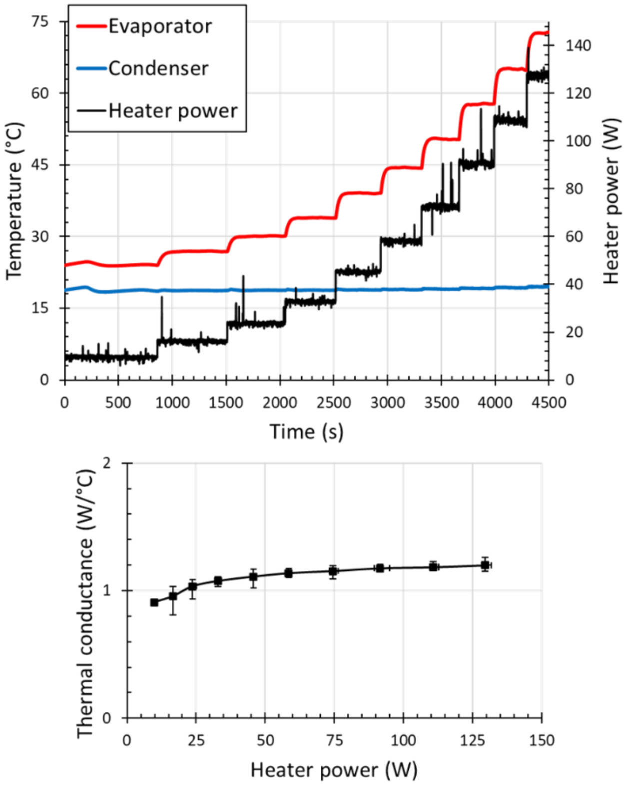

Figure 4. Wall temperature profile and thermal conductance of aluminum conduction plate heat spreader

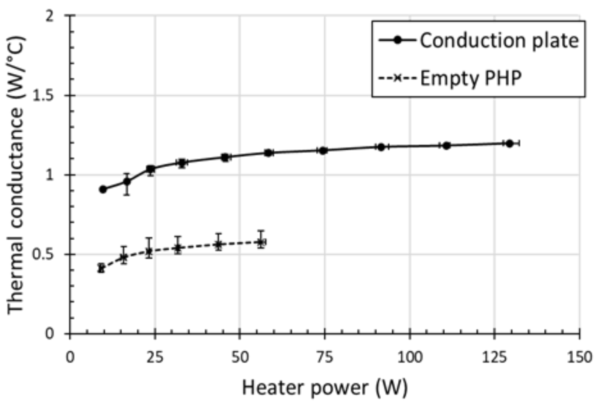

Figure 5. Thermal conductance comparison of conduction plate and empty PHP plate heat spreaders

Since the PHP plate heat spreader had subsurface fluid channels after removing solid material, the thermal conductance of the empty PHP was also determined for estimating improvement in thermal performance with the working fluid. Figure 5 shows the thermal conductance comparison between the conduction plate and the empty PHP plate heat spreaders. The difference in the thermal conductance is indicative of the solid area that was removed from the baseline case. The mean thermal conductance of the empty PHP plate was 0.53 W/°C with an average variability of 0.05 W/°C. The empty PHP was able to deliver a maximum heater power of only 60 W (< 5 W/cm^2) at a similar operating temperature. From computation, it was estimated that approximately 51.4% of the material area was removed from the solid conduction plate.

3.2 Thermal Performance of PHP plate heat spreader

The PHP plate was charged with propylene as the working fluid. Previous studies indicated propylene [6, 7] as a suitable working fluid. For performance investigation, the PHP condenser set point temperature and the fluid charge ratio were investigated as parameters of interest. The performance testing was performed in both horizontal mode and also in vertical mode.

3.2.1 Thermal performance comparison of PHP against baseline heat spreader

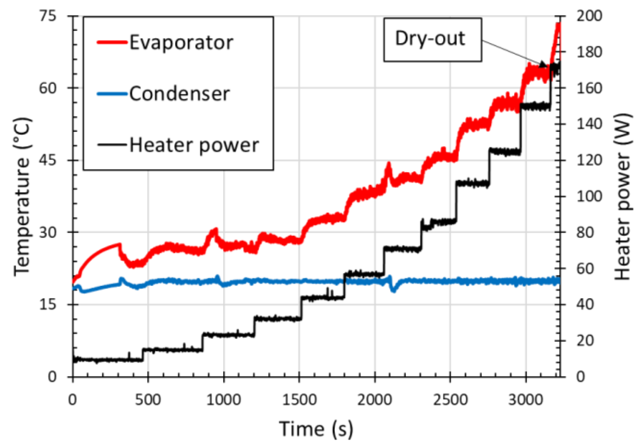

Figure 6. Wall temperature profile of PHP plate heat spreader

Figure 6 shows the wall temperature profile of the PHP heat spreader at condenser set point temperature of 20 °C in horizontal mode. The PHP was charged with propylene up to 75% of the volume. The PHP evaporator temperature gradually increases with increasing heater power. The instantaneous pulsation in the evaporator temperature is indicative of the PHP operation. The PHP delivered up to 150 W heat reaching evaporator temperature of 63.5 °C. When the heater power was increased to 170 W, significant instantaneous increase in the evaporator temperature was observed indicating dry-out in the PHP.

Figure 7 shows the thermal conductance comparison of the heat spreaders. The blue line indicates the thermal conductance of the PHP plate heat spreader. The thermal conductance increases with increasing heater power as the two-phase operation improves and reaches an optimal value at 1.56 W/°C. The variability for a 95% confidence level was only 0.054 W/°C. The improvement in thermal conductance compared to the conduction plate was 43%, while compared to the empty PHP, the performance improvement was 194%. Previous investigations showed that the propylene-charged PHP was more suitable for lower operating temperatures [5]. These conditions exist in cold weather locations and/ or in space applications [7].

Below, the performance of the PHP is presented with varying lower condenser set point temperatures, along with varying fluid fill charge ratios. In addition, the influence of the orientation of the heat spreader on the performance is also presented.

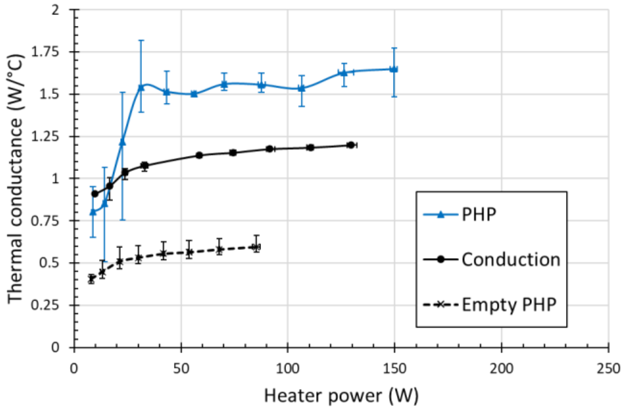

Figure 7. Thermal conductance comparison of heat spreaders

3.2.2 Thermal performance of PHP heat spreader at varying operating temperatures

The performance testing of the PHP plate heat spreader was undertaken at condenser set point temperatures of -25 °C, -10 °C, and 0 °C for low operating temperature applications. The working fluid volume fill charge ratio was maintained at 75%. The tests were performed at least three times at each data point and the corresponding error bar is shown for the performance data obtained.

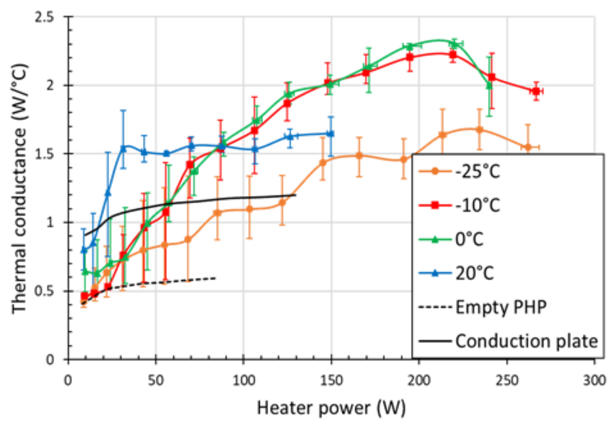

Figure 8. Thermal conductance of PHP heat spreader at different condenser set point temperatures at 75% fill ratio

Figure 8 shows the thermal conductance of the PHP plate heat spreader at different condenser set point temperatures. At a condenser set point temperature of -25 °C, the thermal conductance of the PHP plate gradually increased with increasing heater power. While, the thermal conductance was greater than the empty PHP, the thermal performance of the PHP with fluid at this condition was only equal to the conduction plate at a heater power of 120 W. However, above this heater power, the thermal conductance further increased to a value greater than 1.5 W/°C, with the PHP delivering 260 W. At this point, the evaporator temperature was approximately 72 °C, so the testing was stopped after this point. The peak thermal conductance of 1.65 W/°C was obtained at this condition. At condenser set point temperature of -10 °C and 0 °C, similar thermal conductance was obtained with the PHP. The thermal conductance sharply increased with increasing heater power, reaching a value greater than 2 W/°C at a heater power of approximately 150 W. Beyond this heater power, a marginal increase in the thermal conductance was obtained with a peak value of 2.2 W/°C at -10 °C and 2.3 W/°C at 0 °C, condenser set point. As indicated above, the mean thermal conductance of the PHP at the condenser set point temperature of 20 °C was 1.56 W/°C. These results indicate that the PHP, charged with propylene is suitable for applications when the heat rejection set point is at or below the water freezing point. When the condenser set point increased from a very low value of -25 °C to -10 °C/ 0 °C, the fluid properties were more ideal, thus, demonstrating a high thermal conductance. However, when the condenser set point increased to 20 °C, the PHP operated at a reduced performance value, potentially indicating the operation at a partial dry-out mode.

3.2.3 Thermal performance of PHP heat spreader at different fluid fill charge ratio

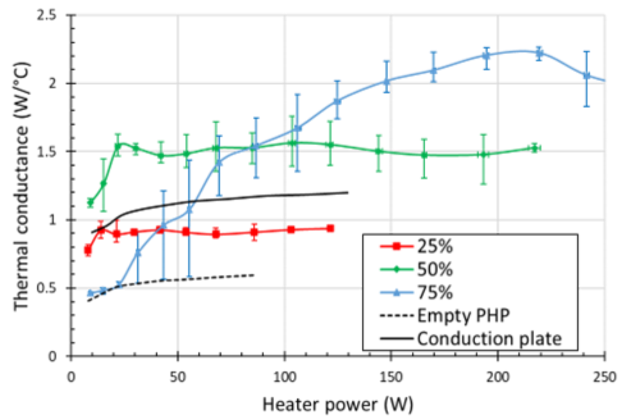

Figure 9. Thermal conductance of PHP heat spreader at different fill ratios at set point temperature of -10 °C

To investigate the influence of fill ratio, the PHP was tested at a condenser temperature of -10 °C and the results are shown in Figure 9. At a very low fill ratio of 25%, PHP operation was observed even at very low heater powers with a thermal conductance of 0.93 W/°C. While the two-phase improvement with propylene was determined to be 75%, the thermal conductance was still lower than the conduction plate. When the fill ratio was increased to 50%, a steady thermal conductance of 1.51 W/°C was obtained at heater powers above 30 W. The improvement in thermal conductance compared to the empty PHP and the conduction plate were 185% and 38.5%, respectively. At 75% fill ratio developing PHP operational behavior was observed when heater power was below 100 W. The thermal conductance increased from 0.51 W/°C to above 1.5 W/°C within this range. When the heater power further increased, further improvement in thermal conductance was obtained reaching a value above 2 W/°C above 150 W. Peak thermal conductance of 2.2 W/°C was obtained at 220 W heater power. The improvement in thermal conductance over empty PHP and the conduction plate was 315% and 102%, respectively. From this analysis, it was determined that a fill ratio of around 50% was appropriate for lower heater power applications, but the performance improvement was less than 50% compared to the conduction plate. At higher powers, a fill ratio of 75% gave more than 100% improvement in thermal conductance. It can be deduced that, based on the applied heater power, the optimal fill ratio can be between 50% to 75%.

3.2.4 Thermal performance of PHP heat spreader at varying orientation

A major benefit of the PHP plate heat spreader compared to other heat pipe technologies is operational insensitivity to orientation without requiring a wick structure. The PHP fluid channels are of capillary size and the influence of gravity is low compared to other hydraulic forces during normal operational mode. To determine this behavior, the PHP heat spreader was tested at both horizontal and vertical configurations. In the results mentioned above, the PHP heat spreader was in the horizontal configuration. In the vertical configuration, the fluid channels were aligned in the direction of gravity, and a similar test methodology was adopted. Since the heat source was in the middle of the plate, one evaporator-condenser pair was assisted by gravity, i.e., bottom heater and top condenser condition, and the other pair was acting against gravity, i.e., top heater and bottom condenser condition.

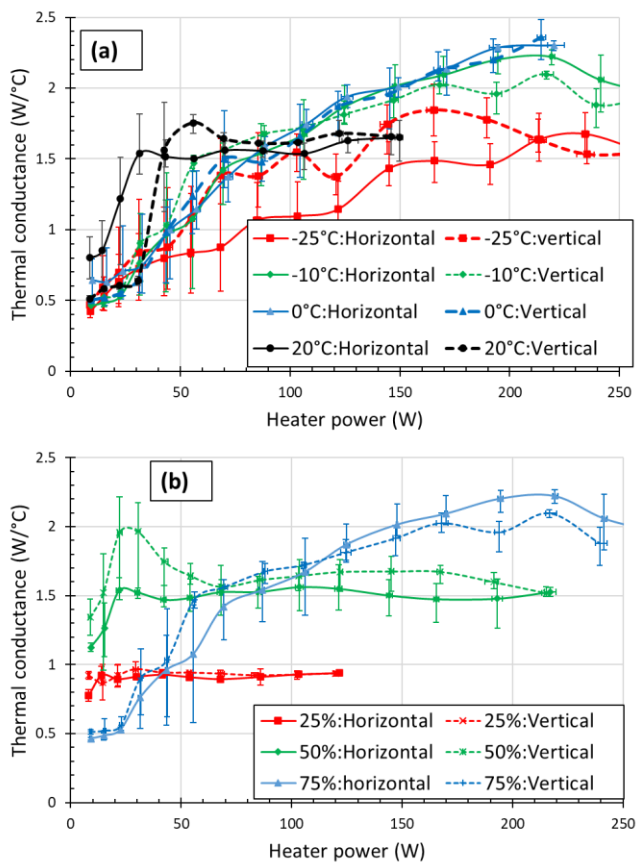

Figure 10. Performance of PHP heat spreader in horizontal and vertical configuration (a) with varying condenser set point temperatures at 75% fill ratio, and (b) with varying fill ratio at condenser set point temperature of -10 °C

Figure 10 shows the thermal conductance of the PHP heat spreader at varying orientations for both operational parameters of varying condenser set point temperatures at 75% fill ratio and varying fill ratio at condenser set point temperature of -10 °C. The thermal conductance for horizontal configuration is shown as solid lines and for vertical configuration is shown as dotted lines. In case of varying condenser setpoint temperatures, as shown in Figure 10 (a), some variation in performance was observed at lower condenser temperature of -25 °C, but the general trend showed a gradual improvement in thermal conductance with increasing heater power. With developing fluid properties, gravity has some influence on the performance under this condition. Above 150 W, the nominal thermal conductance at horizontal configuration was above 1.5 W/°C, while in vertical configuration reached a value of 1.85 W/°C. At higher condenser set point temperatures, the influence of orientation was minimal negligible. Likewise, with varying fill ratios as shown in Figure 10 (b), very small influence of gravity was observed only at lower heater powers, but this influence became negligible with increasing heater power where the thermal conductance of the PHP became steadier.

Conclusions

Experimental investigation on PHP plate heat spreaders, as a high-performance two-phase alternative to conventional conduction plate heat spreaders was presented here. Propylene was used as the working fluid in the PHP. When the condenser was maintained at a standard room temperature of 20 °C, about 43% improvement in thermal conductance was obtained in comparison to the conduction plate. In a similar comparison against the empty PHP, about 194% improvement in thermal conductance was obtained indicating the significance of two-phase performance for heat spreader.

The investigation was performed on performance parameters of 1. Varying operating temperatures, 2. Varying fluid fill ratios, and 3. Orientation. In general, the thermal conductance increased with increasing heater powers, showing developing PHP operational behavior, eventually reaching steady behavior.

- Varying condenser set point temperatures: At a very low condenser set point temperature of -25 °C, the fluid properties improved as the temperature increased with the heater power, thus, resulting in a steady increase in thermal performance. When the condenser was maintained at -10 °C and 0 °C, a similar thermal conductance profile was observed. More than 100% improvement in thermal conductance was observed for heater power greater than 150 W compared to the conduction plate.
- Varying fluid charge ratios: The PHP operated under tested fluid fill ratios of 25%, 50%, and 75%. However, the 25% fill ratio did not perform better than the conduction plate. A fill ratio of 50% reached a steady thermal conductance of 1.51 W/°C at lower heater powers, but the performance improvement compared to the conduction plate was only 38.5%. At a higher fill ratio of 75%, the thermal conductance gradually improved with heater power reaching a value of above 2 W/°C above 150 W, showing up to 100% improvement in performance over the conduction plate.
- Varying orientation: The orientation showed some influence only at very low condenser set point temperatures,

but was minimal for all other parameters. In general, the performance of the PHP was less affected by orientation.

PHP heat spreaders investigated for 3U form factor demonstrated increased conductance compared to their aluminum counterparts. However, the PHP must be specifically designed with a working fluid and fill ratio for the expected usage condition. The current propylene PHP shows promise for operation at low temperatures, and other working fluids may be selected if operating at higher temperatures.

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