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THERMAL PERFORMANCE OF MINI FLAT PLATE HEAT PIPES FOR HIGH-POWER CHIPS

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Abstract. *The waste heat generated by the high-power chips increases their operating temperature, reducing their performance and service life. Flat plate two-phase devices are promising cooling solutions for power electronics. Among them, the thermosyphons and pulsating heat pipes, which respectively promote the fluid circulation by gravity and oscillatory motion of liquid slugs and vapor plugs, are interesting devices to be investigated, as both show excellent heat transfer capacities. In the present work, the thermal performance of a mini flat plate thermosyphon is experimentally investigated and compared with that of a pulsating heat pipe, aiming for the thermal management of waste heat produced by miniaturized high-power chips. Both two-phase devices have the same external dimensions (100 x 55 mm^2) and were manufactured by diffusion bonding technology. Distilled water was used as the working fluid. Tested in the same conditions, both operated successfully for the gravity-assisted mode; however, the thermosyphon, the lighter device, was able to transfer more heat. In the horizontal position, the pulsating heat pipe showed excellent thermal performance after the startup, working until high heat loads. In general, it was observed that the PHP became independent of gravity action for heat loads above 100 W.*

Keywords: *flat plate heat pipe, pulsating heat pipe, thermosyphon, thermal performance, electronics cooling.*

1. INTRODUCTION

The fast development of information technology increases the demand for data transmission in electronic gadgets, causing power consumption enhancement. Modern microprocessors of data centers, for instance, can dissipate up to 200W or more. The waste heat generated by the high-power chips increases their operating temperature, reducing their performance and service life (Qian et al., 2018).

Flat plate two-phase devices have been considered a promising cooling solution for power electronics, as they are simple, compact, and small, fulfilling the main requirements for such applications as high heat transfer capacity from concentrated thermal loads (Winkler et al., 2020).

Heat pipes are a massive family of passive technologies that transfer heat efficiently using a two-phase cycle of a working fluid. Despite the peculiarities of each type, they are all basically divided into three regions: the evaporator, the adiabatic section, and the condenser. The heat pipe operation begins by delivering heat to the evaporator section, which causes the working fluid to change of phase. Due to pressure differences, the vapor goes to the condenser region, where it loses heat, condensing. The condensed liquid is pumped back to the evaporator by the capillary effect, provided by the wick structure (Mantelli, 2021).

Considered the simplest biphasic device, thermosyphons are similar to heat pipes but, instead of wick structures, they use gravity to return the liquid from the cold side to the heated side. Latent heat transports the majority part of the heat in thermosyphons. They are, therefore, efficient, light, easy to manufacture, and inexpensive, being, in their simplest configuration, composed by only an involucre and the working fluid. However, as a drawback, their gravity dependency requires evaporators to be located below the condensers (Mantelli, 2013).

On the other hand, pulsating heat pipes (PHP) transport heat by the oscillatory motion of confined liquid slugs and vapor bubbles (plugs) in a closed loop, formed by several intercommunicated channels. PHPs do not have a capillary structure, and the liquid displacement is promoted by the confinement of vapor bubbles that, during its growth, pushes liquid slugs in the condenser direction. The heat transfer happens mainly by the liquid sensible heat, being independent of gravity action, in some configurations. Despite the high capacity in thermal transportation, PHP operating principle is complex and requires some special conditions for the startup, such as a minimum temperature difference to displace the large bubbles (Khandekar and Groll, 2003; Winkler et al., 2020). Moreover, the literature shows that, although their great thermal performances, large PHPs are considered not suitable for actual applications, as most of them showed good performances only in the vertical position, with gravity assistance such as for thermosyphons (Takawale et al., 2019; Thompson and Ma, 2010; Yang et al., 2009).

Besides, flat miniaturized two-phase devices for cooling high-power chips face fabrication challenges related to their reduced size, as conventional welding processes may block and/or deform the channels. Diffusion bonding is an alternative solid-state welding technique. In this process, two or more flat plates are joined by applying pressure at a highly controlled temperature (approximately 80% of the fusion temperature) during a specific time. After the thermal cycle, the result is a monolithic piece with well-controlled sizes and shapes.

In the present work, the thermal performances of two mini flat plate two-phase devices, a thermosyphon and a pulsating heat pipe, are experimentally investigated for the thermal management of waste heat produced by miniaturized high-power chips. Diffusion bonding is used to fabricate two-phase devices of exactly the same size. Basically, both are made from sandwiches of two closing plates with different fillings. For the thermosyphon, parallel wires were used as the filling, while, for the PHP, a comb-like machined plate played this role. The thermal tests are performed in gravity-assisted and horizontal orientations to determine the position influence in the operation of the two-phase devices.

Besides the flat plate two-phase devices, the application of diffusion bonding for manufacturing flat heat pipes can be regarded as a literature contribution, once just a limited number of groups worldwide domain this fabrication process for two-phase devices.

2. EXPERIMENTAL SETUP

A mini thermosyphon and a mini pulsating heat pipe were manufactured by diffusion bonding technology and thermally tested. As they were developed to fit in miniaturized high-power chips as a cooling system, the flat geometry was selected, with 100 x 55 x 2.6 mm^3, small enough to be used in most tablets, laptops, and CPUs. Figure 1 shows the schematic designs of the proposed two-phase devices.

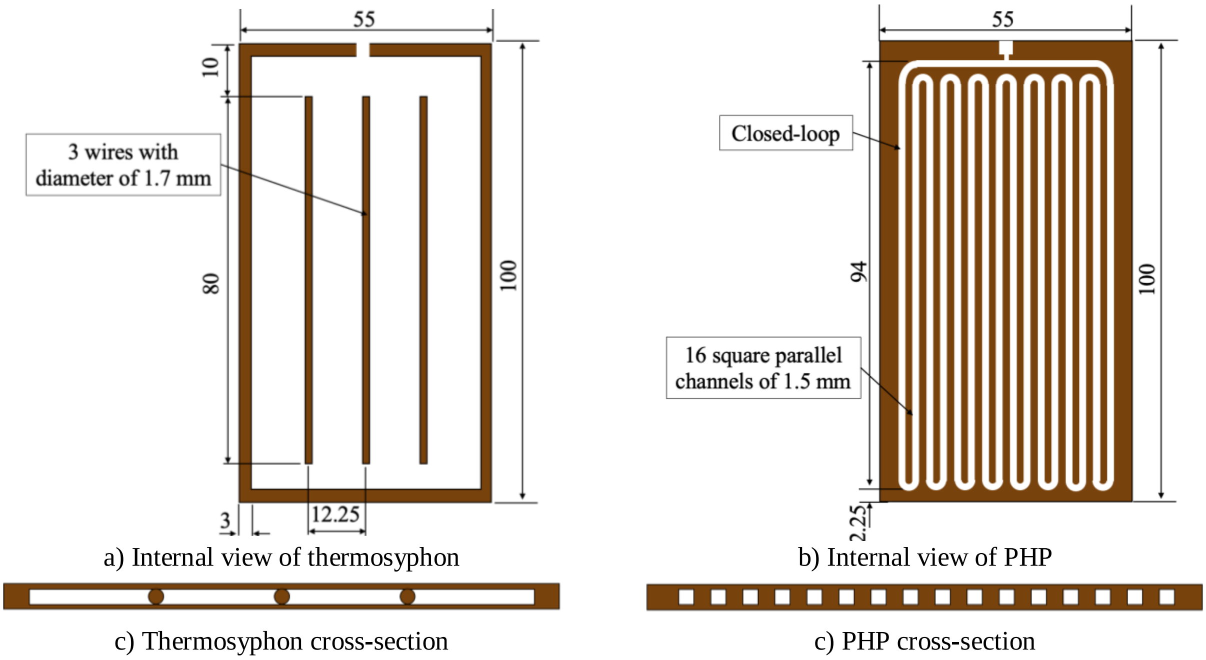


Figure 1. Schematic design of two-phase devices [mm].

2.1 Fabrication of mini flat plate two-phase devices

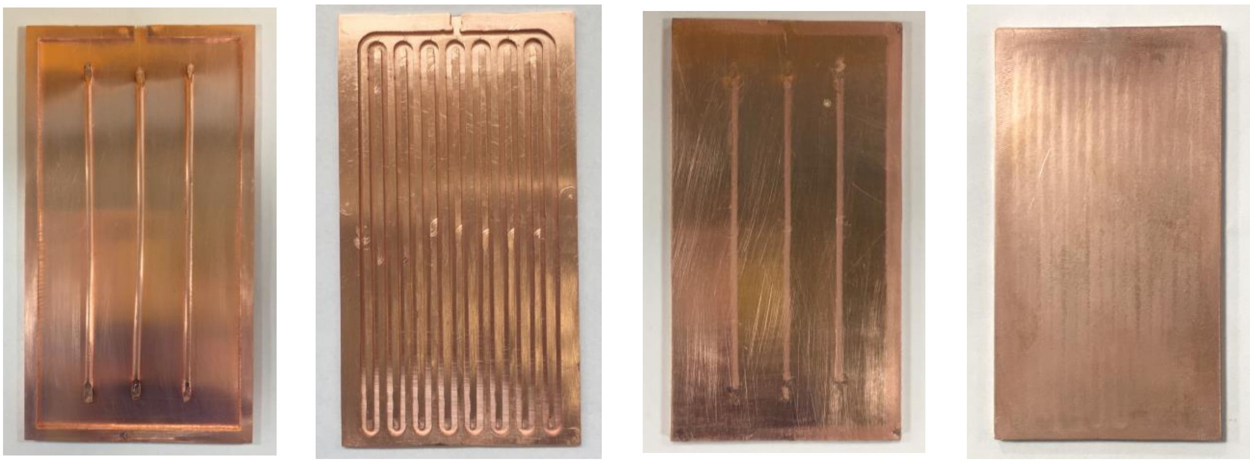
The thermosyphon involucre was composed of two external copper sheets (0.55 mm thickness), a hollow frame (thickness of 1.5 mm), and three copper wires (1.7 mm in diameter and 80 mm in length), which are used to prevent deformations during the diffusion bonding cycle, as shown in Figure 1a.

The mini flat plate pulsating heat pipe consisted of two outer copper sheets (0.55 mm thickness) and an inner machined plate (thickness of 1.5 mm) with 16 square channels (1.5 x 1.5 mm^2) in a closed loop, as presented in Figure 1b.

The water-cut process was used to cut and machine all the plates, followed by cleaning with acetone and sulfuric acid.

In both devices, the inner structure (machined plate or frame and wires) was piled over an external sheet, fixing their relative positions by spot welding, as shown in Figure 2a and Figure 2b. After that, the closing plate was stacked, making a sandwich, ready to be diffusion bonded.

The diffusion bonding was performed by submitting the stacked plates to a pressure promoted by stainless steel matrixes and screws, under a 100 Nm torque. In the sequence, the thermal cycle was applied, where the temperature of 875 °C was maintained for 3600 s in an inert atmosphere of Argon, resulting in two monolithic pieces. The bonded thermosyphon and PHP are shown in Figure 2c and Figure 2d, respectively. Observing the traces of boron nitride marked on the external surfaces of the devices (after a first cleaning), the photos show that the inner geometry of both devices cannot be considered deformed.



a) Open thermosyphon b) Open PHP a) Closed thermosyphon b) Closed PHP

Figure 2. Before and after the diffusion bonding cycle.

Finally, the filling tube was brazed, and leakages were checked in an Edwards Spectron™ 5000 Helium leak detector, getting it ready for the filling procedure. First, a vacuum better than 4 x 10^{-5} mbar was provided by a compact turbomolecular pumping station (*Edwards*™ T-Station 85). After that, the working fluid was inserted, followed by a purging realization as suggested by Cisterna et al. (2020). Degassed distilled water was used as the working fluids. A study, not shown here, determined the best filling volume for each device (see Table 1) considering their best thermal performances. Although the external geometry of the two-phase gadgets is the same, the thermosyphon is much lighter when compared to the PHP, as shown in Table 1.

Table 1. Characteristics of the mini flat plate heat pipes.

Characteristics	**Symbol**	**Thermosyphon**	**Pulsating Heat Pipe**
Thickness [mm]	t	2.60	2.60
Mass [g]	m	75.6	105.26
Internal void volume [ml]	V_{void}	5.12 ± 0.02	2.85 ± 0.02
Working fluid volume [ml]	V_{fluid}	1.55 ± 0.02	1.72 ± 0.02
Filling ratio ($100^*V_{fluid}/V_{void}$) [%]	FR	30	60

2.2 Experimental apparatus

An experimental workbench was specially created to evaluate the thermal performance of the heat pipes, as sketched in Figure 3. A programmable power unit delivered voltage to a cartridge-type thermal resistor inserted in a copper block, 14 x 55 x 15 mm^3, in thermal contact with the evaporator, designed to mimic the waste heat from high-power chips. Cooling water from a thermal bath flowing into a hollow metallic block, 15 x 55 x 22 mm^3, was used as the heat sink, in the condenser section.

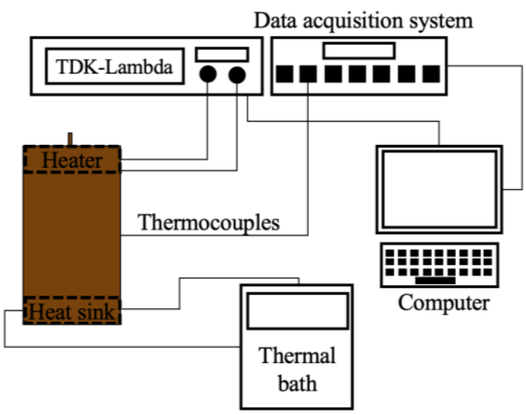


Figure 3. Experimental workbench.

The cooling and heating systems were attached to the same side of the device using thermal grease to reduce the contact resistances, as shown in Figure 4. On the opposite side, nine T-type thermocouples, *Omega Engineering*™, were distributed and attached to the outer surface by a thermosensitive adhesive strip, *Kapton*™, as shown in Figure 4. The temperature sensors were connected to the data acquisition system that acquired the experimental data, which were stored on a laptop (*Dell*™) and controlled by software (*Labview*™). Also, a thermocouple measured the ambient temperature, T_{amb}. An *Isoglas*™ blanket, with a thickness of 30 mm, was used to insulate the experimental setup.

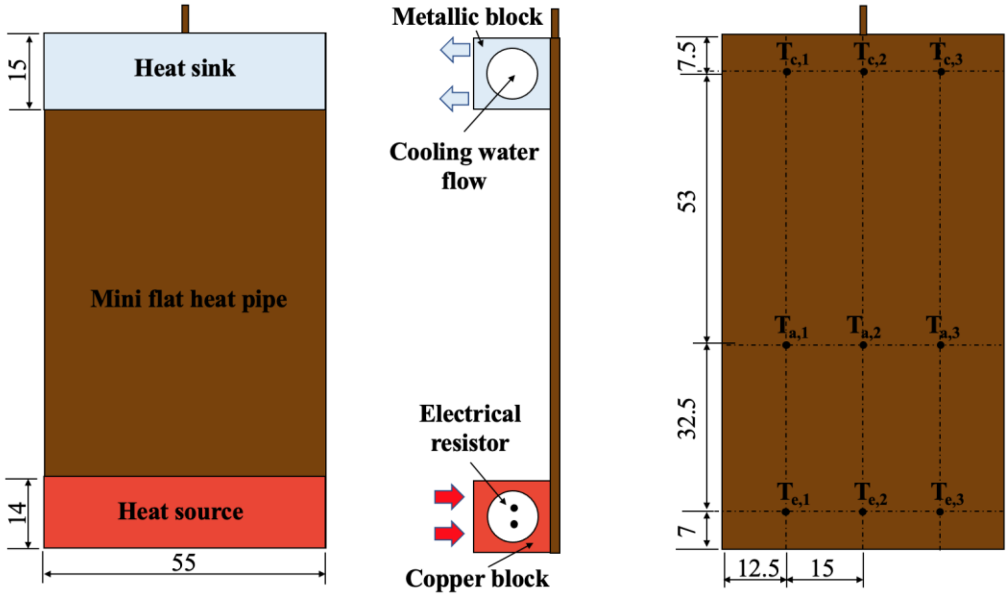


Figure 4. Experimental setup and thermocouple distribution [mm].

2.3 Experimental procedure

The experimental procedure, for both devices, consisted of applying heat transfer rates from 10 to 200 W (which correspond to heat fluxes from 1.3 to 27.3 W/cm^2, dividing the heat load by the heater area) under horizontal and gravity-assisted (evaporator above condenser) orientations, until the steady-state condition was achieved. The experiment stopped when the devices achieved 100 °C, the safe operating temperature for electronics. Exceptionally, for the PHP, the maximum temperature of activation (when the PHP starts showing typical temperature oscillations) of 120 °C was allowed. After that, the same 100 °C limit was observed. The cooling water was kept at 20 °C during all the experiments. Experimental data were recorded at a rate of 1 acquisition/second. The temperature distributions and steady-state performances of the thermosyphon and PHP were compared. Additionally, the two-phase devices without working fluid were tested to estimate the heat transfer only by conduction.

The thermal resistance, *R*, was used as the comparison parameter in the analysis of the thermal performance of the mini two-phase devices, defined by:

$$R = \frac{\overline{T}_{evap} - \overline{T}_{cond}}{q} = \frac{\overline{T}_{evap} - \overline{T}_{cond}}{V \times I} \tag{1}$$

where $\overline{T}_{evap}$ and $\overline{T}_{cond}$ are the average temperature at the steady state of the evaporator and condenser, respectively. q is the total heat load, V is the voltage, and I is the electric current applied at the resistor. The heat loss was neglected as the heat leakage from the experiment to the surroundings summed less than 1 % of the total thermal load q.

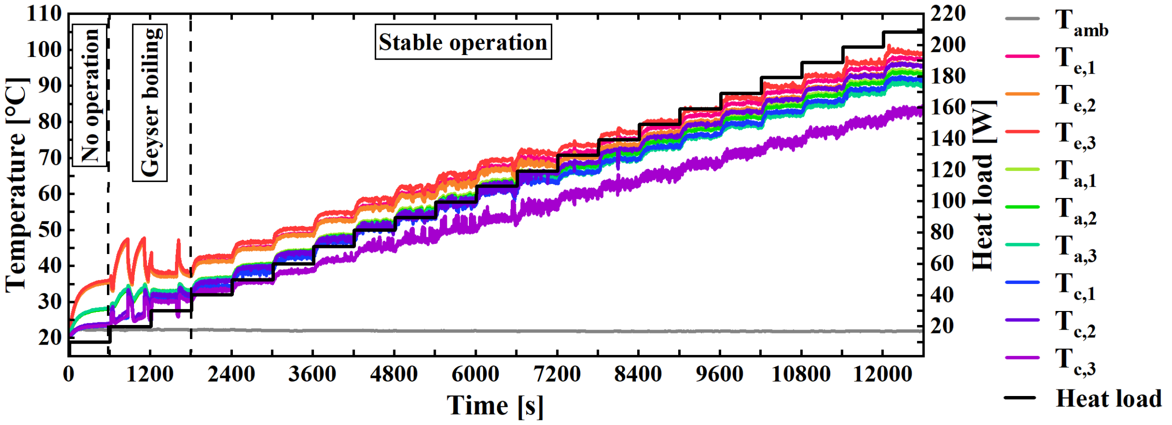
The experimental uncertainties were estimated by the error propagation technique proposed by Holman (2011), considering the uncertainties from the thermocouples, the data acquisition system and the power supply unit. An experimental setup calibration provided a temperature uncertainty of ± 0.23 °C. According to the power unit manufacturer, the voltage and current uncertainties were 0.03 V and 0.0085 A, respectively. The thermal resistance uncertainties are shown by vertical error bars in the graphs.

3. RESULTS AND DISCUSSION

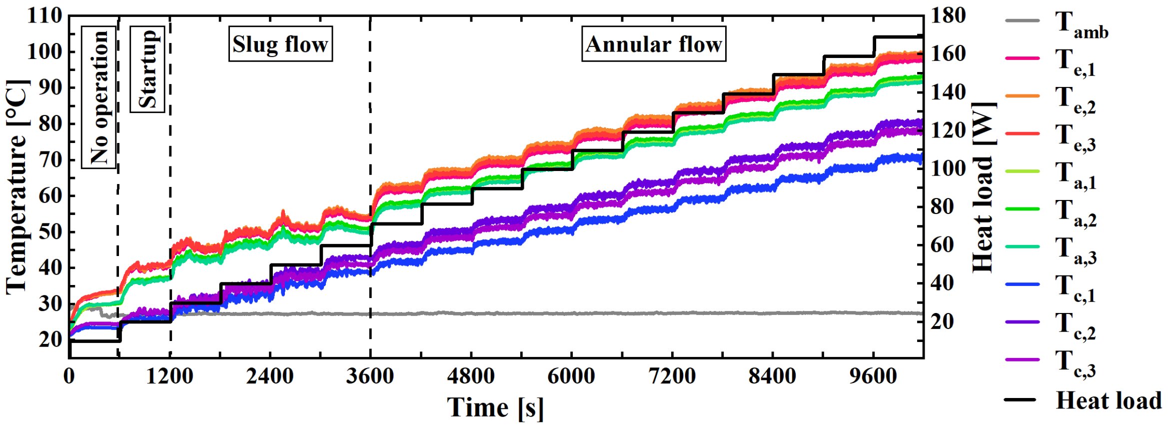
The temperature transient behaviors for the thermosyphon and the PHP, under heat loads varying from 10 up to 210 W, at the gravity-assisted orientation, are presented in Figure 5, where the left vertical axis shows the temperatures and the right axis (and the full black curves), the power inputs. In both cases, after the thermal load was applied, temperatures rose until reaching steady-state conditions. No dry-out was experienced during any operating conditions.

The startup happens when the vapor reaches the condenser, reducing the evaporator and increasing the condenser temperatures. This temperature rise was observed for both devices at 20 W. However, the thermosyphon operated was influenced by the geyser boiling phenomena from 20 to 30 W, reaching almost 48 ºC during temperature peaks, as shown in Figure 5a. It means that the formation and burst of large bubbles occurred in the evaporator, characterizing the evaporator temperature increase and spray heating in the condenser (Mantelli, 2021). After 40 W, the thermosyphon temperature fluctuations reduced, leading to a stable operation mode until the evaporator reached 100 °C, at 210 W.

The PHP with square channels activated and worked until 60 W in a pulsating mode (slug flow pattern in a random direction), shown by the temperature oscillations. At 60 W, the intensity of fluctuations reduced, reaching a more uniform and stable operation for the PHP, characterizing an annular flow. The PHP maintained the same pattern until 170 W when the evaporator achieved 100 °C.



a) Thermosyphon

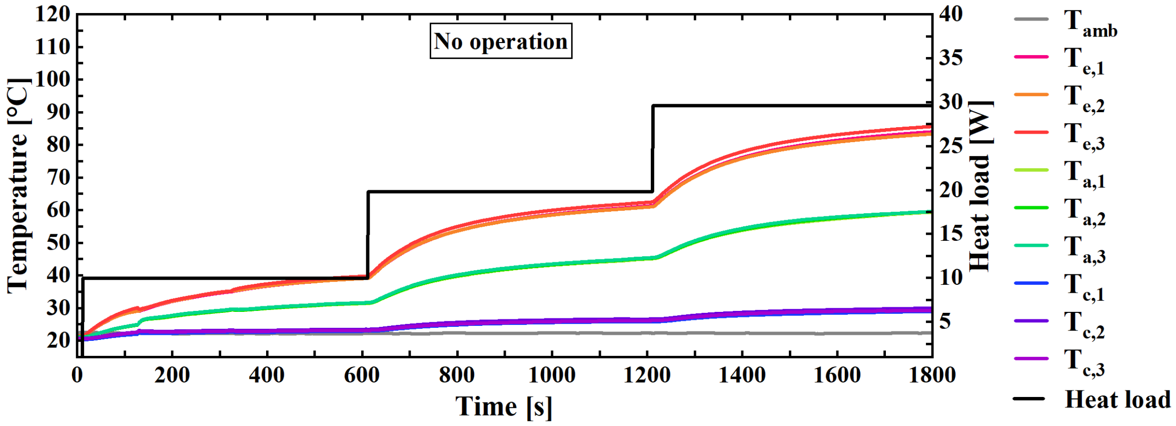


b) PHP

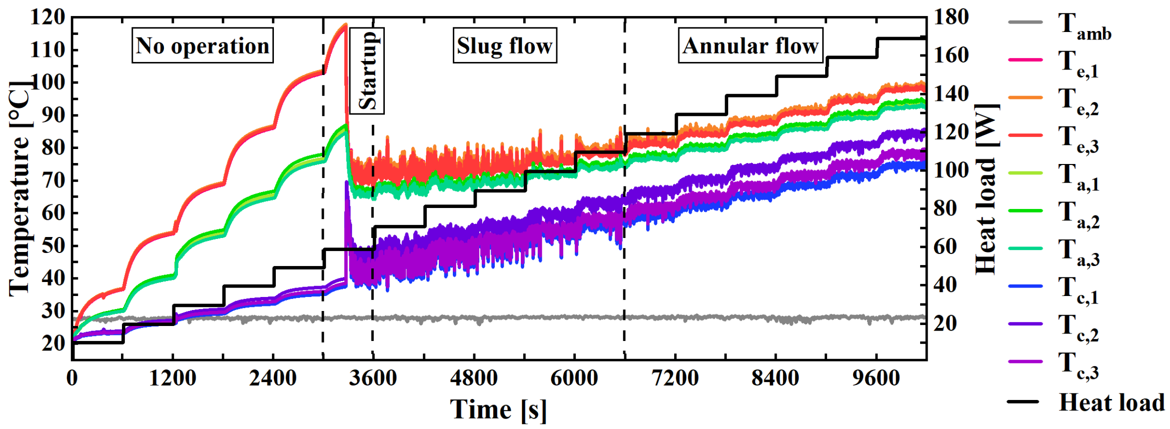
Figure 5. Temperature distribution in the gravity-assisted orientation.

Figure 6 presents the temperature distribution behaviors for both devices in horizontal orientation (without gravity assistance), under thermal loads between 10 and 170 W. As for the vertical position, a steady-state condition was reached for each heat load. The main difference in this position is that the thermosyphon was incapable of operating efficiently. As seen in Figure 6a, the vapor reached the adiabatic section and condenser at 10 W. However, the liquid did not return to the evaporator, which increased the temperature. Even without proper operation, it transferred a maximum of 30 W inside the limited temperature range, mainly by conduction.

In contrast, in Figure 6b, PHP started at a heat load of 60 W, at the evaporator temperature of proximately 115 °C. After that, the temperature oscillations and slug-plug flow continued until 110 W. At 120 W, an annular flow was reached, noticed by more stable operation and smaller temperature amplitudes. This condition was observed up to 170 W, when the test was finished because the evaporator temperature achieved 100 °C. No dry-out was seen for any power input.



a) Thermosyphon



b) PHP

Figure 6. Temperature distribution in the horizontal orientation.

Figure 7 presents plots of the thermal resistances, for the proposed PHP and thermosyphon, as a function of the applied heat load (and heat flux), with measurement uncertainties (vertical error bars). The thermal resistances of the empty devices (only conduction heat transfer) are also shown, which were approximately 1.86 ± 0.41 °C/W and 1.37 ± 0.41 °C/W for the thermosyphon and PHP, respectively.

In gravity-assisted orientation (pink lines), the thermal resistances decreased from the first applied heat load, when the devices already started up, as observed by the thermal resistances, smaller than that without working fluid. Also, as the heat load improved, the thermal resistances decreased. For low power input, the thermal resistances of the thermosyphon and of the PHP are similar within the uncertainty ranges. The minimum thermal resistance for the thermosyphon was 0.03 ± 0.01 °C/W at 210 W (27.3 W/cm^2), and for the PHP was 0.11 ± 0.01 °C/W at 170 W (22.1 W/cm^2), at the maximum power input, when the evaporator reached 100 °C. In this way, it can be considered that the thermosyphon presented better thermal behavior over the entire heat load range tested once it showed equal or lower thermal resistances than the PHP.

The thermal resistance behaviors of the thermosyphon and PHP (blue lines) at the horizontal position were completely different, as expected. The thermosyphon (blue line with triangles) did not work at the lower power inputs and quickly achieved the evaporator 100 °C limit, showing a thermal resistance similar to that of the empty heat pipe (black line with triangles). However, while the PHP did not work only at low heat loads (its thermal resistances were close to the pure conduction thermal resistances from 10 to 50 W), it started at 60 W, when the thermal resistance drastically decreased to nearly 0.5 °C/W. After that, the thermal resistance dropped slowly, until achieving a minimum of 0.13 ± 0.02 °C/W at 170 W (22.1 W/cm^2). Moreover, at 100 W, the PHP became independent of the gravity action, once its thermal resistance in the gravity-assisted mode presented practically the same values as those of the horizontal orientation.

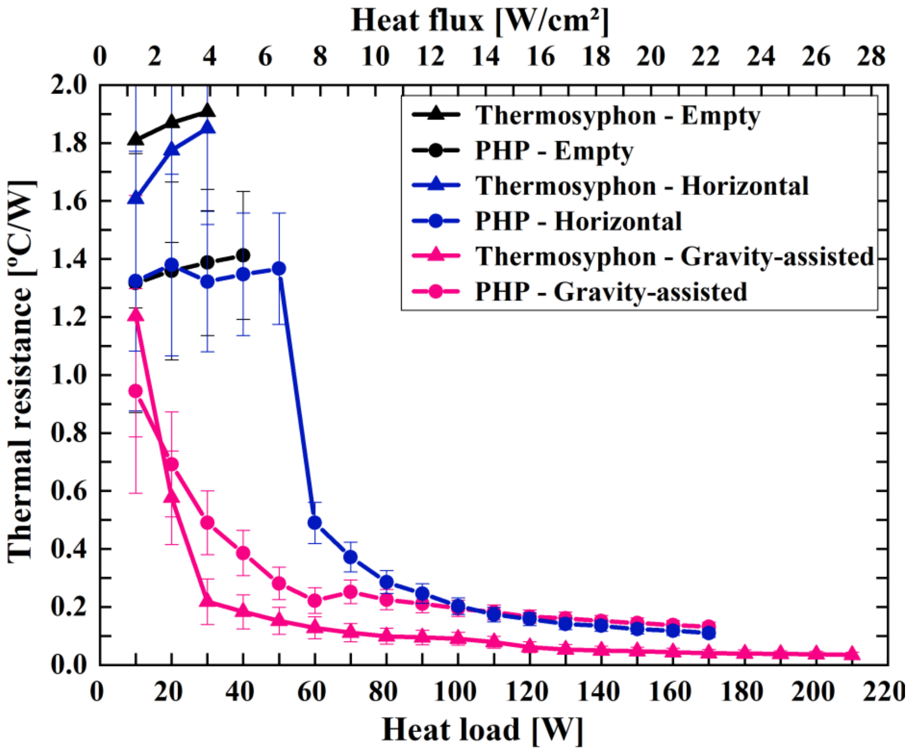


Figure 7. Thermal resistance comparison between the thermosyphon and PHP under both orientations.

Both wickless devices work successfully for the tested conditions in the gravity-assisted orientation. The pulsating heat pipe is largely considered as the device that can transfer a high amount of heat; however, in the present work, the thermosyphon proves to be capable of transferring more heat, is more efficient thermally, and is lighter than the PHP. In this context, it does not justify the use of PHP in this position, despite the high number of publications considering the assistance of gravity. However, the thermosyphon could not operate in the horizontal position due to its dependence on gravity, as expected. In the horizontal orientation, the pulsating heat pipe demonstrates excellent thermal performance, including an independency of the gravity action at high heat loads. As a negative point, the PHP presents difficulties in the start-up, requiring a high temperature for activation.

The near future work must focus on the improvement of the pulsating heat pipe technology to enhance its operating temperature range, startup and thermal performance, for applications at the horizontal orientation, also enabling and expanding cooling devices for high-power chips under a microgravity environment, for instance, for satellites and spacecraft.

4. CONCLUSIONS

A mini thermosyphon and a mini pulsating heat pipe were manufactured by diffusion bonding technology and thermally tested. The two-phase devices were designed for the thermal management of waste heat of miniaturized high-power chips. As a result, their dimensions are suitable for most tablets, laptops, and CPUs. The thermal performance in the gravity-assisted and horizontal orientation was investigated and compared. The main conclusions of this research are:

- In gravity-assisted orientation, both wickless two-phase devices operate successfully for the tested conditions. However, the thermosyphon proves to be a better cooling solution than the PHP for this position, as it is capable of transferring more heat, is more efficient thermally, and is lighter.
- In the horizontal orientation, the pulsating heat pipe has an excellent thermal performance after the startup, being able to transfer up to high heat loads. Also, the PHP becomes independent of gravity action from heat loads of 100 W. As a negative point, the PHP presents difficulties in the startup, requiring a high temperature for the activation. The thermosyphon is not indicated for this operating position.
- The diffusion bonding demonstrates an efficient technology to produce mini flat plate two-phase devices, as they can produce several types of gadgets with high quality and without leakages.

The near future work must focus on the improvement of the pulsating heat pipe technology to enhance its operating temperature range, startup, and thermal performance for applications at the horizontal orientation, also enabling and expanding cooling devices for high-power chips under a microgravity environment, for instance, for satellites and spacecraft.

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