Study of diffusion bonded flat plate closed loop pulsating heat pipes with alternating porous media

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Abstract. This work aims to discuss the application of diffusion bonding process in the fabrication of flat plate pulsating heat pipes and to analyze the thermal performance effect of porous media structures applied to alternating channels in the evaporator section and compare it with a smooth conventional flat plate pulsating heat pipe. For that, two different copper flat plate pulsating heat pipes with five turns and 1.5 mm of inner diameter channels were fabricated, using diffusion bonding. Samples were made with two different diffusion process to evaluate the ability of the resulting device to keep the vacuum, avoiding the use of filler material during the welding process, which could result in contamination and, therefore, undesirable corrosion on both internal and external heat pipe surfaces. The results allowed to assess the quality of the bonded interface of two different configurations of the diffusion process. Microscopic results obtained on controllable pressure furnace and non-pressure control were analyzed, where the diffusion process with controlled pressure presented best results of continuity, alignment, and tightness. A comparison of the heat transfer characteristics between the two devices was performed under the same experimental conditions; for both devices, the thermal resistance in horizontal position showed to be like heat transfer of pure conductive copper plate. However, pulsating heat pipe containing smooth channels showed the lower thermal resistance in vertical position and filling ratio of 50%.

1. Introduction

Pulsating heat pipes (PHP) are highly efficient heat exchanger devices, consisting of an evacuated small diameter closed tube bended in multiple turns, in which a certain amount of working fluid is inserted. PHPs are composed of two main regions: evaporator, where heat is inserted, and condenser, where heat is removed from, as schematically presented in Figure 1. An adiabatic section, a thermally insulated region, located between the evaporator and the condenser, may have a variable dimension, or even not exist. PHPs operate in closed two-phase chaotic cycles. Confined saturated liquid, when heated, forms slugs of liquid and plugs of vapor as shown in Figure 1. Due to the confinement, PHPs use latent heat of vaporization to generate vapor, expanding the bubbles and pushing the liquid slugs to the condenser region. The high-speed cycles are responsible for the efficiency of the working fluid latent and sensible heat transportation.

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When heat power is provided to the evaporator zone, vapor is generated and, due to pressure perturbations, transported along the pipeline to be rejected in the condenser zone. Two simultaneous phenomena occur in a PHP: bubble-growing (and pressure increase) at the evaporator and bubble-collapsing at the condenser, inducing the pressure decrease in this region. This growing-collapsing process produces the fluctuation of the liquid slugs, trapped between the vapor plugs. Heat is transferred by two means: liquid-vapor and vapor-liquid phase change and sensible heat, due to the displacement of liquid slugs [1] [2]. PHPs are a promising solution for heat flux management, since they are wickless, easy to manufacture and present fewer operating limitations.

Some researchers studied the thermal performance of closed loop PHP by introducing valves in the circuit or by increasing the number of turns. Although efficient, check valves increase the manufacturing complexity of the device [3]. Moreover, the increase of the number of turns can improve the thermal performance of PHP; however, it can represent a geometry limitation in actual applications. According to [4], the fabrication simplicity of a PHP contrasts with the complex thermo-hydro-dynamic operation principles that drive its operation and which include the effect of the surface tension dominance over the two phase bubble liquid slug formation inside the tube.

PHP can be classified between meandered closed loop and flat plate PHP. The second is a device that contains channels on a planar surface, welded against another channelled or flat plate. In this case, the heat is also transferred by conduction through the plate where the channels are made, besides the pulsating effect of the working fluid. Among the advantages, the design of flat plate PHP is almost unlimited, as practically any channel geometry can be achieved, and the channels surface can be easily modified before joining both plates. The alteration of chemical composition and/or properties of the surface, such as roughness or porosity, directly affects friction and wettability of the working fluid with the channel. Different forms of capillary unbalancing have been reported by different authors, who concluded that this type of device is less sensitive to the inclination angle. Also, the device’s thermal resistance decreased with the increase of the heat input and the vertical arrangement showed a lower thermal resistance when compared to horizontal positions [3] [5] [6].

Diffusion bonding in solid state is a technique that produces coalescence of surfaces in intimate contact, by the application of a pressing force during a thermal cycle under vacuum. The main mechanism of the joining process is the interdiffusion of atoms across the surfaces, after the plastic deformation of surface asperities [7]. Such technique relies on the combination of three main variables: temperature, pressing load and holding time, which vary according to the material pair, its surface finishing, and the expected service conditions. Unlike conventional processes, the diffusion bonding preserves the base metal microstructure and properties at the interface, since it can be performed without filler materials, localized thermal gradient nor melting. However, the surfaces to be joined require more preparation than for conventional welding.

**Figure 1.** Schematics of a pulsating heat pipe.
processes; whole parts are subjected to longer thermal cycles and equipment costs are usually high [8]. Diffusion bonding was used in this work to bond commercial copper plates in the fabrication of two different flat plate closed loop PHPs. A conventional one and another with asymmetrical sintered porous media onto alternating channels at the evaporator. The first one was fabricated using a commercial diffusion bonding furnace and the second one using a conventional resistive tubular furnace. This work compares the thermal performance of two flat plate PHPs produced with and without porous media and evaluates the resulting microstructure of the channels with surface modification and of the joint regions for the different processing routes.

2. Fabrication process
Two flat plate PHP of 5 U-turns formed by two machined copper plates were fabricated using different experimental apparatus for the diffusion bonding, detailed in sequence.

Semi cylindrical grooves with 1.5mm of diameter was milled by CNC in two flat plates (see Figure 2a) and united against each other, to form circular cross section channels. To remove surface contaminants, the parts were cleaned by immersion in a 10 vol% aqueous solution of H₂SO₄. In sequence, the planar surfaces to be bonded were grinded with silicon carbide paper, with fine grit size (1500), to obtain the smoothness required to assure uniform contact. Eight holes were drilled to host removable steel pins of 3mm of diameter, used to avoid misalignment of plates during the diffusion bonding process. The available contact area for diffusion bonding in each device was of 3,862mm².

2.1. Conventional flat plate pulsating heat pipe
After surface preparation, the diffusion bonding of the conventional flat plate PHP was performed in a high vacuum heat treatment furnace with an integrated pressing unit, PVA TePla MOV 653HP. The copper plates were positioned in the furnace and submitted to a thermal cycle, as detailed in Figure 2b and c. A pressure of 8MPa was applied to the device during the diffusion bonding thermal cycle, under vacuum of at least 5x10⁻⁵mbar and followed by slow cooling inside the furnace (Figure 3).

![Figure 2. Plates preparation and assembly before the diffusion bonding cycle](image)

![Figure 3. Diffusion bonding thermal cycle.](image)
2.2. Flat plate pulsating heat pipe containing porous media in alternating channels

The second flat plate PHP also consists of two machined plates with the same geometry as the other one, but with modified (wicked) channels by sintering particulate copper at the evaporator zone, as indicated in Figure 4a and b. The step consisting of sintering loose copper powder over the surface of the channels was performed before the diffusion bonding of the copper plates. No particle deformation occurs during the loose powder sintering process, a pressureless shaping technique of powder metallurgy, which favor the manufacture of highly porous materials or layers [9]. A commercial copper powder (PAC-Metalpó) was sieved and the particles retained in sieve with 400µm mesh size were selected and poured in alternating channels of the evaporator, forming a layer with 40mm of length and around 0.25mm of thickness.

![Porous media distribution](image)

Figure 4. Porous media distribution; a) Overall dimensions and porous media distribution at evaporator zone; b) Typical Cu particle morphology and size distribution.

The concave format was obtained using a graphite core of 1mm of diameter, laid up over the poured powder, as presented in Figure 5a. The sintering of powder was performed in a resistive furnace (Figure 5b), at 900°C during one hour and under controlled atmosphere of 95%Ar and 5%H₂. Heating was programmed to increase in a rate of 10°C/minute. Despite all the benefits of using a commercial furnace for diffusion bonding, the elevated energy consumption, operational costs, and time-consuming cycles must be considered. As an alternative, the diffusion bonding was performed using a resistive furnace with the help of a pressure applying matrix, a device consisting of two stainless steel thick plates with passing screws near its edges to provide the needed pressure for intimate contact of the surfaces [10].

The flat plates with modified channels were positioned between the boards hold by fourteen M10 screws, which applied an initial pressure of 10bar to the copper plates by hydraulic press. The whole system was placed inside the furnace Figure 5b and heated up to 900°C maintained for one hour, using a heating rate of 10°C per minute, and cooled naturally inside the furnace.

![Powder distribution](image)

Figure 5. Powder distribution; a) Graphite core over the powder bed. b) plates-screws assembly inside the conventional resistive furnace.

After the fabrication of both devices, the vacuum leakage was tested up to 10⁻⁷ mbar.l/s to evaluate if the fabrication process used was able to produce sealed bonded surfaces.
3. Experimental setup
For charging the working fluid, the devices were first vacuumed by a vacuum pump (Edwards RV8) up to 1x10^{-6} mbar. An Edwards Spectron 5000 Leak Detector equipment checked the sealing of the device. The working fluid was first degassed by continuous vacuuming cycles, by utilizing a volumetric pump. The temperature distribution of the flat plate PHP was measured by eight type T thermocouples (±0.9°C of maximum uncertainty), distributed along the device, according to Figure 6a. A DAQ-NI SCXI-1000 data acquisition system was used to record experiment data. In the condenser region, heat was removed from the PHP by an aluminium heat sink, as shown in Figure 6b. This heat sink has two channels within which water flows from a thermal bath (Lauda® Proline RP1845). This equipment can keep the temperature at constant levels of the order of ±0.01°C. The thermal contact between the flat plate PHP and both the evaporator and the condenser is improved by spreading, over the heat exchange contact surfaces, a thin layer of Omegatherm® 201 thermal grease (2.3 W/m·°C). Heat is provided to the evaporator by four cartridge heaters (outer diameter 10mm and 40mm length) embedded in a copper block, thermally insulated by mineral wool. The heaters are connected to a power supply (TDK-Lambda GEN300-17).

![Figure 6](image)

**Figure 6.** Experimental setup; a) eight thermocouples: three at evaporator zone, two at adiabatic zone and three at condenser zone; b) experimental setup including PHP, heater and heat sink.

3.1. Experimental procedure
Tests were conducted in horizontal and vertical positions bottom heat mode, for both PHP evaluated. Power levels started at 10W and reached 100W at steps of 10W. The working fluid used was 3M HFE7100 at four different filling ratios (FR) of 0, 25, 50 and 75% of the total internal volume, for each PHP. Two inclination angles (0° and 90° heating at bottom position) were also adopted as testing parameters.

4. Experimental results

4.1. Fabrication process
Microstructural analysis comparing the cross-section area of the bonded plate interfaces produced by different diffusion bonding routes, indicated a direct influence on the final microstructure, explained as follows.

4.1.1. Fabrication using a non-controlled pressure furnace. The plate interfaces of the PHP fabricated using the conventional resistive furnace (non-controlled pressure furnace), did not presented continuity of the material, as can be observed in Figure 7a and b. This microstructural aspect directly influenced the sealing capacity of the device, which was not able to maintain the necessary vacuum of 10^{-7}mbar-l/s. Furthermore, Figure 7 shows that the semi-circles did not match well to form a circular channel, due to misalignment. Although the misalignment was less than 0.2 mm, this distortion forms grooves that effect the nucleation sites during liquid-vapor working fluid phase change and meniscus formation. discontinuity between the planar bonded surfaces (Figure 7b) is due to insufficient mechanical intimacy of metal-to-metal contact, a necessary condition to obtain a satisfactory diffusion union. The pressure applied by the screws on the stainless-steel matrix device was not enough to provide a homogeneous
plastic deformation of surface asperities. As a final step of the fabrication process, additional high vacuum glue was applied to the borders to keep the stagnation of the device.

![Image](a) ![Image](b)

**Figure 7.** Interface in PHP with porous media. a) Channel; b) Interface.

On the other hand, the copper powder sintered successfully to the channel surface and among particles with the used set of parameters. However, the resultant porous media was not homogeneously distributed through the channel surface, as shown in Figure 8a. This is associated with the adopted powder pouring technique, which must be optimized. Within the continuous porous media, a homogeneous porous layer can be observed, as zoomed in Figure 8b.

![Image](a) ![Image](b)

**Figure 8.** Porous media distribution; a) porous media in alternating porous media PHP; b) zoom of porous media.

4.1.2. *Fabrication using a controlled pressure furnace.* The conventional flat plate PHP, fabricated using the high vacuum heat treatment furnace with an integrated pressing unit, presented more continuous joint interfaces. Furthermore, the plates matched better and the misalignment (gap formed between the semicircles) decreased considerably, as shown in Figure 9a. This better union quality can be attributed to both the controlled pressure, which allowed the necessary mechanical intimacy, and to the high vacuum atmosphere, which allowed the reduction of surface oxides, improving the metal to metal contact necessary for the interdiffusion of atoms through surfaces. Grain growth through the joint interface was observed in some regions (Figure 9b). Such interface continuity improvement resulted in a better vacuum capacity of the device, which could maintain the pressure of $10^{-7}$ mbar.l/s, without leakage.
4.2. Thermal results

Differences of the mean temperatures ($\Delta T$) at evaporator and condenser regions are presented in Figure 10 as a function of time, where $\Delta T$ is the difference of mean temperatures at evaporator zone ($\bar{T}_e$), condenser zone($\bar{T}_c$), where:

$$\bar{T}_e = \frac{(T1 + T2 + T3)}{3}$$  \hspace{1cm} (1)

$$\bar{T}_c = \frac{(T6 + T7 + T8)}{3}$$  \hspace{1cm} (2)

Figure 10 shows the transient $\Delta T$ variation, start-up for conventional PHP, operating in vertical position and FR of 25 and 50%, start-up happened at power levels less than 40W. $\Delta T$ was lower for wicked PHP, FR of 25% and power input of 10 and 20W; however, $\Delta T$ increased once in the range from 30 to 40W, decreasing again at power level of 70W. Wicked PHP at vertical position and FR of 50 and 75% and smooth conventional PHP with FR 75% achieved start-up at power input of 60W.

![Figure 10. Differences of mean temperatures; C and PM are conventional and porous media PHP, FR of 25, 50 and 75% and vertical position (V).](image)
However, start-up at horizontal position was not observed for all the experimental tests, although some temperature oscillations were observed, heat transfer mechanism at horizontal position is mainly the conductive one.

Using $\Delta T$ for each the thermal power supplied ($Q$), the thermal resistances ($R_t$) are defined as:

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

(3)

The thermal resistances observed for the PHPs working at the several operation conditions selected in this paper are presented against heat power input in Figure 11. Lower thermal resistances were obtained for both PHPs in vertical position, as expected from Figure 10, as in this condition, the PHPs operate in thermostyphon mode. Moreover, less time was necessary for the wicked PHP and FR of 25% to achieve start-up at low power inputs; however, when the power supplied was found between 30 and 60W, thermal resistance rises for this experimental case. Conventional PHP with FR of 25 and 50% and vertical position started to work at 20W and the thermal resistance followed a decreasing trend for all the power range, achieving a thermal resistance about of $0.4^\circ$C/W and $0.5^\circ$C/W for FR of 50 and 25% respectively. Other filling ratios at vertical positions decreases the thermal resistance around of $0.5^\circ$C/W.

As told before, both devices with any filling ratios did not work at horizontal position; thus, the thermal resistance measured in this case was only due to the conduction heat transfer. Pure conduction was effectively measured for the PHP with 0% of filling ratio (void device). The overall resistance of the empty PHPs is close to the PHPs operating in the horizontal positions, showing that phase change is practically not generating oscillations. The device with alternating porous media, horizontal position and charged with FR of 25% tried to work, as one can see by some small decreasing of the thermal resistance curve. From all the configurations tested, the conventional PHP and FR of 50%, operating in vertical position presented the lowest thermal resistance. Thermal resistances uncertainty was calculated to be less than 10% at power levels from 10 to 50W and less than 2% for power inputs higher than 60W.

![Figure 11. Thermal resistance, where C and PM are conventional and porous media PHP, FR of 25, 50 and 75% and H and V are horizontal and vertical positions.](image)

5. Conclusions
This article presents two flat plate closed loop PHPs fabricated using the diffusion bonding technology, with and without the application of sintered loose power wick porous media over the internal surfaces
of alternated evaporator channels. Both PHPs were tested under the same experimental conditions. From the present work, on can conclude that:

Microscopical investigations revealed that the application of pressure in combination with a reducing atmosphere is of utmost importance to achieve continuous joint interfaces, which directly affected the devices ability to maintain the vacuum necessary to service operation. Such analysis also indicated that the loose powder sintering is a suitable technique to produce the porous media that can recover channel surfaces of minichannels as flat plate PHPs. However, to obtain channels with a homogeneous distribution of porous layer, optimizations on the powder pouring process need to be developed.

The mismatching of the plate grooves due to assembly deviation results in deformed channels that yields capillary gaps between united plate surfaces, affecting the thermohydraulic performance of the PHPs. Further analysis needs to be focused on this phenomenon.

Porous media in alternating channels hinders the fluid motion due to pressure drops, results does not show improvements in the overall device thermal performance. Nevertheless, the wick allowed a weak early PHP start-up at filling ratio of 25% and only for power inputs up 20W.

The thermal resistance of the conventional PHP operating in vertical position decreased by almost 45% for 50% of filling ratio, when compared to the empty PHP, where no phase-change takes place. This means that the conduction heat transfer is important in this case, as expected, once the device has a considerable mass of solid material (copper), of high conductivity and high density. Further studies need to be developed, focusing on optimizing the plate geometry, aiming the decrease of the thermal resistance and thermal inertia.

6. Nomenclature

| Symbol  | Description                      |
|---------|----------------------------------|
| C       | conventional                     |
| CNC     | Computerized numerical control   |
| FR      | Filling ratio [%]                |
| H       | Horizontal                       |
| PHP     | Pulsating heat pipe              |
| PM      | Porous media                     |
| $R_t$   | Thermal resistance (°C/W)        |
| $\Delta T$ | Temperature difference (°C) |
| $Q$     | Thermal power supplied (W)       |
| $T_e$   | Mean T at evaporator zone (°C)   |
| $T_c$   | Mean T at condenser zone (°C)    |
| V       | Vertical position                |

7. References

[1] Mangini D, Mameli M, Georgoulas A, Araneo L, Filippeschi S and Marengo M 2015 A pulsating heat pipe for space applications: Ground and microgravity experiments Int. J. Therm. Sci. 95 53–63
[2] Charoensawan P, Khandekar S, Groll M and Terdtoon P 2003 Closed loop pulsating heat pipes - Part A: Parametric experimental investigations Appl. Therm. Eng. 23 2009–20
[3] Chien K H, Lin Y T, Chen Y R, Yang K S and Wang C C 2012 A novel design of pulsating heat pipe with fewer turns applicable to all orientations Int. J. Heat Mass Transf. 55 5722–8
[4] Karimi G and Culham J R 2004 Review and assessment of pulsating heat pipe mechanism for high heat flux electronic cooling Inter Soc. Conf. Therm. Phenom. 52–9
[5] Yang K S, Cheng Y C, Liu M C and Shyu J C 2015 Micro pulsating heat pipes with alternate microchannel widths Appl. Therm. Eng. 83 131–8
[6] Tseng C Y, Yang K S, Chien K H, Jeng M S and Wang C C 2014 Investigation of the performance of pulsating heat pipe subject to uniform/alternating tube diameters Exp. Therm. Fluid Sci. 54 85–92
Acknowledgement
The authors acknowledge the help of all the members of the Heat Pipe Laboratory LABTUCAL and Materials Laboratory LABMAT at the Federal University of Santa Catarina.