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MULTILAYER SINTERED POROUS MEDIA MINI HEAT PIPE

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ABSTRACT

The main objective of this work is to evaluate the thermal performance of mini heat pipes produced with multilayer capillary structures. Multilayered sintered porous media is able to produce high working fluid pumping capacity while keeps the pressure drops in low levels, optimizing the heat pipe thermal performance. Multilayer heat pipes are made of overlapping layers of sintered copper powder. The tested mini heat pipes have the nominal dimensions: 100mm x 30mm x 2mm and their porosities vary between 42 and 52%. Flat copper plates are used as the closing sheets and wires of 1.70mm of diameter are used to improve the mechanical resistance of the system. These sintered materials are produced with atomized copper powder of 95% of purity and average particle sizes of 20 and 50μm. A particle circularity factor of 70% is observed for the powder. Distilled water is used as working fluid. The effective thermal conductivity and permeability are experimentally measured using an experimental apparatus especially designed and built for this purpose. The thermal performances of multilayered and conventional mini heat pipes are compared. Models available in literature are used to evaluate the mini heat pipe. A simple hydraulic resistance model is proposed to evaluate the capillary limit in multilayer mini heat pipes. The wick porous size distribution and porosity are determined by image analyses using software IMAGO®.

KEY WORDS*:* mini heat pipes, multilayer porous media.

1. INTRODUCTION

Mini heat pipes (MHP) can be employed as thermal control devices for electronic equipment cooling, in the aerospace, automotive, computer, and other industries (Faghri, 1995). LABTUCAL (Heat Pipe Laboratory) of UFSC (Federal University of Santa Catarina - Brazil) works in the development of MHP with sintered wick structure since 2005.

Conventional porous media shows a limited heat transfer capacity in mini heat pipes. A porous media with small pores presents high working fluid pumping capacity, but on the other hand, a large liquid pressure drop. Actually, the fluid pumping capacity improvement is obtained reducing the pore diameter, which, in turn, reduces the media permeability. One of the possible ways to achieve the mini heat pipe maximum performance, is to construct porous media composed with layers of different permeabilities. These arrangements show a high capillary pumping capacity and no significant decrease in the global permeability.

The main objective of the present work is the application of a novel wick technology in heat pipes, to improve its thermal performance. Wicks formed by multilayers of sintered metal with different characteristics are studied. These media are able to combine high capillary pumping capacity with low pressure drops, enhancing, therefore, the heat transfer capacity of the device.

2. LITERATURE REVIEW

Most of the research in heat pipes around the world has been focused on developing new structures and capillary pumping configurations for porous media. The literature shows that different types of grooves, sintered porous media (metallic and ceramic) and screens are employed.

Groove wicks have attracted great interest, as reported by Cao and Faghri (1993) and Peterson

(1990), due to its high permeability and low manufacturing costs, compared to other wicks. However, sintered materials have higher pumping capacity that compensates the lower permeability, as stated by Vasiliev (2006).

Berre et. al (2003) produced a micro heat pipe, with mini V-shaped channels. Adjacent smaller channels below the main channel, or arteries, are assembled. Their micro heat pipe tube was made of thin silicon wafers. These micro channels further allowed an independent path for the flow of condensate to the evaporator. The experimental results using methanol as the working fluid showed that the artery arrangements increase the conductivity of mini heat pipe, compared to the conductivity of silicon.

Paiva (2007) developed a mathematical model and an experimental prototype of a mini heat pipe formed by wires and copper blades. These mini heat pipes were tested in gravity and micro-gravity environment. In his work, a methodology for manufacturing mini heat pipes was developed, as described by Mantelli et al. (2002). Tests using distillated water as working fluid showed that these devices were able to deliver 55 W with thermal resistance of 0.5 K/W.

Xiao and Franchi (2008) used a combination of different porous structures to improve the capillary pumping characteristics, by increasing the surface area between the solid and the working fluid and enhancing the amount of open pores. These researchers designed and manufactured different hybrid structures, using copper screen and sintered powder of copper and nickel, arranged in different compositions. The tests were conducted using distilled water as the working fluid. Different configurations showed an increase of around 70% of the working fluid pumping capacity. All these measurements were made with the heat pipes in a vertical position. A maximum power of 15 W was transported.

The direct mixing of powders in the fabrication of sintered porous media has been studied and reported by Yeh et al. (2009). These researchers produced a capillary structure formed by "biporos". According to the authors, this structure provides greater interconnection among the formed pores, providing a greater heat transfer capacity due to phase change (evaporation) of the working fluid in the evaporator.

3. EXPERIMENTAL TESTS

In the present work, the thermal resistance and the capillary limit of multilayer MHPs are evaluated. MHP samples with four different combinations of sintered material layers are experimentally studied. The samples are tested in two conditions: vacuum of 0.001 mbar (no working fluid) and filled with several different volumes of saturated distilled water. Factorial design of experiments technique is employed, with two replicates in a single level.
The MHP wicks are produced by loose sintering metallurgy process. Atomized copper powder is employed to produce the multilayer and the conventional porous media. These selected powders have commercial names PAC and PAM. PAC has a fine and PAM a coarse average particle sizes. Copper is selected for the reason that it is commonly used in MHP wick structures and is compatible with water. Other copper interesting characteristics are the high thermal conductivity and low cost (Dunn and Reay, 1994).

The MHP produced presents a parallelepiped shape with nominal dimensions of 100mm x 30mm x 2mm. The closing cases are built using 0.3mm thickness copper sheets. Before closing, the case is filled with a controlled amount of powder and them sintered in an oven, forming the first layer. The second layer was deposited over the first layer and sintered again. After the porous media is ready, the cover sheet is diffusing welded to the base, using the same oven.

The resulting samples are denominated as: 100PAM, PAM75PAC25, PAM50PAC50 and PAC100, according to the thickness of the layers, respectively: 100% PAM, 75% PAM plus 25% PAC, 50% PAM plus 50% PAC and 100% PAC, as depicted in Figure 1.

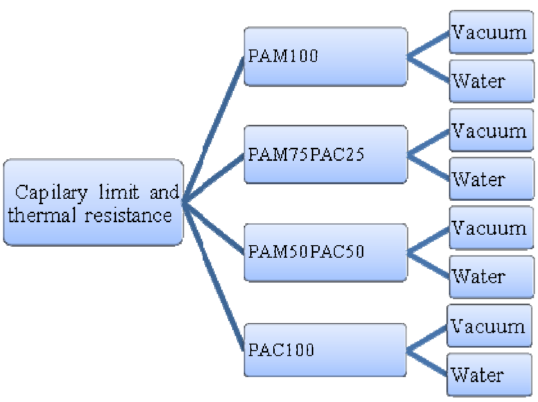

Figure 1. Tests description

The sintering heating rate is 5°C/min and the system is left inside the oven for 50 minutes, after reaching the 850°C. The sintering process is conducted in a vacuum furnace with commercial H_2 controlled atmosphere, available at the UFSC Materials Laboratory. In the final step, the MHP case walls receive a oxy-acetylene welding to guarantee the vacuum. A capillary tube is provided to allow the selected working fluid filling.

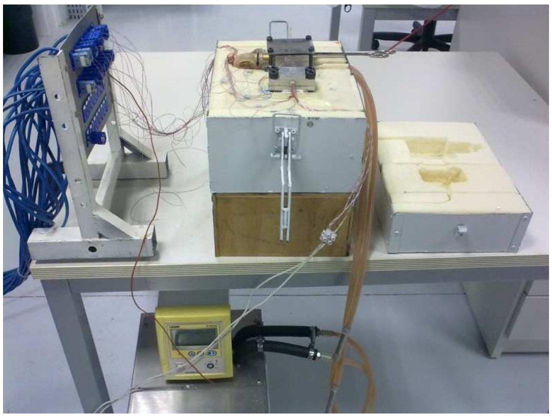

Figure 2. Experimental apparatus

An experimental apparatus is designed and built especially for testing the thermal performance of MHP. Heating plates are connected to the evaporator and a small heat exchanger is attached to the condenser. This assembly is housed inside a metallic box filled with polyurethane foam as insulating material, according to Figure 2. The heat is removed by cooled water from a thermostatic bath, maintaining the temperature condition set in 40ºC during the tests.

The temperatures are measurement by type T thermocouples. The position of the thermocouples can be seen in Figure 3. The red color represents evaporator and blue color condenser sections.

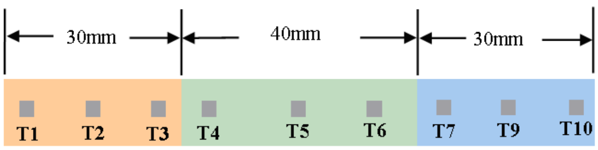

Figure 3. MHP Thermocouple distribution

The power is supplied to the four electric heaters, with a total capacity of 50 W, by a power supply. The software Labview 8.6 is used as the graphical interface for recording the thermocouple readings.

4. THEORETICAL ANALYSIS OF MHP

4.1 Capillary limit model

To determine the MHP capillary limit, the Faghri (1995) and Chen (2001) models, with the addition of two terms is employed, resulting in Equation 1. One of the added terms, in the left side of the equation, is relative to the capillary pumping for each layer of the porous material. It is considered that the two porous media layers work as capillary pumps in series. In the right hand side of the equation, one term is added to the fluid pressure drop term, consisting of pressure losses of parallel paths, according to Darcy's law, resulting in:

$$2\sigma \cos\theta \left(\frac{1}{r_{c1}} + \frac{1}{r_{c2}}\right) = \left(\frac{C\left(f_v Re_v [\;]\mu\right]_v}{2{r_{h,v}}^2 A_v \rho_v h_v}\right) l_{ef}\, q + \frac{1}{\left(\frac{\mu_l l_{ef}}{\rho_l K_1 A_{w1}}\right)^{-1} + (\ldots}$$

The following hypotheses are considered: laminar flow regime; Darcy´s equation is valid and steam is incompressible (Mach number less than one). The properties are considered constant and obtained for the adiabatic section temperature. The MHP operates in steady state.

4.2 Global thermal resistance

The global thermal resistance is defined as the ratio between condenser and evaporator temperature difference and the power transferred, being given by:

$$R_t = \frac{\bar{T}_{eva} - \bar{T}_{cond}}{P_e} \qquad (2)$$

where $\mathbf{P_e}$ is the heat transfer for the MHP, $\bar{\mathbf{T}}_{\mathbf{e}\square\mathbf{a}}$ and $\bar{\mathbf{T}}_{\mathbf{co}\square\mathbf{d}}$ are the average temperatures of the evaporator and condensation sections, respectively. The heat loss through the insulation was determined to be around 4%.

5. TEST RESULS AND DISCUSSION

5.1 Wick properties

The results of measurements of the properties of porous media are present in Table 1. The properties were measured according to procedures described in Florez et al. (2011) and Nuernberg et al. (2011).

Table 1. Wick properties

Property	PAC	PAM

Permeability $[m^2]$	3.71E-13± 0.15	2.89E-12± 0.42
Critical radio $[\mu m]$	9.4	19.7
Porosity $[\%]$	41.31 ± 0.60	51.95 ± 0.71
Effective thermal conductivity $\left[W/(m \cdot K)\right]$	52	36

The thicknesses of the two layers are controlled during the fabrication process and measured later by image analysis. It is observed that, between these layers, there is a third transition interfacial layer, which thickness was determined applying statistical image analysis, using software IMAGO®, as proposed by to Nuernberg et al. (2011). Porosity and frequency correlations were employed as parameters of evaluation of the produced layered wick. Table 2 shows the thickness of each sintered material layer. The thickness of the interfacial layer is of the order of magnitude of the sum of the particles average diameters of each layer. .

Table 2. Wick thickness.

Thickness wick [µm]	PAM	PAC
PAM100	670±10	0
PAM50PAC50	260±10	330±10
PAM75PAC25	430±10	170±10
PAC100	0	670±10

5.1 Analysis of fluid working volume for multilayer sintered porous media

The wicks of the MHP are filled with distilled water in different volumes. The resulting MHP are tested with several power input levels. The working fluid volume varied starting form values below the theoretical amount needed to saturate the porous medium. Table 3 shows the theoretical working fluid volumes for each sample, obtained from the image analysis.

Table 3. Theoretical working fluid volume.

Theoretical amount water [ml]	Total	PAM	PAC
PAM100	1.65	1.65	0
PAM50PAC50	1.50	0.83	0.67
PAM75PAC25	1.57	1.24	0.33
PAC100	1.33	0	1.33

The tested MHP tubes were gradually loaded with working fluid and its thermal resistance measured until the optimum operation conditions were achieved. The measurement uncertainties obtained were calculated to be around $\mp 12\%$ for the start up period. For steady state, the overall thermal resistance uncertainty was approximately ±3%. A confidence level of 95% and a Student-t coefficient of 2 were used in the uncertainty calculations.

In Figures 4, 5 and 6, the x-axis represents the power input while the y-axis represents the overall thermal resistance.

Figure 4 shows that the thermal resistance in vacuum conditions was approximately $4\ ℃/W$ for sample PAM100. Approximately the same resistance for vacuum conditions can be observed for other samples, as it can be seen in Figures 5 and 6. For PAM 100, the lowest thermal resistance is obtained for 1.2 ml of working fluid, reaching values below $0.5\ ℃/W$, for heat transfer powers varying from $50\ W$ to $80W$. This fluid volume was about 72.7% of the theoretical fluid amount enough to saturate the porous media.

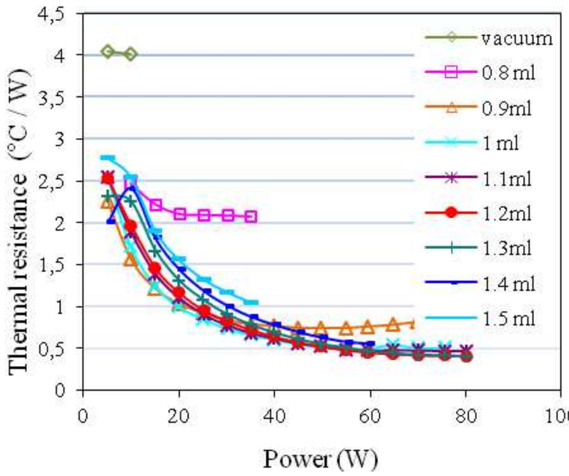

Figure 4. Experimental data for MHP PAM100 for several working fluid loads

Figure 5 shows the experimental thermal resistance for PAM50PAC50 sample, for different amounts of fluid. The lower thermal resistance observed was around $0.35\ ℃/W$, for heat transfer power larger than 60W, with 1.5 ml of distilled water. This amount of fluid showed the best performance, being able to transfer up to $104W$. This working fluid amount represents 100% of the volume necessary to saturate the porous wick.

Figure 6 presents the data for PAM75PAC25. The results show a higher thermal resistance related to the other two MHP samples. For this configuration, the best result was obtained for a load of 1.4 ml, which corresponds 89.2% of the amount needed to saturate the porous media. This low thermal performance can be explained by the fact that the PAC layer does not provide the appropriate capillary pumping.

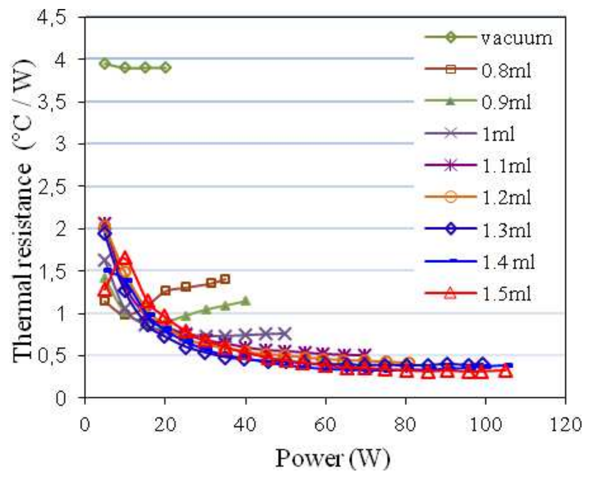

Figure 5. Experimental data MHP PAM50PAC50 several loads

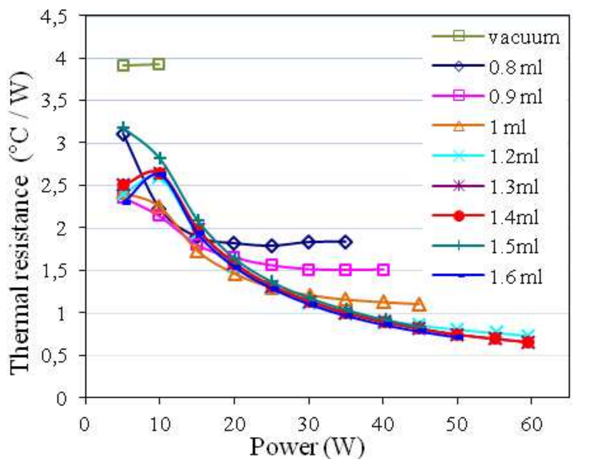

Figure 6. Experimental data PAM75PAC25 several loads

In Figure 7, it is presented a comparison between the best configurations for each sample studied, in terms of thermal resistance. From all tested samples, the lower thermal resistance is obtained is for PAM50PAC50, which is 20% lower than the MHP built with a single layer PAM100.

In Figure 7, it is also possible to observe the dry-out for PAM100, PAM75PAC25 and PAM50PAC50 samples. According to Paiva (2007), this behavior can be observed by a change in the slope of the resistance curve against thermal power input. Usually, as the heat power increases, the thermal resistance tends to decrease and a sudden increase shows that the capillary limit is reached. The PAM100 MHP reaches its capillary limit for a power input approximately 20% lower than that observed for PAM50PAC50. In this figure, one can also observe that the smallest resistance is obtained for the PAM50PAC50 sample.

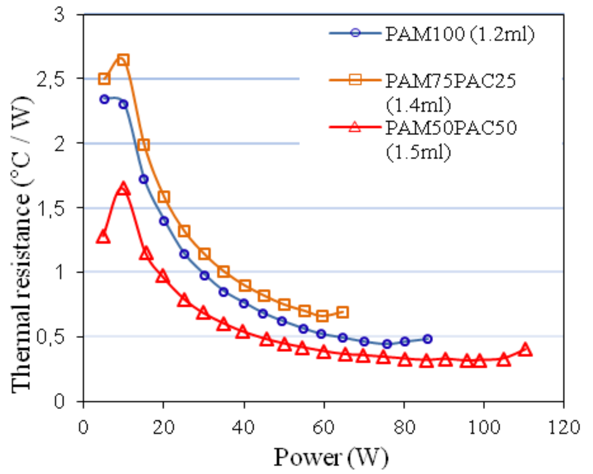

Figure 7. Compare of the thermal resistance of the three MHP

Figure 8 shows the temperature profiles for different power inputs for the PAM50PAC50 samples. The evaporator achieves a temperature of 76 ºC for a power of 100W.

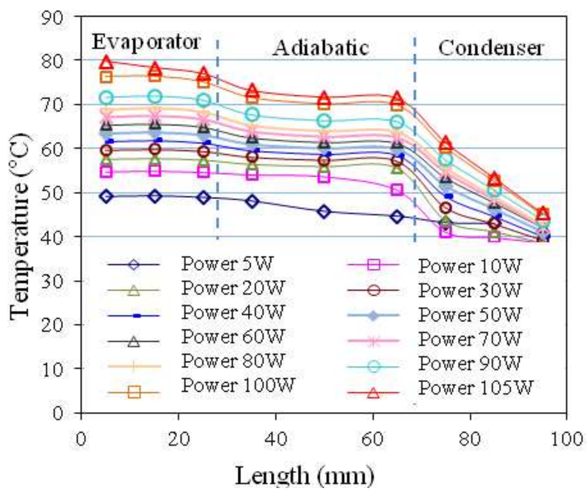

Figure 8. Experimental data sample PAM50PAC50 1.5ml

For the working fluid volume of 1.5 ml, the MHP has the lower the thermal resistance 0.35 °C/W. The model expressed by equation 1, when applied to this configuration and to operating temperature of 75ºC, predicts a capillary limit of the 108W. The experimental data indicate that the tube is able to transport up to 100W, for an average evaporator temperature of 76ºC. As already observed, for the 104W power level, the evaporator temperature quickly increases, showing the beginning of dry-out. The capillary limit calculated by Equation 1 present an accuracy of approximately 8% for this configuration. However for PAM75PAC25 sample, the comparison between model and data is not good.

6. CONCLUSIONS

In the present paper, is was demonstrated that the use of layers of different porosities modify the thermal behavior of mini heat pipes, showing that his is an interesting configuration as they can combine high pumping capacity and low pressure drop. Tests conducted on the PAM50PAC50 MHP (two layers of same thickness, made of powder of different sizes), showed a 20% increase of the maximum power transported (100W) in comparison to the conventional tube with a single layer of PAM material.

NOMENCLATURE

K	Permeability	$[m^2]$
k_e	Effective thermal conductivity	$[W/(m \cdot K)]$
q	Power	$[W]$
R_t	Total thermal resistance	$[°C/W]$
r_c	Critical radius	$[m]$
C	Fluid constant	
f_v	Friction factor	
Re_v	Reynolds number in vapor	
$r_{h,v}$	Hidráulic radius in vapor	$[m]$
A_v	Transversal area in vapor	$[m^2]$
A_w	Transversal area in liquid	$[m^2]$
h_v	Enthalpy of vapor	$[kJ/kg]$
h_{lv}	Enthalpy of saturation	$[kJ/kg]$
l_{ef}	Effective length	$[m]$
g	Acceleration of gravity	$[m/s^2]$
P_e	Power inlet	$[W]$
$\overline{T}_{eva}$	Average temperature in the evaporator	$[°C]$
$\overline{T}_{cond}$	Average temperature in the condenser	$[°C]$

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