

EFFECTIVE THERMAL CONDUCTIVITY OF LAYERED POROUS MEDIA

J. P. M. Florez^a, G.G. V. Nuernberg^a, M. B. H. Mantelli^a, R. S.M. Almeida^a and A. N. Klein^b

^a Department of Mechanical Engineering (Heat Pipe Laboratory), Florianópolis, Santa-Catarina, 888040-900, Brazil

^b Department of Mechanical Engineering (Materials Laboratory), Florianópolis, Santa-Catarina, 888040-900, Brazil

Tel : +55 (48) 3721-9937, Fax: +55 (48) 3721-7615, E-mail: jpablo@labtucal.ufsc.br

ABSTRACT

Sintered porous media has been employed on mini heat pipes (MHP) in the capillary transport of working fluid from the condenser to the evaporator section. High porosity media has high permeability representing low liquid pressure drop, while low porosity media increases the capillary pumping capacity of the heat pipe. LABTUCAL (Heat Pipe Laboratory – UFSC, Brazil) developed porous media made of layers of different porosities, which can provide high capillary pumping performance and keep low liquid pressure drops. The combination of these two properties should enhance the heat transfer capacity of the mini heat pipe. The effective thermal conductivity of such porous media is an important parameter employed in the design of mini heat pipes. In this work, a set up developed for measuring the effective thermal conductivity of porous media is described. Samples with porous media layers were constructed and tested in vacuum and filled with saturated distilled water. The tests were conducted in the temperature range of 20 °C to 80 °C. The experimental data were compared with literature model results. The samples were tested on a vacuum chamber with a guard heater as radiation insulator. The samples used had nominal dimensions of 200mm x 30mm x 10mm. The two porous media layers were fabricated from 95% of pure atomized copper powder, with different particle size (average size of 20 and 50µm) and deposited as overlapping layers resulting in porosities of 42 and 52%, respectively. The interfacial characteristic length was determined applying statistical image analyses using software IMAGO[®]. Porosity and frequency correlations were used as evaluation parameters. The effect of porosity and of the presence of the working fluid in the effective thermal conductivity was analyzed and evaluated.

Keywords: *effective thermal conductivity, layered porous media, sintered porous media*

1. INTRODUCTION

Mini heat pipes (MHP) consist basically of small heat pipes, able to transport efficiently relatively high amounts of thermal energy. They can be employed as thermal control devices in the aerospace industry, for cooling of electronic equipments, in the automotive industry, among other applications (Faghri [7]).

In portable computers for instance, the increase of their data processing capacity together with the decrease of their size and weight, lead to the development of small processors and other electronic components, that dissipate high amounts of concentrated heat. MHPs have widely used in the computer industry to dissipate this heat, controlling the temperature levels of the device. Actually, the heat dissipation of

electronic components is a major limitation for the development of faster and smaller computers.

Sintered porous media have been applied in the electronic industry as they are able to provide high capillary pumping capacity of the working fluid in MHP. On the other hand they can produce high liquid pressure drops, decreasing the thermal performance of the device.

Wicks formed by layers of sintered metal with different characteristics can combine the working fluid liquid capillary pumping capacity with low pressure drops, enhancing, therefore, the heat transfer capacity of the device. One of the parameters of major importance for the thermal design of MHP with layered wick is the effective thermal conductivity of the porous media. MHP with sintered wick structure has been studied in the Heat Pipe Laboratory in Brazil since 2005.

The main objective of the present work is to propose an experimental apparatus to measure the effective thermal conductivity of layered porous media. A simple model, based on the analogy between electrical and thermal circuits, was developed and its results compared with the experimental data. The fabricated and tested wicks are composed by two layers made from particles of different sizes. Between these layers, a third transition interfacial layer is found. Its characteristic thickness was determined applying statistical image analysis, using software IMAGO[®]. Porosity and frequency correlations were employed as parameters of evaluation of the produced layered wick.

2. LITERATURE REVIEW

In current investigation, a steady state method was employed to define the effective thermal conductivity of multi-layer sintered copper porous media. Many literature works treat all porous media equally, independently of the technology employed for its construction. Actually, there is a large difference among the porous media produced employing different technologies. For instance, the thermal conductivity of sintered and bed packed metal powder are very different. Tsao [11], worked with compound materials, proposing a model to estimate the thermal conductivity, based on the concept of different porosities in different directions. Handley [8], conducted an experimental work where he tested porous media made of a mixture of two different packed metal powders. The powders were modeled as solid spheres. In his model, the effective thermal conductivity was considered as three distinct phases: two solid (for each metal powder) and a fluid phase. An average volumetric theory was applied. He proposed a parameter that describes the degree of particle consolidation. Analytical solutions of Chan and Tien [4], Cunningham and Peddicord [5], and numerical methods of Argento and Bouvard [1], and also of Veyret et al [12] were developed for modeling the thermal conductivity of packed spheres.

The literature also reports other porous media for mini heat pipes. The effective thermal conductivity of wire sintered screen media was theoretically and experimentally studied by Li and Peterson [10]. They concluded that the thermal conductivity of single and multilayer wire screens represent 4 to 25% and 6,4 to 35% of the solid metal thermal conductivity, respectively.

Atabaki and Baliga [2] presented a correlation based on experimental data of Handley's [8] work. They also proposed a new correlation for the consolidation degree of wicks, this time for sintered porous media. An interesting model for effective thermal conductivity is proposed in the PhD Thesis from Alexander (1972), apud Atabaki and Baliga [2], for metal felts, sintered powders, layers of wire cloth and unconsolidated beads.

It is important to note that the present authors did not find any literature theoretical or experimental works concerning the thermal conductivity of porous media composed of different layers of sintered metal.

3. EXPERIMENTAL FACILITY

In the present work, an apparatus was built to measure the effective thermal conductivity of layered porous media. Figure 1 illustrates a scheme of the experimental apparatus. The experimental set up is divided in three sections: heater, sample holder and cooler. The heater section is composed by two electric cartridge resistances with 50W power each, placed inside an aluminum block. The heat is transferred by conduction to the sample, using two pure copper blades, of known thermal conductivity, of 85 mm x 10 mm x 2 mm, that work as flux meters. The multi-layer porous sample to be tested is placed in series between the reference samples (flux meters). Two pairs of aluminum plates work as clamping mechanisms and connect the flux meters to the testing plate. The heat conducted through the sample is transferred through the flux meters. The heat flux through the sample is, therefore, measured as an average of both flux meters measurements. The heat flux, in turn is measured using the heat conduction Fourier law, once the temperature distribution and the thermal conductivity of the flux meter material is known. The cooling system is kept at a prescribed temperature by means of water recirculation, which temperature is controlled by a thermal bath. Two copper guard heaters, of total length equal to the flux meter lengths plus the sample length, are thermally connected to the heat source and sink and installed in parallel to the measuring set up, so that the temperature distribution in the plate is very similar to that observed along the lower flux meter, sample and upper flux meter. They work as radiation insulators.

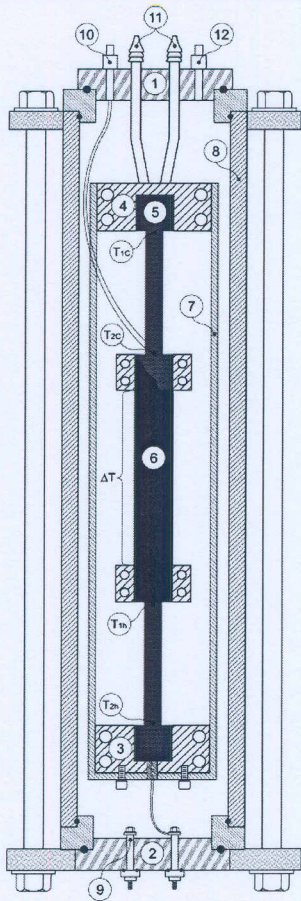


Figure 1. Scheme of the experimental apparatus:
 1 Top flange; 2 Bottom flange; 3 Heater; 4 Cooler; 5 Flux meter; 6 Sample; 7 Guard heater; 8 Polycarbonate tube; 9 Filling through; 10 filling tube; 11 water recirculation; 12 vacuum tube.

The convection heat transfer from the testing sample is avoided, placing the system inside a evacuated polycarbonate tube. During tests, the device is located in a vertical arrangement. The tested sample has a rectangular plate shape, with dimensions of 200mm x 30mm x 10mm. The porous media is sintered over a copper plate. The layers are made from two different commercial atomized copper powders, denominated PAM and PAC, with 95% purity, and a case. The case is built with copper blades of 0,3 mm of thickness, in two parts: a thin rectangular case and a cover sheet. The case (housing) is filled with a controlled amount of powder and the system is sintered, forming the first layer. The second layer is deposited over the first layer, after sintering the first one. The sintering heating rate was 5°C/min and the system was left for 50 minutes, after reaching the 850°C level. After the layers were sintered, the cover sheet is welded to the case edges with oxy-acetylene, closing the case. A capillary tube is provided to allow the

sample filling with the select working fluid. Samples were tested in vacuum (0,001mbar) or filled with saturated distilled water. The testing temperature range is 20° C to 80 °C. The temperatures are measurement by means of type T (copper-constantan) thermocouple, which are connected to the data acquisition system, which, in turn, sends the signal to the computer, where it processed using the software Labview 8.6. The positions of the thermocouples are found in Fig. 1.

Samples with four combinations of layers thicknesses were fabricated: 100% PAC, 100% PAM, 75% PAM and 25% PAC and 50% of PAM and 50% PAC. The total thickness of the porous media is always 10 mm.

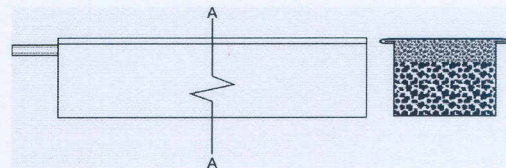


Figure 2. Scheme of sample.

A transition region between both layers is observed. The thickness of this interfacial region was determined applying statistical images analyses, using software IMAGO®. Porosity and frequency correlations were employed to evaluate the wick parameters.

3.1 Measurement and uncertainties

The heat flux was calculated as the average of the fluxes measured by the flux meters connected in series with the sample. The heat flux is defined as the ratio of the temperature differences measured in the flux meters and the known distances by:

$$q = \frac{\Delta T}{L} \quad (1)$$

where q is the average heat flux, k represents the thermal conductivity of the flux meter material, e are the flux meter temperatures; x_1 and x_2 are the position of temperature sensors. Using the Fourier model and the well known definition of thermal resistance, the porous media effective thermal conductivity, can be calculated by:

$$k_{eff} = \frac{\Delta T}{L} \quad (2)$$

where R_{case} represents the conduction resistances of the case, ΔT is the temperature difference measured in the sample and L is the sample length. The welding thermal resistance between the case and the cover is neglected, because

the case and the cover are considered in the same temperature.

Uncertainties associated with the temperature measurement were taken into account and calculate according INMETRO[9]. The error bars are plotted in Fig.5, but the errors were so small that they can be hardly observed in this figure.

4. RESULTS AND DISCUSSIONS

4.1 Layer porous media characterization

The characterization of particle size distribution was made by laser granulometry, using the Fraunhofer diffraction method and the equipment Cilas 1064. The powder is characterized by the amount of particle which presents diameter up to a certain value. For instance, $dp_{10\%}$ equal to 9.24 to PAC means that 10 % of the PAC particles have diameters up to 9.24 μm .

Table 2. Distribution of the particle size (μm)

	$dp_{10\%}$	$dp_{50\%}$	$dp_{90\%}$	dp_{mean}
PAM	17,25	40,45	93,31	49,04
PAC	9,24	19,45	35,20	20,89

The porosity of a media is defined as the ratio between their void and the bulk volumes Dullian[6]. The sample porosity is measured based on the Archimedes's principle, using a Mettler Toledo model DU 205 VS Dual Range, with 0.0001 g of resolution and automatic system for determining the sample density (ρ_s) and the value of the theoretical copper density (ρ_t). The data is shown in Table 3.

Table 3. Porosity

Sample	PAM	PAC
Porosity (ϵ)	$51,95 \pm 0,71$	$42,52 \pm 0,85$

It is difficult to measure the thicknesses of the two layers as there is undefined transition region between the layers. To overcome this problem, three distinct regions were considered. The first layer corresponds to an infinite thick homogeneous porous layer, a central region, corresponding to the interface between layers, with finite thickness, and a second infinite thick homogeneous layer. To measure this transition region, the image was segmented into several "slices" with a thickness of 100 μm . Then a frequency distribution of each slice was made. This analysis of frequency distribution consists

in the calculation of the probability of finding a black pixel (porous) in distance U_x (μm). When the frequency distribution curves for each slice chance of pattern, one can considered that the material structure is changed. The process started from the region with higher porosity until three distinct regions could be observed. Figure 3 shows an optical microscopy image of the layered porous media and its interface region.

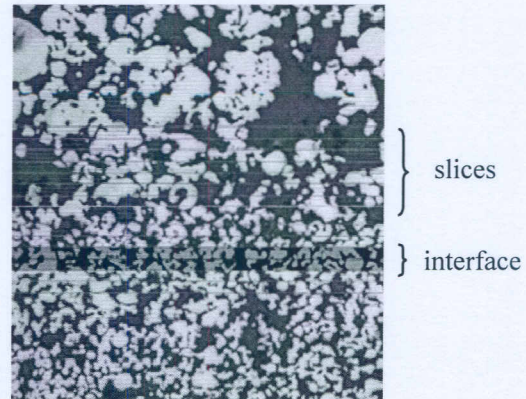


Figure 3. Layers porous media, measure of thickness interfacial layer

4.2 Effective thermal conductivity

Effective thermal conductivity of the double layer porous media developed in this work was measured in two conditions: vacuum and filled with distilled water. Experimental data of the sample with a single porous media (100% PAC and 100% PAM) was compared with Handley's [2] correlation:

$$\frac{k_e}{k_f} = (1 - \alpha_{con}) \frac{\epsilon f_o + k(1 - 2f_o)}{1 - \epsilon(1 - f_o) + k\epsilon(1 - f_o)} + \alpha_{con} \frac{2k^2(1 - \epsilon) + (1 + 2\epsilon)k}{(2 + \epsilon)k + 1 - \epsilon} \quad (4)$$

With,

$$\alpha_{con} = 1 - e^{\left[\frac{-\Lambda \left(\frac{1-\epsilon}{\epsilon} \right)^m}{1 - \left(\frac{k_s}{k_f} \right)^{-n}} \right]}$$

where, $\Lambda = 0,148$; $m = 0,283$; $n = 0,04$, and Alexander's [2] model:

$$k_e = k_f (k_s/k_f)^{(1-\epsilon)\delta} \quad (5)$$

where, for metal felts, $\delta = 0,34$, sintered powders $\delta = 0,53$; layers of wire cloth $\delta = 0,59$ and unconsolidated beads $\delta = 0,44$.

On the other hand, the effective thermal conductivity experimental data obtained for the multi-layered samples was compared with a simple model based on the analogy of thermal and electrical circuits, which scheme is shown in Figure 4.

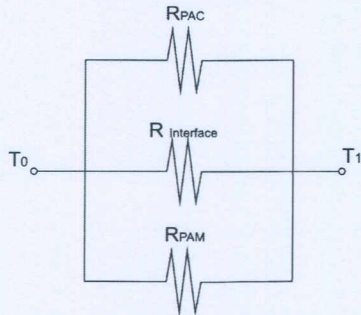


Figure 4. Circuit of thermal resistances in parallel for multilayer porous media

Figure 5 shows the plots of the theoretical effective thermal conductivity calculated for vacuum and water using the models given by Eqs. 4 and 5 and of the experimental data, as a function of the porosity. This figure shows that the effective thermal conductivity has a large dependence of the porosity: the increase in the porosity represents a decrease of the effective thermal conductivity. This result was expected, as the volume of sintered metal, for high porosity materials is lower than that for low porosity materials, affecting the conduction heat transfer through the material. The sintered porous media PAC filled with saturated water, for instance, had effective thermal conductivity of 60W/m.K, that represent four times less that thermal conductivity value when compared with the thermal conductivity of solid cooper.

The experimental data demonstrates best comparison with Alexander's model. Furthermore, the experimental data does not show considerable different in the effective thermal conductivity measured from porous media evacuated or filled with saturated water. The effective thermal conductivity experimental data is compared with the thermal resistance model (Fig. 4) for multi-layered wicks in Fig. 6. For the two types of porous layers, the experimental data exhibits high comparison with the thermal resistance model. The thermal resistance model also shows that the interfacial layer has negligible influence in the effective thermal conductivity of layered porous media.

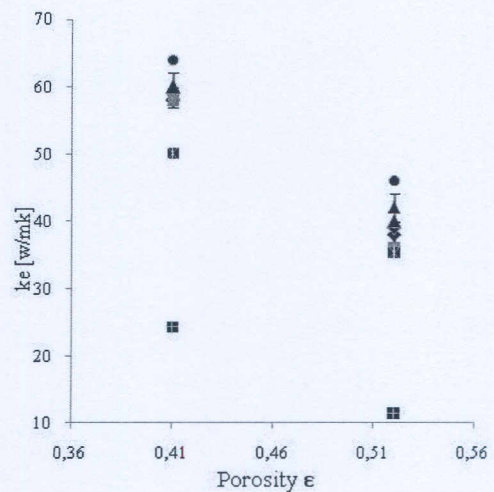


Figure 5. Experimental and literature effective thermal conductivity of 100% PAC (porosity 0.41) and 100% PAM (porosity 0.52) samples.

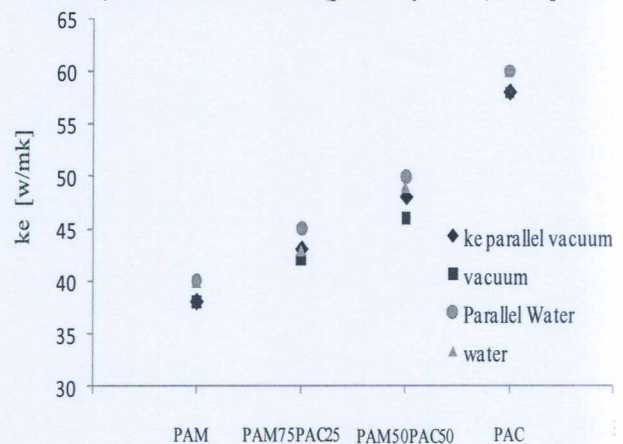


Figure 6. Experimental and theoretical effective thermal conductivity for the tested samples.

4. CONCLUSION

Two different sintered porous media layers were build in four configurations and tested in Heat Pipe Laboratory in Brazil. The sintered porous layers were characterized using image analyses. The characteristic thickness of the interface between layers was determined applying statistical images analyses using the software IMAGO®.

An experimental set up to measure the effective thermal conductivity of sintered porous media was design and fabricated. The difference between the effective thermal conductivity obtained for samples fabricated from PAC and

PAM, with porosities of 0,42 and 0,52 respectively, increased around 50% with the porosity. Samples of sintered porous media were tested with vacuum (0,001mbar) and filled with saturated distilled water. The effective thermal resistance experimental data shows that this parameter is not very influenced by the presence or not of the working fluid. This means that, actually, the heat is conducted through the path formed by the metal after the sintering process, as also observed in the literature. The electrical and thermal analogy circuit model compared very well with the experimental effective thermal conductivity data for all the porous media tested. The thermal resistance of interface showed to be negligible for the determination of the effective thermal conductivity of the porous media composed by layers.

NOMENCLATURE

\bar{Q}	Average heat flux
$T_{2,c}; T_{1,c}$	Outlet temperatures flux meter
$T_{2,h}; T_{1,h}$	Inlet temperatures flux meter
$x_{2,c}; x_{1,c}$	Position of outlet thermocouples
$x_{2,h}; x_{1,h}$	Position of inlet thermocouples
$R_1; R_2$	Thermal resistance of container sample
A	Total transversal area of sample
k_r	Reference sample thermal conductivity
k_e	Effective thermal conductivity
ε	Porosity
ρ	Theory density
ρ_p	Density of porous media
k_f	Thermal conductivity of fluid
k_s	Thermal conductivity of solid
α_{con}	Consolidation parameter in correlation
f_o	Parameter in correlation
Δ	Parameter in correlation

ACKNOWLEDGEMENT

The authors acknowledge CNPq, contract ????? for the funding of the present research and for providing the scholarship for the main author of this paper.

REFERENCES

- [1] Argento, C. and Bouvard, D., "Modeling the Effective Thermal Conductivity of Random Packing of Spheres Through Densification", *Int. Heat and Mass Transfer*, vol. 39, No. 7, pp 1343-1350, 1996.
- [2] Atabaki, N. and Baliga, B.R., "Effective Thermal Conductivity of Water-Saturated Sintered Powder-Metal Plates", *Heat and Mass Transfer*, No. 44, pp 85-99, 2007.
- [3] Chan, C.K, and Tien, C.L., "Conductance of Packed Spheres in Vacuum", *Journal of Heat Transfer*, ASME, pp 302-308, 1973.
- [4] Cunningham, .M.E, and Peddicord, K.L., "Heat Conduction in Spheres Packed in an Infinite Regular Cubical Array", *Int. Heat Mass Transfer*, vol. 24, No. 7, pp 1081-1088, 1981.
- [5] Dullien, F.A.L., *Porous Media Fluid Transport Pore Structure*. San Diego, California, 1979.
- [6] Faghri, A., "Heat Pipe Science and Technology" Ed. Taylor & Francis, 874p. Washington, USA, 1995.
- [7] Handley, G.R., "Thermal Conductivity of Packed Metal Powders", *Int. J. Heat Mass Transfer*, No. 29, pp 909-920, 1986.
- [8] INMETRO, *Guia para Expressão da Incerteza da Medição*. 3a ed. Rio de Janeiro: ABNT, 2003
- [9] Li, C., and Peterson, G.P., "The Effective Thermal Conductivity of Wire Screen", *Int. J. Heat and Mass Transfer*, 49, pp 4095-4105, March 2006.
- [10] Tsao, G.T.N., "Thermal Conductivity of Two-Phase Materials", *Ind. and Eng. Chemistry*, vol. 53, No. 5, pp 395-397, 1961.
- [11] Veyret .D, Cioulachtjian, S., Tadrict, .L, and Pantoloni, .J, "Effetive Thermal Conductivity of a Composite Material: a Numerical Approach", *Transactions of the ASME*, 866, vol. 115, Nov 1993.