https://dx.doi.org/10.22161/ijaers.6.2.26 ISSN: 2349-6495(P) | 2456-1908(O)

Permeability of a Capillary Structure of Sintered Copper Powder Used in Heat Pipes

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***Abstract*— *A heat pipe is a passive device that has a high thermal conductivity, which uses a closed biphasic cycle and the latent heat of the working fluid vaporization to carry out the heat transfer. The capillary structure directly influences the thermal performance of the heat pipe, because it promotes capillary pumping and the flow path to conduct the working fluid inside the heat pipe. Among the main properties of a capillary structure, there are the critical pore radius, porosity, permeability, and thermal conductivity. Thus, in this research, the experimental evaluation of the permeability of a sintered copper powder structure was performed for use as a capillary structure in heat pipes. For this, a Capillary Extrusion Test, based on MPFI Standard 39, was used. The experimental results showed that the average permeability of the copper powder capillary structure was* $7.81 \times 10^{-13} \pm 0.38 \times 10^{-13}$ m^2.

***Keywords*— permeability, capillary structure, sintered copper powder, heat pipe.**

I. INTRODUCTION

The heat pipe is a passive device with a high thermal conductivity due to the uses of a closed biphasic cycle and the latent heat of vaporization of the working fluid to perform heat transfer [1].

The capillary structure directly influences the thermal performance of the heat pipe, because it promotes capillary pumping and the flow path to conduct the working fluid inside the heat pipe [2].

The sintered metal powder capillary structures have been widely used in heat pipes because of the lower effect of the gravity on the performance of this type of capillary structure. The sintered wicks have reduced pores and a higher thermal conductivity, as a consequence of the almost perfect fit of the metal powder [3]. Moreover, the metal powder adheres to the tube wall with a high contact, reducing the thermal resistance between the wick and the tube.

The main properties of a capillary structure are the pore radius, the porosity, the permeability, and the thermal conductivity. The pore must have a small radius to pump the liquid from the condenser to the evaporator, using a high capillary pressure difference, or for a high heat carrying capacity. The permeability must be high for a small pressure drop of the liquid in the capillary structure. The thermal conductivity should be high, which results in lower temperature drops in the capillary structure of the heat pipe, a desirable quality for this passive heat transfer device [1].

In this context, in this research, an experimental evaluation of the permeability of a sintered copper powder structure was performed, which can be used as a capillary structure in heat pipes.

II. METHODOLOGY

A Capillary Extrusion Test, based on MPFI Standard 39 [4], performed the determination of the capillary structure permeability.

2.1 Copper Powder

The sintered capillary structure will be fabricated from an XF copper powder obtained by gas atomization. The copper powder is showed in Fig. 1.

Fig. 1: XF Copper Powder

A micrograph of the copper particles with a magnification of 500x was obtained by Backscattered Electron Detector (BSD) for Scanning Electron Microscope (SEM), and is presented in Fig. 2. The volume-based average particle diameter was 33 μm [5].

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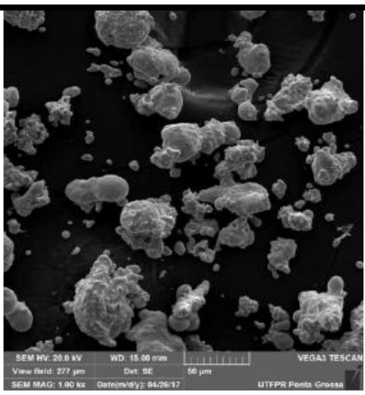

Fig. 2: SEM micrograph of the copper powder (500x).

2.2 Manufacture of Samples for Permeability

Three samples were made, according to MPFI Standard 39 [4], with a diameter of 28.7mm and a height of 3.2mm. The sintering procedure is the same that was applied to the heat pipes subsequently. A sample manufactured is presented in Fig. 3.

Fig. 3: Sample manufactured for the permeability test.

The Figure 4 presents a micrography of the sintered powder capillary structure with a magnification of 500x obtained by Backscattered Electron Detector (BSD) for Scanning Electron Microscope (SEM).

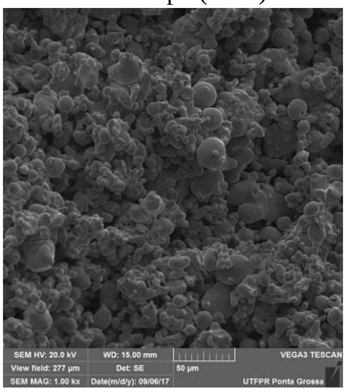

Fig. 4: SEM micrograph of the sintered powder capillary structure (500x).

The experimental apparatus used in the sintering process consisted of a controlled atmosphere horizontal tubular furnace (*Inti*™ FT-1200), a data acquisition system (*Agilent*™ 34970A with 20 channels), and a laptop (*Dell*™) – Fig. 5. The gas used in the atmosphere control was a mixture of 95% of Argon and 5% of Hydrogen. For the evaluation of the temperature inside the furnace, a K-type thermocouple *Omega Engineering*™ was used.

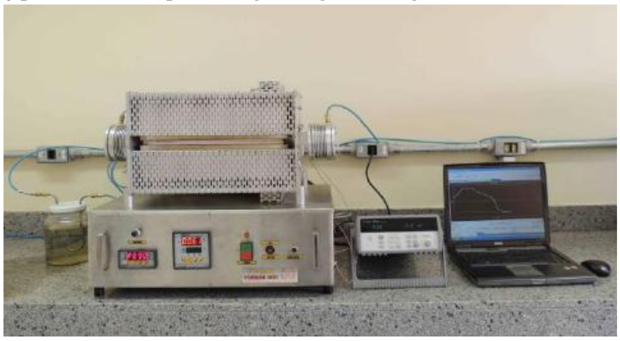

Fig. 5: Apparatus used in the sintering process.

The sintering occurred at a heating rate of 20°C/min, with a 15-minute permanency at a temperature of 800°C, and subsequent cooling by forced convection of air – Fig. 6.

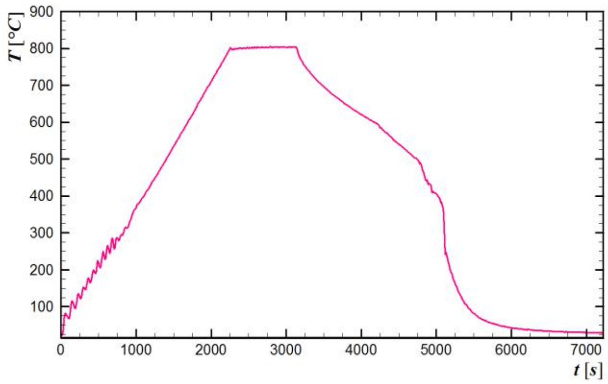

Fig. 6: Sintering curve.

2.3 Experimental Apparatus

An experimental bench consisting of a compressor (*Vonder*™), an air preparation system with pressure regulator and pressure gauge (*Pressure*™), a flowmeter (*Protec*™), a digital pressure gauge (*Digitron*™), a regulating valve, and a test section was developed for the measurement of air permeability in the structure capillary (Fig. 7).

Fig. 7: Experimental bench for evaluation of permeability.

2.4 Experimental Procedure

A flow of compressed air is released into the system until it reaches the test section with the sample. A flowmeter controlled the airflow and a digital pressure gauge recorded the pressure difference. Figure 8 shows a schematic drawing of the fabricated section of tests with the sample placed, according to [4].

From the experimental data obtained, the permeability can be calculated by the Darcy regime, as shown in Equation 1:

$$Q = \frac{K_1 A_{st}}{\mu t} \frac{\left(p_1^2 - p_2^2\right)}{2 p_2} \qquad (1)$$

where, Q is volumetric flow rate [m^3/s], K_1 is the Darcy permeability [m^2], A_{st} is the cross-sectional area of the sample [m^2], μ is the gas viscosity [Pa.s], t is the sample thickness [m], and p_1 and p_2 are the inlet and outlet absolute pressures [Pa], respectively.

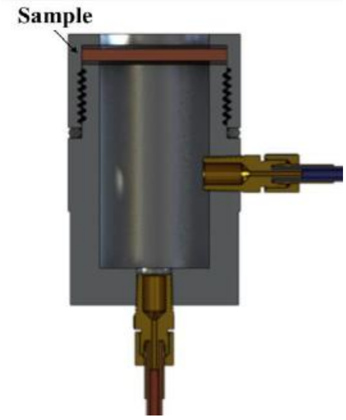

Fig. 8: Test section with the sample.

2.5 Theoretical Analysis

According to [6], the permeability, K, for packaged particulates can be estimated from Equations (2) and (3) proposed by Carman-Kozeny (1927) and Rumpf & Gupte (1971), respectively:

$$K_{\text{Carman-Kozeny}} = \frac{D_s^2 \varepsilon^3}{180(1-\varepsilon)^2} \qquad (2)$$

$$K_{Rumpf\ \&\ Gupte} = \frac{D_s^2 \varepsilon^{5.5}}{5.6} \qquad (3)$$

where, D_s is the average particle diameter of the sintered powder [m] and ε is the porosity of the sintered sample.

III. RESULTS AND DISCUSSION

The experimental results of the permeability with their respective uncertainties for the three samples analyzed are presented in Table 1. The average permeability of the copper powder capillary structure was $7.81 \times 10^{-13} \pm 0.38 \times 10^{-13}$.

Table 1: Experimental results of Permeability

Sample	***Permeability [m^2]***
A	$7.80 \times 10^{-13} \pm 0.38 \times 10^{-13}$
B	$7.41 \times 10^{-13} \pm 0.36 \times 10^{-13}$
C	$8.21 \times 10^{-13} \pm 0.39 \times 10^{-13}$
Average	$\mathbf{7.81 \times 10^{-13} \pm 0.38 \times 10^{-13}}$

Figure 9 presents the experimental results compared to the models proposed in the literature by [6]. The results are compared considering the distribution of the particle size [4], with the diameters corresponding to each quartile of the particle size distribution (11.3 μm, 29.5 μm and 58.3 μm) and the average particle diameter of 33 μm. Moreover, the theoretical analysis considered the experimental porosity of the structure of 55.03%, obtained by [7].

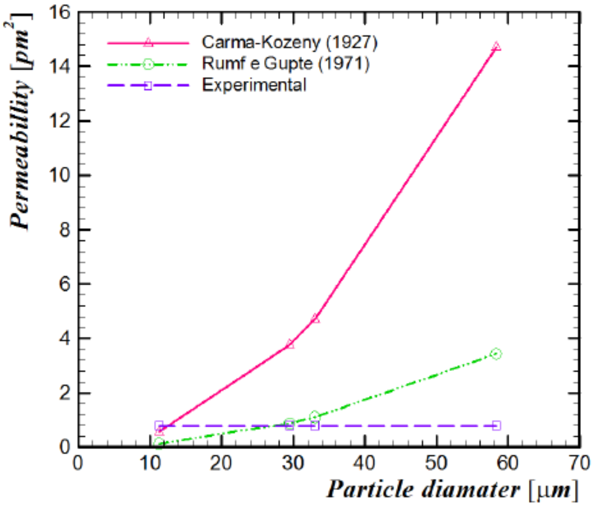

Fig. 9: Theoretical and experimental results of permeability.

The experimental results show a better match with the theoretical models for smaller particle diameter (the particle size of the first quartile). For larger diameters, the discrepancy of the values is very high. This difference can be the result of the particle idealization as spherical in the theoretical models, whereas by the evaluation of the micrograph it can be verified that the particles are not an exactly spherical shape. As a result, when the particle size is small, the shape idealization has no great influence, but for a large particle, the idealization ends up moving away from the theoretical results of the experimental values.

IV. CONCLUSION

In this research was performed an experimental evaluation of the permeability of a sintered copper powder structure, which can be used as a capillary structure in heat pipes. A Capillary Extrusion Test, based on MPFI Standard 39, was used for the permeability determination. The experimental results showed that the average permeability of the copper powder capillary structure was $7.81 \times 10^{-13} \pm 0.38 \times 10^{-13}$ m^2.

ACKNOWLEDGEMENTS

Acknowledgments are provided to the Capes, the CNPq, the PROPPG/UTFPR, the DIRPPG/UTFPR, the PPGEM/ UTFPR/PG, and the DAMEC/UTFPR/PG.

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