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PROCESSING AND MORPHOLOGICAL ANALYSIS OF A TWO-LAYER CERAMIC STRUCTURE FOR CAPILLARY EVAPORATORS

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Abstract. *The present work concerns the manufacturing, characterization of ceramic wicks used in two phase heat transfer devices, as capillary pumped loops (CPLs) and loop heat pipes (LHPs). Such devices are designed for thermal control in microgravity applications and use a wick for pumping the working fluid by capillarity. Double layer alumina wicks presenting each a different porosity were manufactured in order to improve their thermal behavior and permeability. The porous structures were obtained by a slip casting method, associated with polyurethane (PU) foams acting as porogenic agent. The foams were immersed in the mold during casting and thereafter removed by pyrolysis during the sintering process. Characterization prior to processing includes rheology optimization of the slurry, through viscosity analysis, sintering steps determination by dilatometry, and SEM microscopy analysis of the strut size and morphology of the PU foams. Ceramic wick's characterization included porosity, critical diameter and capillary pressure. Each layer presented, respectively average porosity of 39.95% and 45.61% , average critical diameters of 14.9 μm and 91.2 μm and average capillary pressure of 19.7 kPa and 3.2 kPa.*

Keywords: *Ceramic Wick, Slip Casting, CPL, Capillary Pump*

1. INTRODUCTION

Capillary pumped loops are two phase heat transfer devices, which transfer heat through a working fluid phase change. CPLs are comprised of a capillary evaporator, containing a wick (porous element), a condenser, -where the heat is rejected-vapor and liquid lines, and a reservoir - to regulate the loop pressure and to supply liquid for the system. By not requiring gravity, they are adequate devices for thermal control of electronic compounds in microgravity environments, such as satellites and space probes.

Conventionally, porous wicks for this application have been manufactured using sintered metals, such as nickel, titanium and stainless steel, and polymeric materials, such as polyethylene. Due to its chemical inertia, low thermal conductivity, low thermal expansion, and no porosity obstruction during machining operations, the porous wick structures presented in this work were manufactured in ceramic material (Santos, 2012; de Oliveira Hirschmann, 2008; Berti, 2008b; Reimbrecht, 2002).

In studies aiming to improve the CPL performance, there are two main tradeoffs to be considered during the wick structure design. Firstly, there is pore size: small pores increase not only capillary pressure, but also pressure drop. Since an important component of the total pressure loss is the porous wick (Santos, 2012), there is a compromise that must be made concerning pore size during the porous wick design (Choi, 2014). Secondly, there is wick thickness: a ceramic wick must be as thin as possible to reduce pressure drop, while still remain sufficiently thick to avoid the vapor formation in the evaporator inlet due to the heat transfer through the wick, which obstructs the liquid supply and leads to systems collapsing.

In this experiment, differently from most cases of porous wick design - in which variables are optimized in order to produce one homogeneous porous structure - the structure was split in two layers. Promising studies have shown porous wicks presenting two layers with different pore sizes (Choi, 2014; Xu, 2013; Semenic, 2008, 2009). In such structures it is possible to have smaller pores with higher capillary pressure in one side of the element while in the other side to have bigger pores, which promote low pressure drop and rewetting of the system inlet (Xu, 2013; Choi, 2014).

2. CERAMIC WICK MANUFACTURING

Ceramic manufacturing aimed to produce a ceramic wick presenting two different porosities. Each layer was prepared and characterized separately and for future assembly by superposition for testing in the CPL.

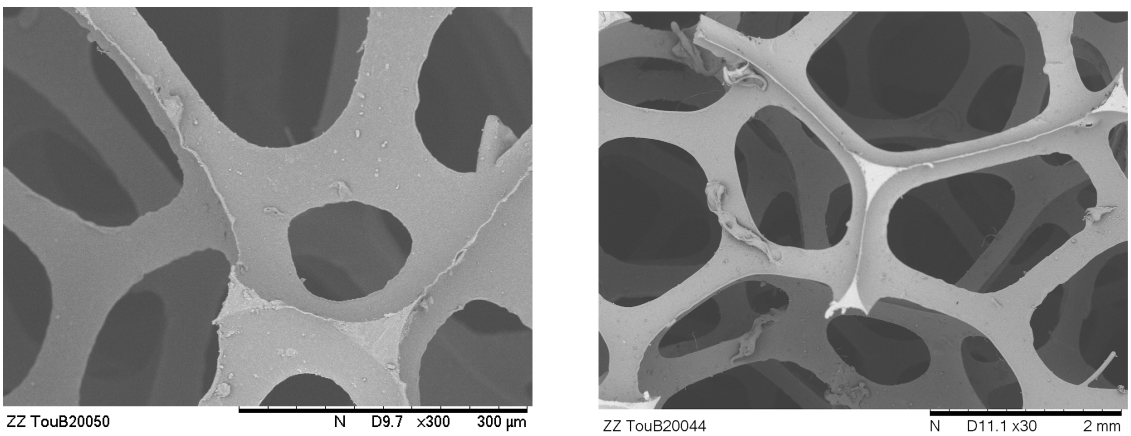
There is one layer in the wick's structure (layer A), which is the effective pump in the system. This layer is in direct contact with the heat source. It is made of very small pores and therefore presents the largest pressure drop in the system (Santos, 2012). As a result of that, it should be as thin as possible. Therefore, in order to maintain a certain wick thickness, so as to avoid the formation of bubbles there is a second layer of wick (layer B), presenting much larger pores, which provide just enough liquid mass flow to the upper layer. In other words, layer B acts as an assistant to layer A, since it is now possible to reduce layer A's thickness and maintain the wicks total size, properly insulating the liquid from the heat source, without adding too much pressure drop.

2.1 Processing Investigation

The manufacturing of the porous ceramic wick was accomplished through a slip casting method associated with polyurethane (PU) foams, used as sacrifice material.

The process consists in producing a cast mold, inserting a PU sponge that fills the entire mold's cavity and then casting the slurry so as to fill all pores with ceramic suspension. After air-drying, the sample is removed from the mold and submitted to a thermal treatment in which the sponge is pyrolized and the ceramic is sintered. The pores formed are a copy of the sponges, presenting pore size and morphology identical to the foams' struts.

In order to visualize strut size and morphology, different PU foam (Crestfoam, USA) samples were analyzed by Scanning Electron Microscopy (SEM Hitachi TM3030). The chosen sponges are shown in Figure 1. For layer A, the smallest strut available was selected, corresponding to an 80 ppi foam (according to supplier). For layer B a 22 ppi (according to supplier) foam was selected.



(a) SEM image 300x of a 80 ppi foam

(b) SEM image 30x of a 22 ppi foam

Figure 1. SEM images of the selected foams.

The alumina (Al_2O_3) powder Almatis CT 3000 LS SG was used in the ceramic wick manufacturing. Supplier information, such as particle size and surface area can be found in Table 1.

Different slurries were then prepared varying the water/solid ratio and the amount of dispersant. The best combination, which presented a high solid percentage while still remaining compatible to the process - that is, to stay sufficiently fluid in order to properly fill the sponge's pores - consisted of 65 %wt alumina, 35 %wt water and 0.5 %wt of solid content of Dolapix CE 64. Its rheological behavior was measured at 25 °C using a torque rheometer (HAAKE Viscotester 550 coupled to SV2P and NV2 geometries) is show in Figure 2.

In order to understand the sintering behavior of the ceramic powder, a dilatometry essay was performed up to 1450 °C

Table 1. Powder information according to supplier.

Property	**Typical**
Specific surface area (BET)	7.80 m^2/g
Particle Size/ D50	0.5 µm
Particle Size/ D90	2 µm

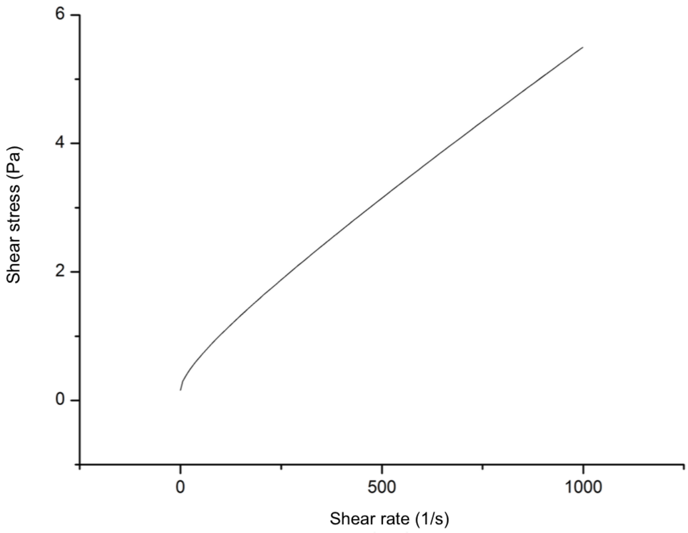


Figure 2. Rheological behavior of the selected suspension.

with a heating rate of 5 °C/min. The result is presented in Figure 3 .

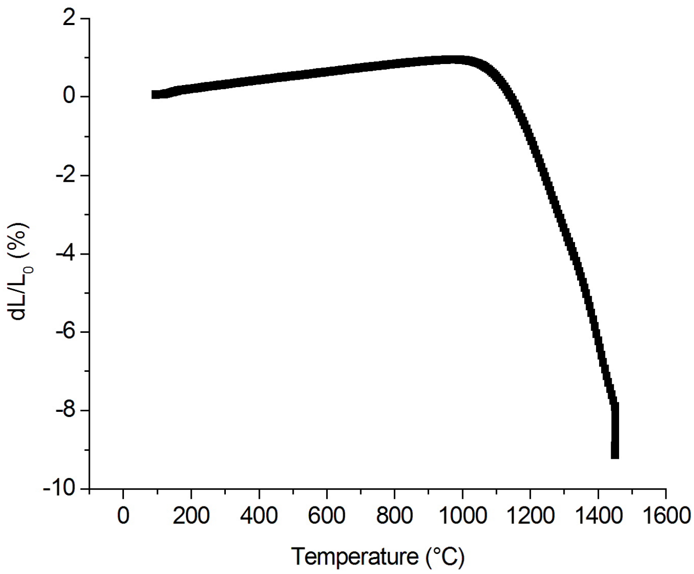


Figure 3. Linear expansion as a function of temperature for Almatis CT 3000 LS SG alumina powder.

It is possible to see in Figure 3 that densification begins around 1100 °C. As the ceramic wick needs to be machined for installation and testing in the CPL, full sintering was not possible, as it makes the following machining operations unfeasible. It cannot be performed prior to sintering either, since dimensional precision would be spoiled due to retraction. The maximum treatment temperature selected was therefore 1100 °C, sufficient mechanical strength while not derailing the machining process.

2.2 Ceramic Wick Preparation

Samples were casted into 32 x 32 x 15 mm slow cure cast molds, prepared from a 70 %wt cast and 30 %wt water combination. The whole setup was inserted in a vacuum container at 21 kPa to remove air bubbles that might have remained in the sponge. After 48 h drying at room temperature, samples were sintered as shown in Figure 4. The initial rate of 1 °C/min aimed slow degradation of the polymeric foam, so as to not compromise the sample structure and to avoid residues of incomplete firing.

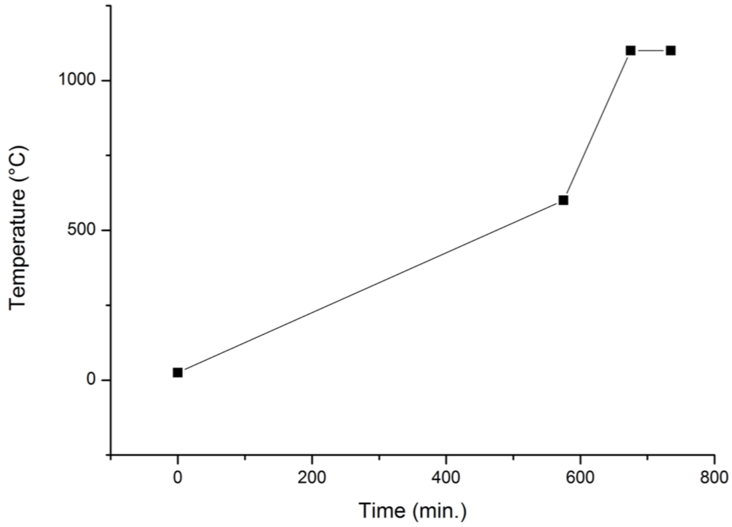


Figure 4. Thermal treatment of pyrolysis and sintering of the ceramic wicks.

3. CERAMIC WICK CHARACTERIZATION

3.1 Porosity

The porosity was obtained by weighting samples before and after water intrusion (Shimidzu AX200) and measuring the alumina powder density by picnometry (Multipicnometer QuantaChrome and Marte AL500C weighting scale).

$$\epsilon = (m_s - m_w) \times (\frac{m_s}{\rho_s} + \frac{m_w}{\rho_w})^{-1} \times 100 \qquad (1)$$

Where m_s is the dry weight of the sample; m_w is the weight of the water impregnated sample; ρ_s is the measured density of alumina (3.85 g/cm^3); and ρ_w is the water density (1 g/cm^3)

The measured porosity in volume percentage for each group of samples can be found in the table below:

Table 2. Porosity

Layer	Average Porosity (%vol)
A	39.95 ± 1.17
B	45.61 ± 0.12

As expected from observation of the PU foams used as sacrifice material, the percentage of porosity is lower than those found in works using other pore forming techniques (Santos, 2012; Choi, 2014). It must be noticed however, that the present pore forming structure presents highly homogeneous and interconnected pores, increasing porosity and therefore being expected to present a performance compared to other processing techniques which present higher porosity.

3.2 Capillary Extrusion

Capillary pressure and critical diameter were obtained through capillary extrusion. The apparatus consist in two chambers divided by the ceramic wick sample one wishes to characterize. In the chamber below the porous element there is nitrogen, whose pressure can be regulated by means of a valve. The gas pressure was measured by a pressure transductor (Omega PX137-015AV). In the chamber above the porous element, there is a controlled amount of water. The upper chamber is transparent, so it is possible to see when the nitrogen's pressure is important enough to push bubbles through the wick. The upper chamber is open, so that the pressure above the water column is always the atmospheric.

Before installation in the apparatus, the sample is previously soaked in water. The experiment begins with the lower chamber empty. The nitrogen valve is then gradually open, and the pressure in the lower chamber therefore increases. The experiment is ceased when bubbles start coming from the porous element to the upper chamber. Using the gas pressure (P_g) in the lower chamber and the equation bellow, it is possible to calculate capillary pressure and critical diameter. Symbol correspondence to Eq.2 can be found in Table 3.

$$d_c = \frac{4\sigma cos\theta}{P_g - \rho gh} \quad (2)$$

Table 3. Variables of the Eq.2.

g	9.81 m^2/s
h	height of the water column
θ	water contact angle (0°)
ρ	water density (1000 kg/m^3)
σ	water surface tension (0.07197 N/m)
$P_g - \rho gh$	capillary pressure

Table 4 presents average results of the capillary extrusion essay performed to ten samples, five of each layer. Layer A presented a capillary pressure six times higher than layer B. This characteristic is desired once the layer B must offer low resistance to the working fluid flow. Both layers present critical pore diameters and capillary pressures seen in previous works of successful CPL testing (Choi, 2014; Berti, 2008b,a; Xu, 2013; Semenic, 2008).

Table 4. Capillary extrusion results.

Layer	Average Capillary Pressure (kPa)	Average Critical Diameter (μm)
A	19.7 ± 3.4	14.9 ± 2.6
B	3.2 ± 0.2	91.2 ± 6.6

4. Concluding Remarks

The chosen manufacturing technique was able to meet reference characteristics, such as critical diameter and capillary pressure, found in successfully tested evaporators as Choi (2014), Berti (2008b), Berti (2008a), Xu (2013), and Semenic (2008). This processing route provided very homogeneous samples, presenting properties with low standard deviation. Therefore it is expected that the ceramic wick will operate satisfactorily when assembled and tested in a capillary evaporator.

5. ACKNOWLEDGEMENTS

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