Journal of Colloid and Interface Science 342 (2010) 155–165

Contents lists available at ScienceDirect

Journal of Colloid and Interface Science

www.elsevier.com/locate/jcis

Transport properties of real metallic foams

O. Gerbaux [a], F. Buyens [b], V.V. Mourzenko [c], A. Memponteil [a], A. Vabre [b], J.-F. Thovert [c], P.M. Adler [d,*]

[a] *CEA, Laboratory of Applied Thermal-Hydraulics, 38054 Grenoble Cedex 9, France*
[b] *CEA LIST, LID, 91191 Gif-sur-Yvette Cedex, France*
[c] *LCD, SP2MI, BP 30179, 86962 Futuroscope Cedex, France*
[d] *UPMC Sisyphe, 75252 Paris Cedex 05, France*

ARTICLE INFO

Article history:
Received 22 June 2009
Accepted 7 October 2009
Available online 12 October 2009

Keywords:
Metallic foams
Microtomography
Finite volume method
Lattice Boltzmann
Permeability Conductivity

ABSTRACT

Three dimensional samples of three different foams are obtained by microtomography. The macroscopic conductivity and permeability of these foams are calculated by three different numerical techniques based on either a finite volume discretization or Lattice Boltzmann algorithm. Permeability is also measured and an excellent agreement is obtained between the various estimations. Calculated conductivities are successfully compared to available data.

1. Introduction

Metallic foams are important for many industrial fields because of their mechanical and acoustical properties. They are also employed as catalyst supports due to the low pressure drop that they induce. They can enhance hydraulic and thermal performances of heat exchangers and they have a great potential for fluid distribution in fuel cells and electrolysis applications.

The major purpose of this work is to make a detailed study of three different foams which consists of three steps. First, the foam structure is measured by microtomography. Second, the foam permeability is experimentally determined. Third, permeability is numerically computed by solving the local Stokes equations in the porous structures measured in the first step. In addition, the macroscopic conductivity is computed and compared to available experimental values.

Extended literature surveys have been made on the characterization of macroscopic properties of metallic foams such as [1,9] to which the reader is referred. The studies can be split into two classes. The first one which is still predominant uses classical measurements of permeability and rationalizes the results by overall correlations such as the Darcy–Forchheimer equation. The recent contributions of [2–5,9] are devoted to various aspects such as compressed foams and the relation between permeability and the structural parameters.

The second class which is more recent uses microtomography to characterize the foam structure on the pore scale and combines it with a resolution of the local partial differential equations such as the Stokes equation in order to determine permeability.

If many experimental studies have been performed, the number of studies which compare experimental and numerical properties of foams is still relatively small. Ref. [6] characterized a Ni–Cr foam manufactured by Recemat© with a porosity of 0.935 (referred to as RCM-NCX-116). The flow equations are solved by a recent Lattice Boltzmann algorithm where the boundary conditions are well taken into account. The relative errors when numerical and experimental permeabilities are compared are smaller than 19%. Ref. [7] studied an Inconel 625 based SR-foam with a low porosity of the order of 36%; thermal and flow properties were measured and compared to numerical results obtained by a finite element code; the comparison for thermal conductivity is better than 50% at various temperatures while the ratio between the computed and the measured permeabilities is ranging between 0.5 and 2.6 depending on the unit cell chosen for the calculations.

This paper is organized as follows: Section 2 is devoted to the characterization of three different foams by microtomography. Section 3 describes the experimental and numerical methodologies which are used to derive permeability and conductivity. Section 4 details and discusses the experimental and numerical results which are obtained for the permeability of the foams; in addition thermal properties are computed. A systematic comparison with the literature data is made.

Various conclusions and possible extensions of the present studies are presented in Section 5.

---

* Corresponding author. Fax: +33 1 44 27 45 88.
E-mail address: pierre.adler@upmc.fr (P.M. Adler).

0021-9797/$ - see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.jcis.2009.10.011

2. Microtomography and foam geometry

2.1. Micro CT experiments

2.1.1. Foam samples

Three kinds of commercially available open-cell metallic foams with different characteristics are studied. Two are nickel (Ni) foams; the first one from INCO© supplier is composed of hollow struts with a total porosity of 97% (density 420 g/m^2, pore size 450 µm); the second one, from RECEMAT© (reference NI4852), is composed of solid struts. The third one from ERG© is a solid aluminum (Al) foam characterized by this supplier as an ERG© 40 ppi foam (porosity 94–96%, Alloy 6101). The selected materials are extremely open cell structures, of high porosity ϵ (larger than 90%); the foam samples are characterized by their small thickness e, namely $e \approx 5$ mm for ERG©, and $e \approx 1.6$ mm for INCO© and RECEMAT©. For measurements made by micro Computed Tomography (CT), parallelepipedic sub-samples were cut out of a foam block.

2.1.2. X-ray micro CT set-up

Micro CT experiments were performed at LID (Laboratoire Images et Dynamique), CEA-List, France. The X-ray CT set-up (Fig. 1) is composed of a microfocus X-ray generator, a 2D detector, a sample holder and micrometric translation and rotation stages in order to position precisely the sample in the beam.

The X-ray tube is a commercial product from Feinfocus firm. Its voltage can vary between 30 kV and 160 kV and its power reaches 10 W. This X-ray tube is characterized by its focal spot size, ranging from 1 µm to 10 µm depending on the voltage. For the voltage values currently used for the Ni and Al foams acquisitions, typically 50 kV, the focal spot size is of the order of 2—3 µm. A 5 µm tungsten target deposited on a diamond substrate is used for this application. The 2D detector used in this study is Medipix2 which is a photon counting chip developed through a collaboration of 16 European partners around Cern (http://medipix.web.cern.ch). In contrast to systems based on charge integration, the photon counting principle suppresses noise and leads to larger signal to noise ratios. The detector is a silicium matrix formed by 256 × 256 pixels which represents an active area of about 2 cm^2. The size of the square pixels is equal to 55 µm. The detection efficiency is high for energies smaller than 25 keV. Various detection substrates and thicknesses are available. Here, a silicon substrate of 700 µm thickness is used.

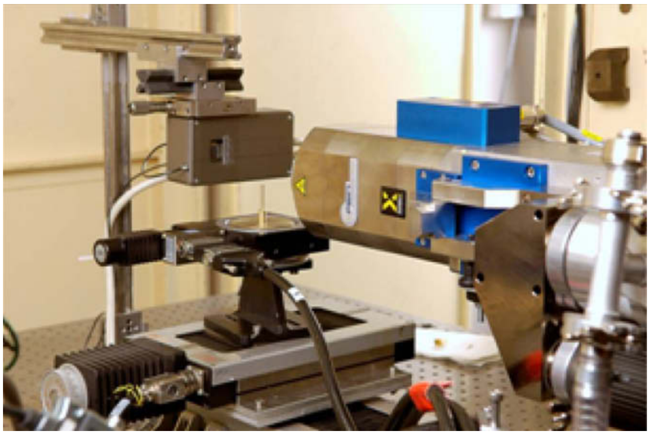

Fig. 1. The micro CT experiment.

The foam sample is located between the source and the detector and it can be moved in order to adjust the resolution. As the sample should fit in the field of view of the detector, a compromise must be found between the maximum sample size and the spatial resolution. For each tomography, the experimental conditions are given in Table 1.

2.1.3. Tomographic reconstructions

Raw projections are corrected by flat field and beam hardening using the Pixelman software, a package for Medipix 2 acquisition control. Sinograms, constructed from the projections as stacks of a line of the detector viewed over 360°, are corrected of global misalignment. This correction is based on the position of the mass center which has to be located on the central pixel of the detector line.

Then, the data sets are reconstructed as stacks of 256 slices of 256 × 256 pixels using the classical algebraic algorithm Ordered Subset Expectation Maximization (OSEM). This algorithm gives reliable results, but it is an iterative method which may converge slowly. In this study, in order to speed up the reconstructions, a parallel version of OSEM using the Message Passing Interface (MPI) library has been implemented.

2.2. Image analysis

Physical parameters such as porosity and specific surface are deduced from the reconstructed volumes of the samples. The porosity is estimated from the segmented volumes, and the specific surface from the three-dimensional meshings of the samples.

2.2.1. Segmentation

The first quantification step is the image segmentation where the foam structure (i.e., the solid phase) is differentiated from the background (i.e., the pore space). Given the large contrast of the reconstructed images, a global threshold method is applied for this purpose; voxels having a grey level larger (respectively smaller) than a given threshold are supposed to be solid (respectively void) with a binary level of 1 (respectively 0) in the resulting image. The threshold is set using the histogram of the grey values of the reconstructed volumes. Fig. 2b illustrates the application of segmentation to the reconstructed volume of INCO-1 sample. This segmented image may be compared to the same original slice extracted from the reconstructed volume (Fig. 2a). Fig. 2c shows the reconstructed INCO-1 foam sample obtained after segmentation.

Table 1
Experimental acquisition parameters – S: source, O: object, D: detector, FOV: field of view, t_{exp}: exposure time for one projection, No. proj: number of projections.

Foam sample	Sample size (mm^3)	Acquisition conditions							
		Distances			Magnification	FOV (mm)	Pixel size (µm)	t_{exp} (s)	No. proj
		S–O (mm)	O–D (mm)	S–D (mm)					
INCO_1	1 × 1 × 1.6	22.5	127.5	150.0	6.67	2.10	8.3	1	360
INCO_2	5 × 5 × 1.6	98.0	132.0	230.0	2.35	5.97	23.4	5	256
ERG	5 × 5 × 5	74.0	61.0	135.0	1.82	7.67	30.1	1	400
RECEMAT_1	1 × 1 × 1.6	30.0	165.0	195.0	6.50	2.15	8.5	5	400
RECEMAT_2	1.5 × 1.6 × 5	42.0	153.0	195.0	4.64	3.02	11.8	5 × 1	400