Microtomography-based CFD Analysis of Transport in Open-Cell Aluminum Metal Foams

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Abstract. Nowadays, the need for developing more effective heat exchange technologies and innovative materials, capable of increasing performances while keeping power consumption, size and cost at reasonable levels, is well recognized. Under this perspective, metal foams have a great potential for enhancing the thermal efficiency of heat transfer devices, while allowing for the use of smaller and lighter equipments. However, for practical applications, it is necessary to compromise between the augmented heat transfer rate and the increased pressure drop induced by the tortuous flow passages. For design purposes, the estimation of the flow permeability and the thermal conductivity of the foam is fundamental, but far from simple. From this perspective, besides classical transport models and correlations, computational fluid dynamics (CFD) at the pore scale, although challenging, is becoming a promising approach, especially if coupled with a realistic description of the foam structure. For precisely recovering the microstructure of the foams, a 3D X-ray computed microtomography (\(\mu\)-CT) can be adopted. In this work, the results of \(\mu\)-CT-based CFD simulations performed on different open-cell aluminum foams samples, for laminar flow regime, will be discussed. The results demonstrate that open-cell aluminum foams are effective means for enhancing heat transfer.

1. Introduction

Heat transfer augmentation is of conspicuous importance in many fields like, to name a few, renewable energy production and conversion, fossil fuels and thermal control of electronic devices. The possibility of enhancing the heat transfer rate will lead to both energy savings and the employment of equipments of reduced size, weight and cost. Metallic foams are among one of the most promising candidates for this purpose, since they might guarantee an increase of the heat transfer rate with an acceptable increment of pressure losses, and the added benefit of lighter and more compact devices.

Metal foams are a class of porous materials with low densities and tortuous and irregular flow passages. They have been available since the 1980s but at the beginning, in view of the high manufacturing costs, were mainly used in the aerospace industry. Nowadays, metal foams are employed also in multifunctional heat exchangers, solar collectors, heat pipes, and so on, and can also serve as fluid distributors in fuel cells and electrolysis applications, or as catalyst supports in reactors. Moreover, in view of their structural strength and mechanical energy absorption capability, they can also be utilized in lightweight structural sandwich panels and car bumpers and, thanks to their acoustic properties, they can also be exploited as sound absorbers and...
silencers. Most commercially available metal foams are made of aluminum, nickel, copper, and metal alloys. Two kinds of foams exist, namely the open-cell and the closed-cell metal foams. As the name implies, in open cell metal foams the flow paths are interconnected, which is beneficial for heat transfer applications. Typically, the pore density of uncompressed open-cell foams varies between 5 to 100 PPI (pores per inch), while the porosity $\varepsilon$ ranges from 80% to 97%. The cross section of the fibers is function of the porosity, and varies from a circle at $\varepsilon = 0.85$ to an inner concave triangle at $\varepsilon = 0.97$.

Metal foams have a great potential for enhancing thermal performances of heat exchangers for several reasons, i.e., their high surface area to volume ratio, the high conductivity of the solid ligaments and the enhanced flow mixing due to their tortuous flow paths, which is sometimes referred to as thermal dispersion. Literature provides several examples of metal foams solutions for heat transfer applications, dealing with both experimental, numerical and analytical studies: metal foam channels [1–7], metal foam covered tubes [8, 9], metal foam filled tubes [4, 10] and double tubes [11], metal foam tube bundle [12, 13], metal foam heat sinks [14, 15], and so on. Mahjoob and Vafai [4] registered an increase in the heat transfer rate of 8-13 times for a metal foam filled tube, and of 15 times for a metal foam channel heat exchanger, at the expense of a limited additional pressure drop. Much more promising are the results of Lu et al. [10], who analytically predicted a heat transfer enhancement up to forty times for the metal foam filled tube. Kim et al. [14] experimentally tested an aluminum foam heat sink and observed a reduction of the thermal resistance by up to 28% compared to a plate fin heat sink, while Seyf and Layeghi [15] proved numerically that a metal foam pin fin heat sink is about 2-3 times more effective in heat removal than a pin fin array, with only a moderate increase in pressure drop. They also noticed a contraction of the recirculation behind the pins with the foam inserts.

Usually, it is common to assimilate the foam to a homogeneous medium having an effective thermal conductivity which depends, to varying degrees, on conduction in both the solid and fluid phase, convection and radiation. At ambient temperature, with this assumption, the heat transfer is mostly governed by thermal conduction; the radiative contribution is important only at higher temperatures. As declared in [10], metal foams are scarcely effective when the thermal conductivity of solid is close to that of the fluid.

The proper characterization and identification of transport and thermal properties of metal foams - hydraulic permeability and effective thermal conductivity- is fundamental for design purposes but far from simple, due to the geometric complexity and the random orientation of the solid phase. Moreover, this information is, at present, quite scarce and mostly based on simplifying assumptions and simpler models, as described in [16]. This lack of information constitutes a fundamental limit in the employment of metal foams in practical and industrial applications. More recently, Computational Fluid Dynamics (CFD) has demonstrated to be a promising means for predicting the flow through open cell metal foams and recovering their characteristic properties. For modeling flows in porous media, two different strategies can be followed, i.e., a macroscopic or microscopic approach. In the former, also known as volume averaging approach, the governing equations are volume averaged, thus they ignore the small-scale details and treat the porous solid-fluid system as homogeneous. In the latter, also known as representative elementary volume (REV) approach, the complex (real or idealized) geometry of the medium is taken into account, and the small-scale flow details are captured. This approach, which is potentially more accurate than the macroscopic one but even more costly, has shown encouraging results for metal foams.

Numerical simulations on idealized geometries have been presented by several authors [17–20]. Furthermore, at the moment a significant effort is devoted to using more realistic representations of the foam structure. From this perspective, X-ray computed microtomography ($\mu$-CT) seems a promising and appealing approach for characterizing the 3D foam structure at the pore level.
In this paper, the results of microtomography-based CFD simulations performed on three different open-cell aluminum foams samples, having different pore density (10-20-30 PPI), will be illustrated. This work is the natural extension of [16], which illustrated the preliminary results of the µ-CT characterization of the three samples. The high resolution X-ray µ-CT imaging was performed at the TomoLab station [26], a cone-beam µ-CT system developed at the Elettra Synchrotron Radiation Facility [27] in Trieste.

Figure 1: Aluminum foam samples employed in the µ-CT analyses: (a) photographs of the specimens and (b) reconstructed volume for the 20 PPI sample.

2. Methodology

X-ray µ-CT is a non invasive X-ray based method allowing the 3D reconstruction of an opaque sample by illuminating it in different directions [28]. Several radiographs of the object are recorded at different angles, corresponding to the projection of the linear attenuation coefficient. In absorption µ-CT, the modality employed in this activity, the difference between the linear attenuation coefficients of the two phases determines the contrast of the sample. Afterwards, with the help of a suitable algorithm, a 3D image of the object is reconstructed and then, in the case of two-phase materials (as metallic foams), a segmentation process can be applied thus to distribute the voxels, i.e., the elemental digital units forming the reconstructed volume, in only two kinds of elements, that is solid and void, by selecting a proper threshold value in the histogram of the intensities.

For this activity, three aluminum foams samples, shown in Fig. 1(a), having different pore densities (10-20-30 PPI) and manufactured by m.pore GmbH [29], were analyzed. From each sample, a specimen of nearly $12 \times 12 \times 20$ mm$^3$ was extracted and characterized by means of high resolution 3D µ-CT. The metal foam samples were imaged in the following conditions: current = 133 µA, voltage = 60 kV, 0.5 mm thick Al filter, exposure time/projection = 2 s, source-to-sample distance = 80 mm, source-to-detector distance = 220 mm. For each sample 2400 projections were recorded over a 360° angular rotation. A $2 \times 2$ binning was applied to the detector pixels.

The sample volumes were reconstructed with an isotropic voxel size of 9.09 µm by using the commercial software COBRA 7.4 (EXXIM) [30]. It is worth noting that the 9.09 µm-resolution of the tomographic scan is significantly higher than most of the works published in the literature. In Fig. 1(b), the reconstructed volume for the 20 PPI specimen is represented. The choice of performing a high resolution µ-CT allowed us to well capture the surface peculiarities of each sample. The tomographic scan revealed a smooth and regular surface for the 30 PPI foam, and an increased roughness as the pore density decreases. Moreover, in the case of the 10 PPI foam, some spherical lumps of metals can be distinctly recognized.
From each reconstructed volume, a smaller representative cubic volume element was extracted, whose dimensions depended on the PPI of the sample: 548 voxels for the 30 PPI sample, 848 for the 20 PPI sample and 1000 for the 10 PPI one (1 voxel side = 9.09 µm). In the case of the 30 PPI sample, the size of the domain was chosen by comparing the results on domains of increasing size. For the other two samples, the dimensions were selected in order to have a number of foam cells comparable to the 30 PPI, and compatibly with the available computational resources.

In order to generate a volume file usable in the CFD simulations, the foam surface was triangulated with the commercial software VGStudio Max 2.0 [31], and a STL (STereoLitography) file was exported.

The computational domain, sketched in Fig. 2(a), consists of a square duct having an inlet region, an outlet region and an intermediate foam region. The numerical simulations were performed along the three spatial directions, in order to investigate the isotropy of the samples.

Geometrically exact, feature-preserving grids were generated with the commercial software ANSYS ICEM CFD: the central foam region was meshed with an unstructured grid, while a structured mesh was employed for the inlet and outlet regions. The meshing of the foam volumes was not straightforward at all, since its quality was related to that of the surface triangulation. The final meshes were chosen after thorough grid independence analyses. The central foam region of the 30 PPI sample was discretized with about $1.4 \times 10^6$ nodes, while those of the 20 and 10 PPI foams with about $2.4 \times 10^6$ and $4.1 \times 10^6$ nodes, respectively. A detail of the surface mesh for the 30 PPI sample is illustrated in Fig. 2(b).

For the CFD simulations the commercial software ANSYS CFX 13.0 was used. ANSYS CFX is a node-centered, Finite Element-based Finite Volume code. By default, the pressure-velocity coupling is implemented by using the Rhie-Chow algorithm. The linear solver uses an Algebraic Multigrid method based on an additive correction multigrid strategy, and the fully coupled momentum and mass conservation equations are solved simultaneously. The Navier-Stokes equations were solved by using the High Resolution scheme for the advection term.

The boundary conditions applied are summarized in Fig. 2(a). The working fluid was air with constant thermophysical properties, evaluated at 25°C. Only the laminar flow regime was simulated, and the Reynolds number, based on the nominal pore diameter of the foam and the superficial velocity, was made to vary between 1 and 100. This interval corresponds to Reynolds numbers based on the square root of permeability, $Re_K$, varying between 0.1 and 13, similar to those considered in [25].
3. Results and discussion

3.1. The flow field

For illustration purposes, the velocity contours at three different sections, for the case of the 30 PPI foam, are given in Fig. 3. Figure 4(a) plots the pressure distribution along the $z$ direction for the 30 PPI sample at varying Reynolds numbers. As expected, the pressure drop, $\Delta P$, across the foam increases with the Reynolds number. To better compare the pressure trends for the whole set of Reynolds numbers simulated, in Fig. 4(b) the normalized pressure profiles are depicted. These profiles have been computed as $\tilde{P} = 1 - (P - P_{in})/(P_{in} - P_{out})$, being $P_{in}$ and $P_{out}$ the pressure at the entrance and exit of the foam region, respectively. As it can be seen, as the velocity increases, a linear trend is still established, but some local fluctuations appear.

Figure 5 compares the pressure profiles for the three foam samples, evaluated along the three spatial directions for $Re=10$. As it can be seen, the pressure drop reduces as the pore density decreases, since a larger cross sectional area is available for the flow. For the 30 PPI sample...
Figure 5: Pressure distribution along the three spatial directions at $Re=10$ for the (a) 30 PPI, (b) 20 PPI and (c) 10 PPI foam foam.

Figure 6: Detail of the foam structure along the $z$ direction. (a) 30 PPI, (b) 20 PPI and (c) 10 PPI sample.

the value of $\Delta P$ and the pressure profiles along the three spatial directions are very similar and, therefore, the foam can be considered isotropic. On the contrary, for the other two samples, even though an almost linear trend can be observed, the deviations between the three spatial directions are amplified. This fact might be ascribed to the structure of the foams, illustrated in Fig. 6 while in the 30 PPI sample the cells are almost identical along the three spatial coordinates, in the other two samples they appear elongated along the $z$ direction, thus producing the lower pressure drop. It should be investigated whether this structure is an intrinsic characteristic of the foams, or the result of the manipulation and cutting process.

In addition, in order to verify whether the lower pressure drop along the $z$ direction was related to an insufficient length of the domain, for the 20 PPI sample some other tests were performed, by using a larger volume extended in the $z$ direction. The values of the pressure drop along $z$ computed on the new domain differ only marginally from those evaluated on the original domain, and still remain lower than those computed along the other two directions. Therefore, the anisotropy of the foam is not related to the chosen domain but, rather, it is an intrinsic property of the medium.
3.2. Evaluation of the permeability

For calculating the permeability of the foam along the three directions, the Darcy-Forchheimer equation can be written both in its dimensional form:

\[
\nabla P = -\frac{\mu}{K} u_D - C \rho u_D^2
\]

and non-dimensional form:

\[
\frac{\nabla P d_{nom}^2}{\mu u_D} = -\frac{d_{nom}^2}{K} - C d_{nom} Re
\]

being \( K \) the permeability of the medium \([m^2]\), \( C \) the form drag coefficient \([m^{-1}]\), \( d_{nom} \) the nominal diameter of the foam and \( u_D \) the superficial velocity, calculated by dividing the volumetric flow rate by the total cross sectional area. While the linear term of Eq. (1) results from viscous effects, predominant at low Reynolds numbers, the quadratic one accounts for inertial effects which cannot be neglected at higher velocities. Both \( C \) and \( K \) strongly depend on the structure of the porous medium.

The results demonstrate that, while at lower Reynolds numbers the pressure drop is a linear function of velocity, at higher Reynolds numbers the inertial effects become dominant and the pressure drop can be correctly described by the Dupuit-Forchheimer law. In Fig. 7, the dimensionless pressure gradient along the three space directions is plotted. The trends further confirm the isotropy of the 30 PPI sample, while predict a slight anisotropy for the 20 and 10 PPI foams.

The computed values of permeability and of the Dupuit-Forchheimer coefficient are summarized in Tab. 1, while Tab. 2 reports some of the values published in the literature: as it can be appreciated, the present values of \( K \) are comparable with the literature data. It is worth pointing out that, for a fixed pore density, the experimental values of \( K \) published in the literature show a wide dispersion.

Figure 7: Spatial variation and least square fitting of the non-dimensional pressure gradient, for the (a) 30 PPI, (b) 20 PPI and (c) 10 PPI sample.

3.3. The thermal field

For the heat transfer simulations, two different limiting boundary conditions (b.c.) were specified on the foam wall, i.e., a constant temperature, \( T_s = 323K \), and a constant heat flux, \( q''_s = 100 \text{ W/m}^2 \). As remarked in [19], a constant solid temperature may be compatible with the fully developed flow conditions. In Fig. 8 the variation of the heat transfer coefficient \( h = q''_s/(T_s - T_{bulk}) \) is illustrated: the heat transfer coefficient increases with the pore density and is higher in the case of the constant temperature b.c. Furthermore, the trend of \( h \) is not monotonic and manifests a minimum for a certain value of the Reynolds number: this behaviour is well prominent for the
Table 1: Values of permeability $K$ [m$^2$] and of the Dupuit-Forchheimer coefficient $C$ [m$^{-1}$], for the three foam samples (Av.=average). $\varepsilon$ is the porosity of the foam.

|          | 30 PPI | 20 PPI | 10 PPI |
|----------|--------|--------|--------|
|          | $\varepsilon = 0.929$ | $\varepsilon = 0.927$ | $\varepsilon = 0.944$ |
|          | $K \times 10^{-7}$ | $C$ | $K \times 10^{-7}$ | $C$ | $K \times 10^{-7}$ | $C$ |
| x        | 0.872  | 389.0  | 1.965  | 309.4  | 2.906  | 218.6  |
| y        | 0.859  | 392.9  | 1.946  | 346.3  | 3.058  | 255.2  |
| z        | 0.858  | 370.6  | 2.222  | 240.5  | 3.234  | 187.9  |
| Av.      | 0.863  | 384.2  | 2.045  | 298.7  | 3.066  | 220.6  |

Table 2: Summary of some permeability values published in the literature.

| PPI | Porosity | $K \times 10^7$ | Reference |
|-----|----------|-----------------|-----------|
| 10  | 0.9131   | 1.731           | [25], num.|
| 10  | 0.92     | 1.04            | [1], exp. |
| 10  | 0.926    | 4.29            | [6], exp. |
| 10  | 0.949    | 1.49            | [32], exp.|
| 20  | 0.9126   | 1.606           | [25], num.|
| 20  | 0.92     | 0.76            | [1], exp. |
| 20  | 0.9245   | 2.42            | [25], exp.|
| 30  | 0.9      | 1.644           | [33], exp.|
| 30  | 0.93     | 0.63            | [3], exp. |

constant temperature b.c. while, for the constant heat flux b.c, in some directions a monotonic trend can be seen. Therefore, since a quadratic curve scarcely fits the numerical data, a new fitting relation was conceived, $h = a_1 \log(Re)^{a_4} + a_2 Re^{-a_5} + a_3$, providing very satisfactory results for all the samples.

![Figure 8](image_url)

Figure 8: Heat transfer coefficient, for the case of constant temperature (top) and constant heat flux (bottom) boundary condition, for the (a,d) 30 PPI, (b,e) 20 PPI and (c,f) 10 PPI foam. The dot lines represent a 10% variation around the mean values.

3.4. Estimation of the effective thermal conductivity

For computing the effective thermal conductivity of the foam, $k_{\text{eff}}$, only the central foam region was simulated, and an arbitrary temperature gradient was fixed along one direction. The other lateral faces were kept adiabatic, and the conduction equation was solved in both the fluid and the solid region. The momentum equation was not solved, since the fluid (air or water) was considered as static.
The effective thermal conductivity was computed as:

\[
k_{\text{eff}} = - \int J \cdot dA \frac{\partial T}{\partial x_i} = - \left( \int_s J \cdot dA_s + \int_f J \cdot dA_f \right) \frac{\partial T}{\partial x_i} (A_s + A_f)
\]

(3)
in which \( J \) and \( dA \) are the heat flux and the outward pointing area vector, respectively, and the subscripts \( s \) and \( f \) refer to the solid and the fluid, respectively.

Also in this case, the degree of isotropy of the foam seems to be related to the pore density of the medium. In fact, while for the 30 PPI sample the conductivities differ only marginally along the three spatial directions, for the other two samples their values diverge to a larger extent. As already stated in [25], this outcome might be connected to the size of the domains employed. However, the choice of performing a high resolution \( \mu \)-CT limited the size of the scanned samples and preclude the employment of significantly larger domains for the CFD simulations. Besides this, for all the foams, the highest value is encountered along the \( z \) coordinate which, in the case of the 20 and 30 PPI foams, corresponds to the direction of elongation of the cells.

In view of the above considerations, in Tab. 3 only the mean values of the effective thermal conductivity, averaged among the three spatial coordinates, are reported, as in [25]. As it can be seen, the values of \( k_{\text{eff}} \) evaluated with water are slightly larger than those with air, thus proving that the thermal conductivity of the fluid influences, but not in a significant way, the effective thermal conductivity of the foam. In addition, it is worth noting that the values of \( k_{\text{eff}} \) evaluated in this study agree well with the values of \( k_{\text{eff}} \) published in the literature, some of which are summarized in Tab. 3.

Table 3: Prediction of effective conductivity values with air or water as the interstitial fluid and summary of some the values published in the literature.

| PPI | Porosity | \( k_{\text{eff,air}} \) | \( k_{\text{eff,water}} \) | Reference |
|-----|----------|----------------|-----------------|-----------|
| 10  | 0.944    | 3.49           | 4.13            | Present   |
| 20  | 0.927    | 4.97           | 5.76            | Present   |
| 30  | 0.929    | 5.31           | 5.99            | Present   |
| 10  | 0.9131   | 5.34           | 7.05            | [25], num.|
| 10  | 0.949    | 3.9            | 4.8             | [32], exp.|
| 20  | 0.9126   | 6.59           | 7.36            | [25], num.|
| 20  | 0.949    | 4              | 4.95            | [32], exp.|
| 40  | 0.9198   | 5.35           | 6.08            | [25], num.|
| 40  | 0.937    | 4.5            | 5.35            | [32], exp.|

4. Concluding remarks

In this paper, the results of accurate pore scale CFD simulations of flow and heat transfer in three foam aluminum samples, for laminar flow regime, have been presented. The 3D structure of the foams has been recovered through high-resolution X-ray computed microtomography, which allowed to capture the peculiar features of the foams’ surfaces.

For all the samples, the flow is well described by the Darcy-Forchheimer law. In fact, while at low Reynolds numbers the pressure drop varies linearly with the velocity, at higher Reynolds numbers inertial effects are found to contribute.

For all the samples, the computed values of the flow permeability and the effective thermal conductivity agree well with the data, experimental and numerical, available in the literature. Moreover, the simulations demonstrate that the effective thermal conductivity of the foam is mainly given by the conductivity of the solid ligaments, since the contribution of the fluid is only marginal.
The flow and thermal simulations prove that the 30 PPI foam exhibits an isotropic behaviour, while a certain degree of anisotropy is detected for the 20 and 10 PPI foams. This fact may likely be ascribed to the structural characteristic of these two samples, characterized by an elongation of the foam cells along a specific spatial direction.

In view of the good results obtained, the present strategy could be applied to other porous materials, appealing for engineering applications.

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