

Geometric and Fluid-Dynamic Characterization of Actual Open Cell Foam Samples by a Novel Imaging Analysis Based Algorithm

Stefania Falfari, Gian Marco Bianchi, and Giacomo Micci
University of Bologna

Augusto Della Torre, Gianluca Montenegro, and Angelo Onorati
Politecnico di Milano

Sergio Negro
University of Toronto

ABSTRACT

Metallic open-cell foams have proven to be valuable for many engineering applications. Their success is mainly related to mechanical strength, low density, high specific surface, good thermal exchange, low flow resistance and sound absorption properties.

The present work aims to investigate three principal aspects of real foams: the geometrical characterization, the flow regime characterization, the effects of the pore size and the porosity on the pressure drop. The first aspect is very important, since the geometrical properties depend on other parameters, such as porosity, cell/pore size and specific surface. A statistical evaluation of the cell size of a foam sample is necessary to define both its geometrical characteristics and the flow pattern at a given input velocity. To this purpose, a procedure which statistically computes the number of cells and pores with a given size has been implemented in order to obtain the diameter distribution. In particular, a morphological characterization of an actual foam sample was performed by applying an image processing method. The analyzed foam was a cubic open-cell foam made by Silicon Carbide (SiC). Secondly, the pressure drop characterization of the foam sample was performed by means of CFD simulations. In particular, the relative importance of the viscous term and the inertial term was assessed. This analysis was performed including the effect of the porosity and of the mean pore diameter. The pressure gradient was parametrized with respect to such properties, passing through the concept of porosity and morphology. Additionally, the role of turbulence modeling in the simulation of the flow through the foam sample was investigated, finding that the flow pattern is not necessarily laminar and the turbulence is related to the fluid inertia.

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INTRODUCTION

Recently, application of open-cell foams as substrates for exhaust after treatment devices of internal combustion engines has been an active area of research [1, 2, 3]. In particular, for this application open-cell foams are regarded with interest as a substitute for the traditional honeycomb monolithic substrate: the most attractive benefits are related to a better use of the catalytic surface due to the enhanced mass transport and to the quick heat up during engine cold starts. The pressure drop given by the foam is one of the key parameters in the design of devices involving such a porous material. Many works are available in the open literature investigating the phenomena leading to the pressure drop. They focus, in particular, on the influence of the flow regime and on the effects of the geometrical properties. With regard to the flow regime many authors [4, 5, 6] agree that, in generic porous media, the transition from laminar to turbulent flow occurs at a critical Re number. The flow regime

established inside the media for a particular pressure gradient is strictly dependent on the geometrical parameters, namely the porosity and the pore size. To characterize the geometry of a foam sample it is necessary to determine the quantities defining its micro-structure, such as the porosity ϵ , the specific surface S_p , the cell size d_c and the pore size d_p . With regard to an open-cell foam, the pore size determines the average dimension of the pore. It is expressed in terms of pore density (pore per inch, ppi), intending with this definition the number of pores that would subtend one linear inch. The cell size expresses the average dimension of the cell of the foam. Moreover the porosity of the foam is defined as the ratio between the volume of the fluid phase V_f and the total volume of the porous medium V . The specific surface is defined as the ratio between the surface describing the fluid to solid interface S and the total volume of the porous medium V .

Having set the properties of the foam sample, the authors [7] applied a genetic algorithm in order to address the design of catalytic devices equipped by metallic open-cell foam: the input parameters of the optimization process were the intrinsic characteristics of the foam and the external geometric dimensions of the catalytic support. The output parameters process were the pressure drop, the conversion efficiency and the cost effectiveness, related to the specific surface. The authors compared the foam struts with the standard honeycombs finding that the foams can achieve the same efficiency with about 1/4 of the surface needed by the honeycombs.

In the present work, the main focus was to globally characterize the actual geometry of the foam sample, following an image based approach. To this purpose a sample of real silicon carbide (SiC), open-cell foam has been considered. Usually, the real foam sample micro-structure is reconstructed by means of computer tomography. Then, the cell and pore sizes of the actual foam sample are determined resorting to specific algorithms [8]. The approach proposed by the authors in the present work is based on an algorithm used in the image processing field. The starting image could come from a micro-tomography or from a reconstruction of an actual foam, as done by Lucci et al. [9], who created a structure based on randomly distributed Kelvin cells. On the other hand, the main disadvantage of this technique, based on the image analysis, is its limited accuracy, if compared to the one based on the micro-tomography, as it will be shown in the following paragraphs.

In this paper, foam sample geometry is characterized using an image processing technique. In a second phase, the effect of the porosity and of the mean pore diameter on the pressure gradient was assessed. To this purpose, the geometry was artificially modified by applying scaling or surface offset transformations to modify, in an independent way, parameters such as porosity or pore size [10]. Finally the turbulence effect on the foam sample was deeply analyzed by means RANS CFD simulations.

GEOMETRIC ANALYSIS

The geometrical characterization of the sample foam, i.e. the statistical evaluation of the cell and pore size, was necessary to determine more correctly the flow regime at a given inlet flow rate. A procedure allowing the statistical computation of the number of cells and pores of a given size has been implemented in order to obtain a distribution of diameters. The analysed foam sample was an open-cell foam made by silicon carbide SiC (Figure 1). Usually an actual foam sample is converted in an image in stl format by the application of the micro-tomography technique.

The focus of this first part of the work was to demonstrate how it is possible to characterize the foam structure (deriving mean cell and pore sizes) using a simple two-dimensional (2-D) or three-dimensional (3-D) image, not necessarily in stl format. Following this approach, the micro-tomography of the actual sample is no more strictly necessary.

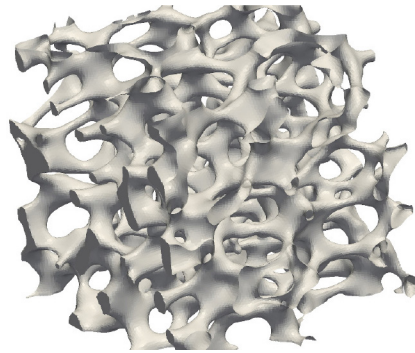


Figure 1. 3D surface reconstruction of the micro-structure of a foam sample.

Geometrical and thermophysical properties of the foam sample are listed in Table 1, where ϵ stands for porosity, S_V for specific surface, V for total volume, ρ for material density, λ for conductivity and c_s for specific heat.

Table 1. Open-cell foam sample geometrical and thermophysical parameters.

Foam sample main parameters	
<i>Length</i> [mm]	15.0
<i>Width</i> [mm]	15.0
<i>Height</i> [mm]	15.0
ϵ [%]	82.6
d_p [ppi]	10
S_V [m^2/m^3]	578.6
V [m^3]	$3375 \cdot 10^{-9}$
ρ [kg/m^3]	3100
λ [W/mK]	270
c_s [J/kgK]	750

The foam properties are primarily determined by their structure: the various production processes configure different morphologies and geometries. Many studies have focused on techniques of representation and analysis of structures with elaboration of models suitable for defining the main characteristics proper to each foam. From a literature survey it appears that the most common models used for both metallic and ceramic foams are:

- The cubic-cell model [11], which is very simple but with obvious limits in the representation of the real structure;
- The model based on the tetrakaidecahedral cell, used for ceramic foams by Xu et al. [12] and for aluminium foams by Mancin et al. [13];
- The model based on the Kelvin cells randomly generated by Lucci et al. [9, 14].

Through these models it is possible to estimate the geometric characteristics of the foam strut and accordingly their fluid-dynamic characteristics. Results are generalized in terms of dimensionless numbers such as Reynolds number Re (flow regime), Sherwood number Sh (mass transfer) and Nusselt number Nu (fluid-solid heat transfer), whose definition requires the need of having a characteristic dimension of the system. The dimensional analysis of the porosity allows to characterize a specific foam structure, which in turns makes feasible the comparison between different types of foams. The parameters characterizing the foam structure are described on

- the cell size, equal to the average diameter of the empty space defined by the cellular structure;
- the pore size, equal to the average width of the windows that connect two contiguous cells;
- the size of the structure, which is a measure of the average diameter of the reticle;
- the porosity.

Dimensional Characterization by Means Mathematical Morphology

The methodology proposed in this work, which is based on the imaging analysis concept, comes from the intention to overcome the necessity of having available a file in the stl format, resulting by a micro-tomography. With this new approach a single two-dimensional or three-dimensional image of the structure under consideration is needed only. The use of a simple image is possible applying both the techniques of image processing and image analysis on the domain being studied. This new approach was applied for the first time in the present work for characterizing the geometry of an actual physical element, such as a metallic foam. The mathematical morphology derives from the theory of sets and was developed with the intent to process the image; it is adaptable to a wide range of industrial applications [15, 16]. The purpose of this field is to obtain information by adopting procedures that make simple the reading of the images. The image to be analysed can be binary, grayscale or both: the basic concepts can be applied to different classes of images. Processing is made via the definition of a *structuring element* chosen by the user: it represents a basic geometric profile, whose shape depends on the analysis to be performed. In essence, the resulting image is a nonlinear transformation, produced by the interaction between the original image and the chosen structuring element.

In [15] all the elementary operations required by the mathematical morphology theory are listed. This theory is based on mathematical filters applied to *discrete* samples, i.e. images for example: they are non-linear translation-invariant images or signal transformations. Mainly there are two kinds of images: gray-tone and binary. In the following description we will refer to the concept of *set* to indicate the binary image, while the concept of function is related to the gray-tone image. More details can be found in [15]. Binary discrete images are represented by 2-D sets in the discrete plane Z^2 , where Z is the set of integer numbers and R is that of the real ones. The following elementary operations used in the present study are defined:

- *Translation*. Given a set $A \subseteq Z^2$ of points $a \in A$ and a point $p \in Z^2$ it is defined translation the set A_p of points $a + p$:

$$A_p = \{p + a : a \in A\} \quad (1)$$

- *Symmetric*. Given a set $A \subseteq Z^2$ of points $a \in A$ it is defined symmetry of A the set A^s such that:

$$A^s = \{-a : a \in A\} \quad (2)$$

- *Erosion*. Given a set $A \subseteq Z^2$ of points $a \in A$ and a structuring element $X \subseteq R^2$, the erosion result is the set of points $p \in Z^2$ such that:

$$X \ominus A^s = \{p \in Z^2 : A_p \subseteq X\} \quad (3)$$

- *Dilation*. Given a set $A \subseteq Z^2$ of points $a \in A$ and a structuring element $X \subseteq R^2$, the dilation result is the set of points $p \in Z^2$ such that:

$$X \oplus A^s = \{p \in Z^2 : A_p \cap X \neq \emptyset\} \quad (4)$$

In details, combining erosion and dilation, spheres having different diameters are used for the evaluation of the pore size of the foam sample, returning a distribution of diameters related to the frequency with which they appear. The combination of these basic operations can generate more complex computations. For instance, the *opening* operation is the result of the application in series of the erosion operation, followed by the dilation one. Considering a structuring element X on a set A , the opening operation is given by:

$$X_A = (X \ominus A^s) \oplus A \quad (5)$$

Although the operations just described are related to the 2-D images, the same considerations can be extended to three-dimensional domains. An image composed by "three-dimensional pixels" may be subjected to the same procedures: discretization of the fluid domain defined by the solid geometry of the foam and application of the filters. Applying the above described methodology in three-dimensions it is possible to determine the cells and pores size of the foam sample. The whole process includes:

- Discretization of the foam domain into appropriate size cubes: small cubes will lead to a more precise geometry definition but will increase the computational cost.
- Definition of the structuring elements S_{struct} , which will be spheres of different diameter and will be also discretized into cubes of the same size used for the fluid domain.
- Application of *erosion* and *dilation* operations, using increasingly smaller structuring elements and eliminating, at each iteration, the volume of the domain resulting from the filtering process performed with the element S_{struct} of a given size.
- Counting how many elements S_{struct} of a given size are resulted from the whole process.

Through a Boolean operation performed using a CAD code, the fluid domain was extracted by the original foam sample. It was necessary to perform a discretization of the volume fluid, which represents the three-dimensional image to be studied (Figure 2). The discretization process was done by the mesh generator of the OpenFOAM® code (*snappyHexMesh*). As structuring element a series of spheres of different sizes has been chosen. This allows to verify the size of the cavities of the foam. Figure 3 shows an example of a spherical structuring element. All the spheres have been discretized with the

same method: each spherical sub-sample was characterized by cubes of 0.2 mm side. The critical point of this process is the size of the cubic elements since the measuring accuracy and the computational cost depend on it. A good compromise has led to the determination of the measurement sensitivity in 0.2 mm , which represents about the 8% of the mean dimension given by the supplier (10ppi equal to 2.54 mm). The resulting porosity ϵ of the discretized fluid domain was:

$$\epsilon = \frac{V_f}{V} = 82.5\% \quad (6)$$

which well approximates the porosity of the actual solid sample in [Table 1](#).

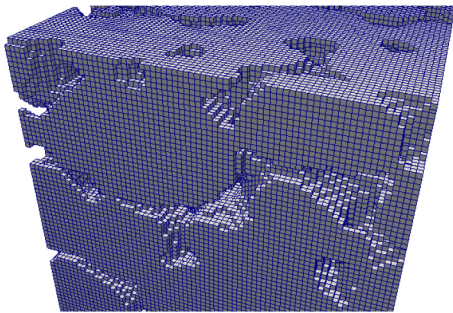


Figure 2. Discretization of the domain.

The tested diameters were varied in the range between 0.7 mm and 5.5 mm in order to represent the whole extension of the distribution. The equations (1, 2, 3, 4) have been implemented in an algorithm written in FORTRAN code without particular changes to the above cited expressions.

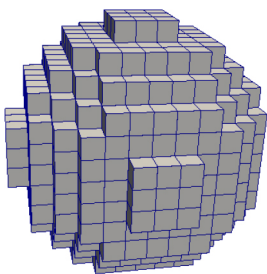


Figure 3. Discretization of the structuring element (sphere of 2.5 mm).

This algorithm has the objective of determining the number of times that a sphere of a given diameter can be contained in the fluid domain.

Note that the symmetry operation is useless because of the symmetry of the spherical structuring element, while the translation operation has the function of moving the center of each spherical structuring element in every point of the fluid domain: for each translation operation it is necessary to check if the examined point is positive to the erosion operation, i.e. the [equation \(3\)](#) is satisfied. If the check is positive, then the dilation operation is performed. In this way it is possible to obtain:

- A list of the erosion points;

- A reconstruction of the geometry through the sample spheres used as a structuring element.

The algorithm examines the sphere of larger diameter, runs the above procedure and then rewrites the fluid domain coordinates discarding the dilation points eventually found. In this way, by repeating the analysis with the spheres of increasingly smaller size, there will be no overlapping points among spheres having different diameter. Note that the procedure excludes from erosion all the points outside the domain, since, due to the lack of knowledge about the foam geometry, it is not possible to verify if the structuring element is entirely contained. If D_m is the diameter of the sphere having the largest diameter, the erosion points must be located at a distance smaller than $D_m/2$ from each edge.

To reduce the computational cost of the procedure, it is useful to simplify the problem reducing it to a 2-D one: the fluid domain is reduced in parallel planes orthogonal to one of the main axes of the foam sample ([Figure 4](#)), while the spheres are in their turn transformed into discs of equal diameter. The 2-D analysis results are analysed hereinafter: note that the erosion dots indicate the location of the center of the spheres used for the reconstruction of the porosity of the foam. In [Figures 5 and 6](#) the points of erosion determined by the 2-D analysis are shown: observing the larger diameters the placement of the centers appears to develop mainly along a direction ([Figure 5](#)), while the smaller diameters are spread much more chaotically ([Figure 6](#)). It can be assumed that the preferential direction, i.e. the one along which the largest pores are placed, could offer a lower resistance to fluid flow. This last result seems to suggest an anisotropy of the foam, which was verified and presented in the next paragraph.

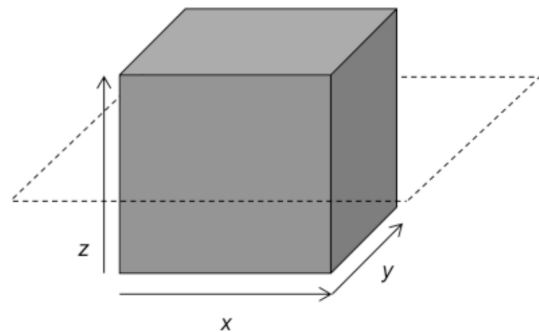


Figure 4. 2-D erosion by planes orthogonal to Z axis.

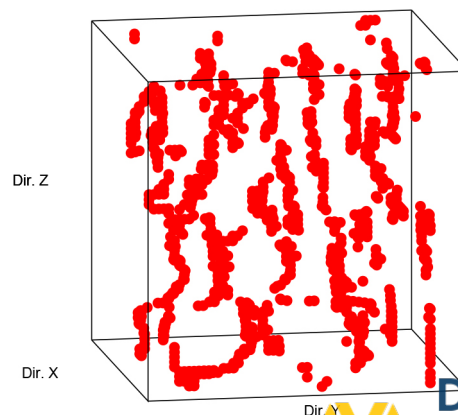


Figure 5. 2-D erosion points for larger diameters ($d > 2.3 \text{ mm}$).