Experimental pressure drops during the water flow into porous materials realized via additive manufacturing

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Abstract. Open-cell foams offer several interesting possibilities in numerous technological fields. In fact, they present high surface area to volume ratio as well as enhanced flow mixing and attractive stiffness and strength. However, their complete and reliable characterization has not been completed yet. In fact, there is still no comprehensive work that relates all the foam geometrical characteristics to their heat transfer and pressure drop features. This paper is the very first outcome of a larger study that aims at realizing open-cell foams via additive manufacturing, testing them, then generating a simulation model based on the real geometries to numerically optimize each parameter. The present manuscript presents the construction of the open-foam via 3D printing and the experimental pressure drop measurements when water flows through the foam.

1. Introduction

Open-cell foams have many interesting combinations of physical and mechanical properties, such as high stiffness in conjunction with very low specific weight or high gas permeability combined with high thermal conductivity. They are currently used in many technological applications in the automotive and aerospace industries, in ship building, in the railway and building industries, but also in sporting equipment and in medical and biomedical devices [1].

However, each application requires a customized design that involves the optimization of several geometrical parameters, such as porosity, pore density, etc. Several works experimentally tested and compared different foam samples in order to describe the influence of each parameter in a peculiar application. In fact, the knowledge of pressure drop is essential for the design and operation of high-performance industrial systems [2].

Nevertheless, it is still missing a comprehensive study able to give rigorous guidelines to choose and optimize a stochastic geometry.

3D printing could remarkably help the designers, since it allows to reproduce a designed geometry and compare experimental and numerical results on the very same geometry [3]. However, it is still not demonstrated that 3D printed metal foam and traditional metal foam perform similarly.

This paper aims to realize and test a 3D printed foam, to experimentally test it and then to compare the results obtained against some classical correlations implemented for traditional foams. More in detail, this manuscript focuses on the water pressure drop generated by water flowing inside a tube filled by a foam designed via software and realized via additive manufacturing.

2. Experimental materials and methods

The aim of this preliminary study is to experimentally investigate and assess the pressure drop inside an open-foam realized via additive manufacturing.

The sample is a 200 mm long tube with an inner diameter of 20 mm that contains a stochastic material, having a porosity of 0.935, and a pore density of 5 PPI (pores per inch). The foam was modeled by Voronoi and Catmull-Clark subdivision algorithm. Figure 1 presents the geometry of the sample, Figure 2 shows a detail of the foam inside the duct, and Figure 3 reports a picture of a section of the sample. This peculiar foam design was realized from a random distribution of point in the space. For the
sake of simplicity and economic savings, the sample has been realized in polyamide 12 by Multi Jet Fusion technology.

The sample was connected in vertical position to a pumped water loop that was set at a constant temperature. The temperature was measured in the inlet and in the outlet of the tube by means of calibrated T-type thermocouples. The thermocouple accuracy is declared ±0.1 °C ($k = 2$) since they are all connected to a K170 Ice Point Reference with stability of ±0.005 °C and accuracy of ±0.005 °C.

The water flow rate was measured with a magnetic volumetric flow meter having an accuracy of ±0.2% of the full scale equal to 0.33·10^{-3} m³·s⁻¹ while the pressure drops through the sample are measured by means of two differential pressure transducers. The first one was used for low pressure drops having an accuracy of ± 0.075% of the full scale of 40 mbar, while the second had an accuracy of ± 0.075% of the full scale of 200 mbar.

3. Experimental results
Four set of experimental tests were carried out. The first three sets were collected at three different water temperatures equal to 20, 30, and 40 °C, respectively. The last set of data, called reversed, was collected at 40 °C with the sample set upside down, to verify the repeatability of the measurements. Each set of tests consists of data collected at different water flow rates.

Figure 4 plots all the pressure drop experimental data as a function of the water flow rate. The temperature effect on the pressure drop is negligible, despite the small variation in density. Furthermore, when positioned upside down, the measured pressure drops are almost the same. This is a valuable result that assures the quality of the 3D printed foam.
Figure 4. Pressure drop as a function of the water flow rate.

The experimental data obtained were assessed against two correlations available in the open literature. There are no correlations implemented with data of foams obtained via additive manufacturing, so it was decided to take into account equations generated on set of data collected on foams realized in the traditional ways and having similar PPI and density values. The correlations by Mancin et al. [4] and by Tadrist et al. [5] were selected and tested. The Mancin et al. [4] model was developed for air flowing through aluminum foams having from 5 to 40 PPI and a porosity from 0.903 to 0.956 but validated also against water data. The Tadrist et al. [5] model was generated on experimental pressure drop data on aluminum foams with a PPI number from 10 to 40 and a porosity from 0.905 to 0.933. Figure 5 presents the comparison between the new experimental pressure drop data and the correlations by Mancin et al. [4] and by Tadrist et al. [5]. The mean relative deviation is 1.7 % and 2 % and the mean absolute deviation is 6.1 % and 6.3 % for the models by Mancin et al. [4] and by Tadrist et al. [5], respectively.

It is impressive to note that both the correlations work well with the experimental data obtain on a sample realized with a total different approach and also with a different fluid (i.e., water instead of air used by Mancin et al. [4]).

Figure 5. Comparison between the experimental data and the correlations by Mancin et al. [4] and by Tadrist et al. [5]
This confirms that it is possible to realize a foam starting from a random disposition of points in the space, creating a geometric model and realizing the object by additive manufacturing. This foam can perform similarly to a traditional foam, but its geometry is well-known, it was designed from scratch; hence, it is possible to generate a numerical simulation on an exact geometry.

The following step consists in numerically study and optimize the foam, with the aim of reducing as much as possible the pressure drops while maximizing the heat transfer performance.

4. Conclusions
This manuscript presents the first step of a larger study on foams performance optimization. To achieve this goal, a stochastic foam was designed from scratch and realized via additive manufacturing.

The remarkably advantage of this approach is represented by the possibility to have a 3D geometrical model of the foam to be realized, so the arrangement of each point and each rod is well-known. In this way, it will be possible to numerically optimize the geometry that has already been experimentally studied. In this framework, the first step was to realize a foam and then experimentally measure its performance.

A series of pressure drop data were collected at different temperatures (from 20 to 40 °C) and at different orientations of the specimen when water flowed through it. No temperature nor orientation effects were observed. The latter is very important because it demonstrates that the 3D printing process does not affect the quality of the foam generated and thus the fluid dynamic.

The experimental data were then compared against two models already available in the literature developed for off-the-shelf foams. The relative and absolute deviations are very small: the mean relative deviation is 1.7 % and 2 % and the mean absolute deviation is 6.1 % and 6.3 % for the models by Mancin et al. [4] and by Tadrist et al. [5], respectively. So, they proved that the foam made via additive manufacturing performs very similarly to the traditional foams, having similar pore density and porosity. This demonstrates that it is possible to work on a foam with a geometry created from scratch through a suitable software, whose hydraulic performance is indicative of a traditional foam used in the industrial field. Following, an optimization of the geometry will be numerically carried out, to understand the influence of each parameter and to optimize its behavior in terms of minimum pressure drops and maximum heat transfer coefficients.

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