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Simulations of filter media performances from microtomography-based computational domain. Experimental and analytical comparison

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ABSTRACT

In this work, synchrotron X-ray microtomography was used to produce high spatial resolution images of one fibrous filter, made of binderless monodispersed fiberglass. Based on these images, representative computational domains were created using the import interface of the GeoDict software. Both flow and collection efficiency simulations were then carried out using the CFD modules of GeoDict. In parallel, permeability and collection efficiency measurements were performed on the same media, to provide an experimental comparison. A very good agreement was found between the experimental and simulated permeability values. However, simulated efficiency values tend to underestimate the experimental ones. In the second part of the paper, an image analysis program based on Matlab® was used to determine the structural properties of the fibrous structures, namely the thickness, the solid volume fraction and the fiber size distribution. These data were introduced into analytical models that successfully predict the permeability and collection efficiency values.

1. Introduction

The use of fibrous media in areas related to air treatment dates back to antiquity [1] and it is very common nowadays. In addition to being easy to use and to maintain, they are one of the most efficient filtration techniques among the various existing devices. They are therefore implemented in many applications, such as engine intake, cleanrooms and in the nuclear industry to retain radioactive particles in normal operation or in accidental situations. The physical mechanisms involved in aerosol filtration by fibrous filters are laminar flow in porous media, particle transport and deposition by Brownian diffusion, interception and inertial impaction. These phenomena have been fully described in the literature since the 60s [2–6]. Nevertheless, the development of predictive models, used in design optimization or lifetime determination, is hardly achievable due to the wide range of operating conditions as well as aerosol and media characteristics. The initial performances of fibrous media are characterized by two important parameters: the filtration efficiency E and the pressure drop ΔP. Among the researches devoted to the modeling of such performances, numerical studies, consisting in designing fibrous micro-geometries together with solving transport equations, seem to be relevant tools. Indeed, these approaches allow the influence of parameters like the fiber orientation [7], the fiber length [8], the solid volume fraction (SVF), the fiber diameter [9] or the fiber diameter ratio for bimodal fibrous media [10–12] to be investigated specifically. All of these parameters are the input data for the structure generation models and their determination involves assumptions. In almost all of the studies, anisotropy, fiber diameter and SVF are assumed as overall values. Moreover, in the case of 3D computations, fibers are designed as long straight cylinders inside the microstructure. In a study regarding the modeling of the initial pressure drop of fibrous filter media, Herman et al. [13] proposed a method to create random fibrous structures, based on log-normal fiber size distribution. Nevertheless, this work was limited to two-dimensional representations of media and the difference between experimental and simulated pressure drop values are significant. We believe that the more appropriate way to determine geometrical parameters is by 3D image analysis. Moreover, from the imaging technique point of view, fibrous structures do not yield sufficient image quality due to their thin thickness, as well as the low absorption contrast of the material. Recently, significant improvements in imaging and post-processing have allowed images to be created, imported and processed from computed-tomography, in order to compute flow and particle

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transport on real structures. They were first applied to studies on cellulose materials [14–16] and recently carried out for fibrous filter media [17]. The main objective of this study is to use synchrotron X-ray microtomography as a way to create representative computational domains, in order to simulate filter media performances. Section 2 of this paper presents the methods used to acquire and process the images, as well as the simulation settings. The experimental set-up and the operating protocols to determine permeability and efficiency are presented in Section 3. In Section 4, we summarize the structural properties of the computational domains from the image analysis and we provide the experimental computations with the simulations. Finally, the analytical modeling and the comparison with the simulations are presented in the last part of this work.

2. Simulations

The set of simulations was performed with the GeoDict software (from Math2Market GmbH, www.geodict.com). GeoDict is a voxel-based code dedicated to predicting material properties by solving transport equations for a virtual material. The mesh is formed of voxels, which can be empty (fluid) or filled (solid). Through an interface dedicated to image analysis, GeoDict also allows data to be imported and processed from computed tomography, in order to use a real structure as the computational domain.

2.1. Image acquisition and treatment

The studied filter medium has been provided by the Bernard Dumas company (Creysse, France). It is made of binderless fiberglass. The nominal fiber diameter (d_f) is given to as 2.6 μm. The given weight is between 72 and 74 g/m^2. The thickness (Z) and SVF are not given. Images were acquired on the ID19 beamline of the European Synchrotron Radiation Facility (ESRF, Grenoble, France). In addition to being non-invasive and non-destructive, synchrotron X-ray microtomography has a high spatial resolution, which can represent the diameter of a fiber by at least 9 voxels in our case. The experimental setup consists of a high resolution microtomograph with a sample-to-detector distance of 5 mm. The beamline energy was 18 keV. Data come from the attenuation of the X-ray beam when crossing the absorbent body. Images are produced from a 9 mm diameter sample. A FReLoN CCD camera with 2048 $\times$ 2048 pixel chip, associated with a $\times$20 objective with $\times$2.5 eye-piece were used, in order to obtain a pixel size of 0.28 μm. Five overlapped scans were carried out to visualize the entire sample thickness. Each of theses consisted of 1995 projections over 360 degrees, with an exposure time of 0.2 s. The method used for phase extraction is based on the single distance phase retrieval approach [18]. Fig. 1 shows an example of two successive tomograms reconstructed from a fibrous medium. The final 3D structure is composed of 4351 tomograms with an edge size of 573.44 μm.

2.2. Image import

The image import protocol is shown in Fig. 2. The 4351 tomograms (a) are first read using the ImportGeo-Vol interface (b). 3D processing parameters are then applied to the images. The resizing step defines a 1024 $\times$ 1024 voxel square area in the center of the structure, avoiding edge effects (c). A median digital filter is used to reduce noise in images. The images are scanned and the filter modifies the value of a pixel with the median value of the neighboring pixel (d). The choice of the relevant threshold value, in order to binarize the images, is the final step of the import (e). Moreover, the structure is cleansed by reassigning the objects comprised under 500 voxels to the fluid zone. The resulting 3D microstructure (f) consists of a 1.2 mm thick fibrous core, with a filtration surface of 0.08 mm^2.

2.3. Computational domains

From the original structure, four non-overlapping subvolumes (SV) were created and used as computational domains (Fig. 3). This choice was made in order to save memory when handling the computational domain and also to have reasonable computational time. The subvolumes considered in this paper are 512 $\times$ 512 $\times$ 4351 voxels with a resolution of 0.28 μm per voxel. The mesh number is therefore greater than 1.1 $\times$ 10^9. To reflect the representativeness of the computational domains, the Brinkman screening length, which is given by the square root of the permeability, is used as a qualitative criterion. According to Clague and Phillips [19], the domain width must be at least equal to 14 times the Brinkman screening length to smooth out the local heterogeneities. Using the permeability experimental value (see Section 3), in this work, the computational domain widths are wider than 24 times the Brinkman screening length.

2.4. Flow simulation

Explicit finite volume solver options are controlled with the FlowDict module. The air flow through the microstructure is

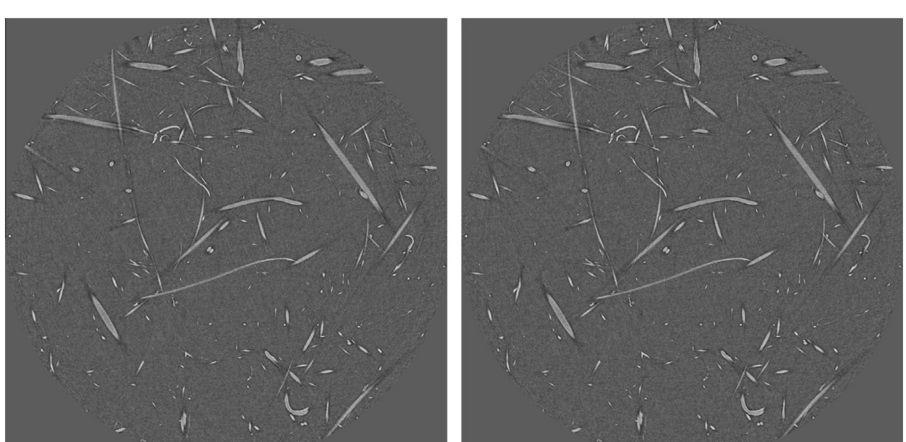

Fig. 1. Illustration of two successive tomograms reconstructed from a fibrous medium.