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Airflow and particle transport simulations for predicting permeability and aerosol filtration efficiency in fibrous media

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HIGHLIGHTS

- Synchrotron X-ray microtomography is used to produce images of fibrous filter media.
- Representative domains are created using Matlab®.
- Flow and efficiency simulations are carried out thanks to GeoDict®.
- Good agreement is found between experimental and simulated values of permeability.
- Simulated values of efficiency give a good approximation of experiments.

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ABSTRACT

In this work, synchrotron X-ray microtomography was used to produce high spatial resolution images of two kinds of binderless and monodisperse fibrous filter media, made of fiberglass and sintered stainless steel respectively. Representative computational domains were created based on these images. Both flow and collection efficiency simulations were then carried out using the flow and particle transport modules of the GeoDict® code. An image analysis program based on Matlab® was used to determine the structural properties of the computational domain, namely the thickness, the solid volume fraction and the fiber size distribution. In parallel, permeability and collection efficiency measurements were performed on the same media, to provide an experimental comparison. Very good agreement was found between the experimental and the simulated permeability values. We showed that, in order to compare collection efficiency from experiments with those simulated with GeoDict®, it was necessary to take into account the difference between the thickness of the fibrous structures that were used to create the calculation domain, and the averaged experimental thickness characterized by SEM. Using this way of comparison, we obtained the first experimental validation of the GeoDict® code on both permeability and efficiency aspects for aerosols filtration.

1. Introduction

Improving the knowledge of the performance of High Efficiency Particulates Air (HEPA) filters, used in the nuclear industry to contain radioactive particles in normal operation or in an accident situation, is a key factor in nuclear safety. This knowledge is crucial because HEPA filters represent the last containment barrier for aerosols, which constitute the main source of contamination. As a part of this research, one specific topic relates to the experimental and numerical characterization of the intrinsic performance of filter media, in terms of pressure drop (ΔP) and collection efficiency (E), depending on the operating conditions (filtration velocity and particles size). While the physical mechanisms involved in aerosol filtration by fibrous media have been fully described in the literature (Fuchs and Stechkina, 1963; Stechkina and Fuchs, 1966; Kirsch and Fuchs, 1967; Kirsch and Fuchs, 1968; Stechkina et al., 1969), the development of predictive models remains hardly achievable due to the wide range of operating conditions as well as aerosol and media characteristics. Given the multiplicity of parameters, the use of a numerical tool is often considered and many studies have been conducted to determine the influence of geometric parameters like fiber diameter and the solid volume fraction (*SVF*) (Tafreshi et al., 2009; Fotovati et al., 2010a; Hosseini and Tafreshi, 2010;

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Gervais et al., 2012), fiber orientation (Fotovati et al., 2010b), or fiber length (Wang et al., 2007) on initial filtration performances.

The primary objective of this work is to validate, by comparison with experimental results, the CFD software GeoDict®, specialized in air filtration. Initial contributions of IRSN for qualifying GeoDict® have been conducted on model fibrous structures, representing ideal fibrous media (monodisperse fibers, without binder) *a priori* well characterized from literature (Gougeon et al., 1995, 1996). The data provided by the manufacturer were used in geometry models (fibers diameter, medium thickness, *SVF* and isotropic orientation). Our results have shown a major gap for the pressure drop. In the case of a laminar flow, the pressure drop allows the medium permeability, an intrinsic property of the material, to be calculated. If values are not consistent with experiments, this may probably come from the creation of the computational domain from the overall characteristics of the fibrous medium. In order to avoid assumptions such as the use of overall values for fiber anisotropy, fiber diameter and *SVF* as well as the design of the fibers as long straight cylinders, we chose to create images from real fibrous media for use as a geometrical support for the calculation of flow and particle transport. In one of our previous papers, X-ray synchrotron microtomography had already been used to create computational domains to simulate the performances of a fiberglass fibrous medium (Gervais et al., 2015). One of the conclusions of this study was that very good agreement was found between the experimental value of permeability and the simulated results from the microtomography-based computational domains. An average difference of less than 5% was observed, which allowed us to validate the representativeness of the computational domains. Nevertheless, a significant gap was found between the experimental and simulated values of efficiency. From our point of view, this was due to not taking into account the electrostatic effects. This work should make possible to use neutralized aerosol and conductor media, such as metallic filter, to be free of any charge effect during the experiments. A completely new experimental set-up was used in the present study. This was the subject of collaboration with the Process Engineering Department of the Occupational Safety and Health Institut (INRS). In a first time, it allowed us to highlight the influence of electrostatic effects. Moreover, these effects were annihilated using an electrostatic precipitator and we obtained the overall range of particle size which are relevant for aerosols filtration using a SMPS and an APS and not only the SMPS. We also use another kind of fibrous media, to enlarge the range of our study. The experimental set-up and the operating protocols to determine experimental permeability and collection efficiency are presented in Section 2. Section 3 of this paper presents the methods used to acquire and process the images, as well as the simulation settings. The structural properties of the computational domains, determined from the image analysis, are also given in this section. Finally, a new interpretation of the comparison of numerical calculations and experiments, especially for the fractional collection efficiency, is presented in the last part of this work. We now take into account the limitation of X-ray microtomography as a mean to create the calculation domain from real media.

2. Experimental determination of filtration performance

2.1. Tested media

As this study aims to complete experimental validation of a simulation tool, we focused on simplified fibrous systems. The idea was to study some media exclusively composed of monodisperse fibers, without binder. In nuclear filtration, glass fibers are most commonly used and ideal fiberglass fibrous media were often dedicated to fundamental research in the past (Gougeon et al., 1995, 1996). So, we first focused on a binderless monodisperse fiberglass medium, provided by the Bernard Dumas company (Creysse, France). The initial results we obtained (Gervais and Ricciardi, 2014) have led us to consider the use of a metallic medium to overcome potential electrostatic effects in collection efficiency measurements. A sintered stainless steel fibrous medium has been provided by the Bekaert company (Zwevegem, Belgium). Table 1 summarizes the target properties of the filter media samples tested. It contains the values of nominal fiber diameters (*df*), thicknesses (Z) and solid volume fractions (*SVF*).

Fig. 1 illustrates the surfaces of both fibrous media obtained by Scanning Electron Microscopy (SEM). As a qualitative comment, we can observe the best monodispersity for the sintered stainless steel medium. For both media, we take note that the fibers are cylindrical and that the tortuosity of the fibers seems to be negligible. Melting points between fibers, resulting from sintering, are readily visible in the case of the stainless steel medium.

2.2. Thickness characterization

The thicknesses of both media were determined by SEM visualization. A fixation method followed by sanding and polishing steps was applied in the same way as the method used by Bourrous et al. (2014) for the samples. Fig. 2 illustrates the slices of both fibrous media as well as examples of the measurements.

Table 2 summarizes the experimental thicknesses characterization of the filter media samples tested. It contains the number of measurements for each medium and the values of experimental thicknesses (Z_{exp}).

While the thickness of the sintered stainless steel fibrous medium, measured experimentally, is very close to the target value required by the manufacturer, a major difference is observed for the fiberglass medium. It reveals the difficulty of designing samples based on target properties due to the technical resources of the manufacturers. However, the experiments and simulations will be performed using the same samples and not the manufacturer's data.

2.3. Experimental set-up

Permeability as well as fractional collection efficiency measurements were conducted at the French Institute for Occupational Safety and Health (INRS, Nancy, France), using a dedicated experimental bench. The set-up (Fig. 3) is based on an pressurized cylindrical pipe (diameter 40 mm) made of stainless steel, electrically grounded. An aerosol of solid sodium-chloride particles is generated using an AGK 2000 nebulizer (Palas GmbH, Germany), supplied with compressed, dry and filtered air and with a 8% solution of NaCl, followed by a drying chamber. The aerosol generated is then transferred to an electrical charging zone. The bipolar Electrostatic Aerosol Neutralizer EAN 581 (Topas GmbH, Germany) is used to control the particle charge. It is based on the corona discharge principle and consists of a mixing chamber with two separate ionization heads and a control unit (Topas, 2014). An electrostatic precipitator (ESP), home designed, can then be used in order to separate charged particles to obtain neutralized aerosol. The airflow, absolute pressure and temperature are directly checked using a mass flowmeter (TSI, USA). Pressure tappings on both sides of the

Table 1
Target properties of the fibrous structures required by manufacturers.

Medium	*SVF* (%)	Z (μm)	d_f (μm)
Fiberglass	10	300	2.6
Stainless steel	20	200	2