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Short communication

On the pressure drop prediction of filter media composed of fibers with bimodal diameter distributions

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Abstract

In addition to collection efficiency, pressure drop is the most important characteristic of a filter medium. While there are numerous analytical expressions available for predicting the pressure drop of the filters made up of fibers with a unimodal fiber diameter distribution, there are not enough studies dedicated to filters composed of fibers with a bimodal (or multimodal) fiber diameter distribution. In this work, the pressure drop per unit thickness of filters made of bimodal fiber diameters is calculated by solving the Navier–Stokes equations in a series of 2-D geometries. These results are used to find the unimodal equivalent diameters of each bimodal filter that could be used in the existing expressions for calculating pressure drop. In agreement with the work of Brown and Thorpe [Brown, R.C., Thorpe, A., Glass-fiber filters with bimodal fiber size distributions. Powder Technology 118 (2001) 3–9.], it was found that the area-weighted averaging of the fiber diameters in a bimodal filter provides a relatively good estimation of its equivalent unimodal fiber diameter. We, however, noticed that in such an averaging the error percentage in the pressure drop prediction is sensitive to the fiber diameter ratios as well as the fraction of each fiber diameter in the bimodal filter. We, therefore, obtained a correction factor for the estimation of the unimodal equivalent diameters as a function of fiber diameter ratio and their number fractions.

Keywords: Fibrous filter; Pressure drop; Bimodal; CFD

1. Introduction

The pressure drop caused by fibrous filters has been studied for many years and numerous analytical, numerical and empirical correlations are available for such media. In almost all these models, a filter is assumed to be made up of fibers with a unimodal fiber diameter distribution. Ignoring the width of the fiber diameter distribution, it is still possible to conveniently calculate the filter's pressure drop using a single average fiber diameter. A great portion of the fibrous filters however, are made up of blends of coarse and fine fibers with widely different average diameters. This is often the case where mechanical strength and filtration efficiency are both important. The fine fibers contribute to the high filtration efficiency (high collection efficiency for a given pressure drop) while the coarser fibers contribute to the medium's rigidity. The fibers may be intimately blended in the case of short fibers like in carded, air-laid, or wet-laid fiber-webs or layered in the case of melt-spun media such as melt-blown and/or spun-bonded webs. Despite their importance, not enough work has been dedicated to calculating the pressure drop of filters with bimodal (or multimodal) fiber diameter distribution. This is probably because of the presence of too many independent but coupled variables which contribute greatly to the complexity of such calculations. The current study is aimed at improving our understanding of the influence of different variables on the permeability of filters with bimodal fiber diameters.

To estimate the pressure drop of unimodal filters, air flow through the media was modeled by solving the flow governing equations over a structured array of fibers in two or three dimensional geometries. Various authors have proposed well-known models for predicting the pressure drop of unimodal filters [1–10]. All these models present the pressure drop per unit thickness of a unimodal filter as:

$$\frac{\Delta p}{t} = f(\phi)\frac{\eta V}{r^2} \tag{1}$$

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For a constant fluid viscosity, η, filter face velocity, V, and fiber radius, r, pressure drop per unit thickness becomes a function of the medium's Solid Volume Fraction (SVF), ϕ, alone. By setting appropriate boundary conditions, it is therefore possible to calculate the flow field in an ordered matrix of fibers in a so-called cell model which leads to an expression for $f(\phi)$. The cell model is based on the assumption that all fibers in the filter experience the same flow field and all fibers are perfectly perpendicular to the main flow direction. Based on 2-D cell models with fibers arranged in square lattice, Sangani and Acrivos via numerical methods [9] and Drummond and Tahir using analytical methods [10] proposed the following equations for $f(\phi)$,

$$f(\phi) = \frac{8\phi}{-\ln\phi - 1.476 + 2\phi - 1.774\phi^2 + 4.076\phi^3 + O(\phi^4)} \tag{2}$$

$$f(\phi) = \frac{8\phi}{-\ln\phi - 1.476 + 2\phi - 1.774\phi^2 + O(\phi^3)} \tag{3}$$

These models are in good agreement with those of other authors [2,3]. In a pioneering work, Brown and Thorpe [11] assumed that for given fluid properties and face velocity, pressure drop per unit thickness of a bimodal filter, $\frac{\Delta p}{t}$, is only a function of the medium's SVF, ϕ, and an equivalent fiber diameter, d_{eq}:

$$\frac{\Delta p}{t} = f(\phi, d_{\mathrm{eq}}) \tag{4}$$

Where d_{eq} can be now used in the above-mentioned expressions for pressure drop calculations (Eqs. (1)–(3), for instance). Brown and Thorpe [11] concluded that the best approximation for d_{eq} is an area-weighted average of the fiber diameters in the bimodal filter. This means that the pressure drop of a bimodal filter is similar to that of a unimodal filter having the same SVF but composed of fibers with a diameter that is obtained by area-weighted averaging of the fiber diameters in the original bimodal filter. Our paper builds up on the work of Brown and Thorpe [11] and is aimed at improving their model and better our understanding of the factors affecting the pressure drop of filters with bimodal fibers. As will be discussed below, predicting the pressure drop of filters with bimodal fibers by using only the area-weighted average diameter can cause considerable errors depending on the ratio of fiber diameters and the number fraction of the coarser (or fine) fibers. Note that our results here are limited to the case of orthogonal fiber arrangement as used in Brown and Thorpe's work [11]. The case of offset fiber arrangement is not considered in this short communication. Readers are referred to the works of Lundstrom and Gebart [12] and Papathanasiou [13,14] for the case of flow through square and hexagonal fiber packing at high SVFs.

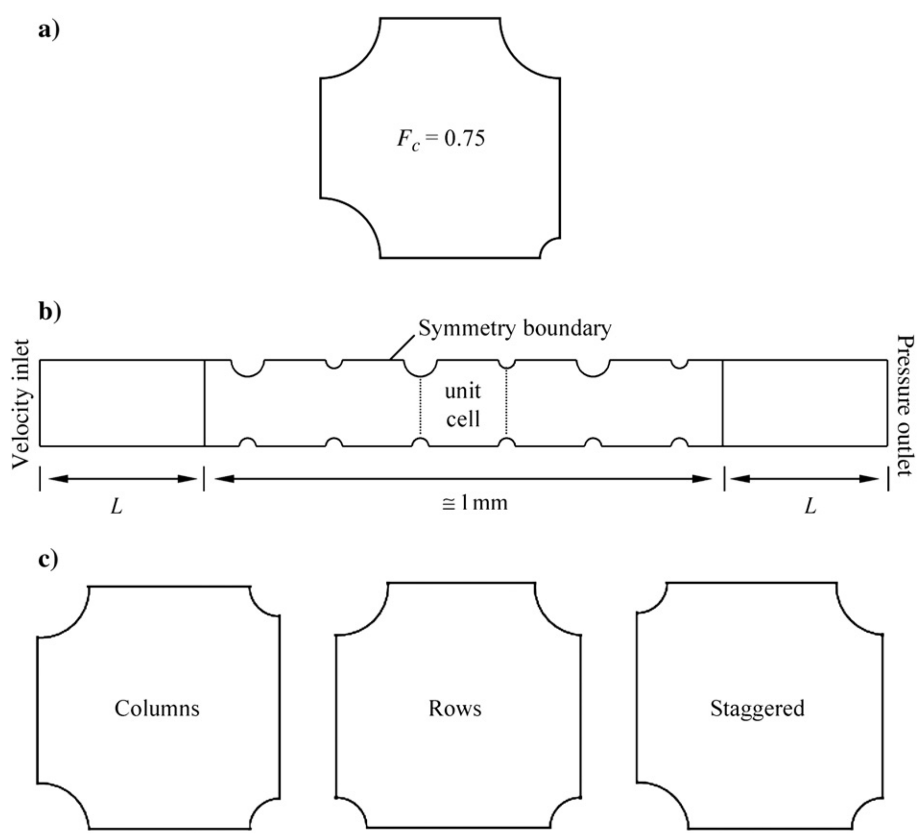

Fig. 1. a) Square unit cell for the case of $F_{\mathrm{c}}=0.75$ with three coarse and one fine fiber arranged on the corners of an orthogonal grid. b) Simulation domain and boundary conditions for the case of $F_{\mathrm{c}}=0.25$. c) Three possible fiber arrangements of columns, rows, and staggered configurations for the case of $F_{\mathrm{c}}=0.50$ in a square unit cell.