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The pressure drop across combined polydisperse spherical particle – Cylindrical fiber networks

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HIGHLIGHTS

- The pressure drop across mixed fiber-particle networks is studied computationally.
- A single dimensionless pressure drop curve explains all results well.
- The characteristic system diameter is based on a moment ratio.

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ABSTRACT

In the fibrous filtration of particles in gas and liquid flows, loading is the act of particles depositing onto fibers. Loaded particles alter the filter microstructure and can have a profound influence on the pressure drop across a filter medium. Of interest is therefore a simple approach to predict the pressure drop across a loaded filter, accounting for both fibers and loaded, spherical particles. In the present study, we use computational fluid dynamics simulations to develop a simple predictive model for the pressure drop across fibrous media composed of a combination of cylindrical fibers and spherical particles. Specifically, the pressure drop is calculated via an in-house written code to solve the incompressible viscous flow equations in a periodic domain, with the particles and fibers accounted for via the immersed boundary method. For calculations, we generate randomly oriented three-dimensional virtual fibrous networks with prescribed microstructures, including network total solidity, fiber orientation angle distribution, fiber radius distribution, and particle radius distribution (both polydisperse). We find that irrespective of network geometry, by defining a single effective network diameter, the product of the dimensionless pressure drop per unit length and the Reynolds number can be expressed solely a function of the total solidity of the network (particle solidity plus fiber solidity) for fiber solidities in 0.03–0.20 range and particle solidities in the 0.0–0.08 range. The effective diameter, employed in both non-dimensionalization of the pressure drop and the Reynolds number definition, is found to depend upon the first and second moments of the fiber diameter distribution functions, and the second and third moments of the particle diameter distribution functions. We develop a regression equation to fit calculation results; the functional form of the equation is based upon a linear combination of the low and high solidity limits for the permeability term in Darcy's Law. We additionally apply this pressure drop relationship in loading simulations to examine the evolution of filter pressure drop and figure of merit as loading proceeds. Test results on model filters show that the pressure drop increases significantly as loading proceeds, with loading of the front regions of filters contributing most significantly to the pressure drop. Interestingly, model results suggest that the figure of merit first increases upon loading and then decreases, justifying preloading of filters to increase performance.

1. Introduction

Pressure drop prediction for fibrous networks utilized as filters is of considerable importance, as it determines the energy requirements associated with filter installation and operation. It has thus

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been discussed extensively in literature (Wang and Otani, 2012). Accurate predictions of the pressure drop require a detailed solution for fluid flow in filter media. Except for instances where the fiber diameter is comparable to the mean free path of the fluid (i.e. the transition regime) (Barhate and Ramakrishna, 2007; Podgórski et al., 2006; Sambaer et al., 2011), the flow in fibrous filters is a continuum, laminar flow, and further falls into the Stokes limit. In spite these simplifications, analytical solutions for the flow field in filter media relevant to industrial filter application are not easily obtained because of the randomness and complexity of fiber network geometries. The three-dimensional fluid flow therefore needs to be modelled or simulated.

In large part, studies developing pressure drop-filter structural property relationships have invoked the use of a so-called unit cell model, wherein a single fiber is enclosed in a domain whose dimensions are based upon the solidity of the media. For a given boundary condition on the cell, the flow field can be analytically obtained by solving the simplified form of the Navier-Stokes equations (with the acceleration terms neglected). Well known examples are the pressure drop/permeability relationships derived by Lamb (1932), Tomotika and Aoi (1951), Kuwabara (1959), and Happel (1959). The single fiber unit cell solution can then be incorporated into Darcy's law to obtain an approximate solution for the pressure drop across an entire filter. While instructive, unit cell based pressure drop models neglect several important features which affect pressure drop in filters, and these features remain to be addressed. First, the influence of the random orientation of fibers is neglected, as the single fiber is assumed to be either perpendicular or parallel to the flow. Second, as loading of the filter proceeds, particles deposited on fibers alter the structure of the media, leading to a significant increase in filter total pressure drop (Kanaoka and Hiragi, 1990; Payatakes and Gradoń, 1980). It is essential to include the effect of the deposited particles, as otherwise the models are only applicable in the initial stages of filtration.

Several modeling efforts have been devoted to consideration of the influence of deposited particles. Kanaoka and Hiragi (1990) developed a model to predict the pressure drop for particle loaded filters using the simplification that particle deposition served to effectively increase the fiber diameter/radius. Thomas et al. (2001) divided a filter into several sections along its depth to account for the inhomogeneity of the deposited particles. In each section, the pressure drop was modelled by considering both the effect of the fiber and the deposited particles. However, the pressure drop model employed was not tested or verified by alternative means and was an ad-hoc modification to existing pressure drop predictions applying to cylindrical fibers only.

More recently, increases in computational power have made it possible to directly simulate the fluid flow in complex fibrous media. The pressure drop can then be calculated without any further assumptions, and the influence of fibrous network microstructure can be examined. Simulations of flow within and pressure drop across porous media have been carried out using both reconstructed and randomly generated networks. In the former cases (Jaganathan et al., 2008; Sambaer et al., 2011), networks were generated by reconstructing images of real filters obtained from scanning electron microscopy (SEM) or digital volumetric imaging (DVI). The advantage of these methods is that realistic filter geometries can be simulated. At the same time, the uniqueness of each filter makes it difficult to systematically study the influence of the network microstructure, i.e. it is difficult to parameterize or characterize reconstructions of filter media and each individual reconstruction is not simple to obtain. In the latter cases, several researchers (Hosseini and Tafreshi, 2010; Wang et al., 2006; Yue et al., 2016) have generated random cylindrical fiber networks in three dimensional domains with prescribed geometric parameters. For example, Wang et al. (2006) and Hosseini and Tafreshi (2010) performed a parametric study (examining network solidity and diameter influences) on randomly generated virtual fibrous networks, finding good agreement between pressure drop prediction with pre-existing pressure drop relationships. However, in all such studies to date, deposited particles have not been considered.

In the present study, we use direct numerical simulation to investigate the pressure drop across three dimensional virtual random fibrous networks, both devoid of particles and loaded with spherical particles. Parameters used to control the network microstructure include the fiber and particle solidities, the fiber and particle radius distribution functions (both monodisperse and polydisperse distributions are considered), and fiber orientation angle distribution. The incompressible viscous flow equations are solved through an in-house developed code employing the immersed boundary method with periodic boundary conditions in the flow direction, and symmetrical boundary conditions in the other two directions. This procedure enables us to calculate the pressure drop without making any further assumptions. We combine results to present a simple regression function to predict the pressure drop across combined fiber and spherical particle laden media with fiber solidities in the 0.03–0.20 range, particle solidities in the 0.0–0.08 range, and arbitrary size distribution functions for both the fibers and particles. Subsequently, results are compared to pre-existing pressure drop relationships and combined into a filter loading model to predict the evolution in filter quality factor/figure of merit.

2. Numerical methods

2.1. Network geometry

To establish a link between pressure drop and flow velocity (parameterized as dimensionless pressure drop and Reynolds number), randomly oriented cylindrical fibers are generated in a dimensionless $10 \times 10 \times 10$ cubic box, with prescribed dimensionless radii; we find that this is a computationally reasonable domain size for the boundary conditions invoked (noted subsequently) as well as the solidity range examined. Fig. 1a and b depicts a sample monodisperse fibrous network (i.e. all the fibers have the same radius), where the inlet flow is perpendicular to the y-z plane. We adopt the following procedure to generate these networks with both monodisperse and polydisperse fiber radii distribution functions. First, the centerline of a cylindrical fiber is specified through randomly picking a point of space through which its center will pass, and through sampling two orientation angles, θ and φ. θ, the angle between the fiber centerline and the *x-y* plane (defining orientation with respect to the flow direction), is sampled from a uniform distribution in the 0-$2\pi/3$ range, while φ, defining the orientation in the *y-z* plane, is sampled from a uniform distribution in the 0-π. These angle distributions prevent fibers from passing through the inlet or outlet of the flow domain (through either y-z plane). Second, the radius of the cylindrical fiber is randomly selected from a prescribed distribution, and the fiber is extended across the domain. The fiber is then completely defined in size and position. For monodisperse fibers, the radius is prescribed as 0.4, while for polydisperse fibers, we elected to sample radii from a uniform distribution in the 0.4–1.2 range (again noting the domain is $10 \times 10 \times 10$ in dimensionless units). After radius identification and fiber extension, we calculate the minimum distance between the newly generated fiber and all other existing fibers to ensure that they are larger than a prescribed value in the 0.2–0.4 dimensionless unit range; this is necessary in order to avoid the overlapping of fibers. The second step is repeated with the new fiber removed and regenerated if overlap or close approach