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Original Research Paper

Study and optimization of the filtration performance of multi–fiber filter

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A B S T R A C T

Fibrous media is the most common method of filtration, which is generally characterized by its pressure drop and filtration efficiency. In this work, the computational fluid dynamics (CFD) technology was applied to simulate the filtration performance of multi–fiber filters. The pressure drop and filtration efficiency with different fiber arrangements, fiber diameters, face velocities and particle sizes were studied. It was found that filtration efficiency changed with the face velocity for different particle sizes. The layered structures with the same fiber diameters and total solid volume fraction (SVF) were compared, indicating that the dense–sparse structure had the highest filtration efficiency for all the simulated particle sizes at the cost of high pressure drop. Then the dense–sparse structure was optimized to achieve a better filtration performance by using less tiny fibers in the front–row and removing some fibers in the back–row.

1. Introduction

The recent rapid development of industry has created serious environmental pollution problems. Air typically contains harmful chemical substances (e.g. SO_2, NO_x) and fine suspended particulate matter (PM), especially for respirable PM [e.g. PM_{10} (PM $\leqslant$ 10 μm) and $PM_{2.5}$ (PM $\leqslant$ 2.5 μm)] that have harmful effects on respiratory immune function, respiratory and central nervous systems [1]. $PM_{2.5}$ is principally generated from the burning of fossil fuels and volatile organic compounds [2] and is harmful for humans to breathe [3]. Therefore, effective protective measures are required to prevent such harmful particles from causing injury.

Respirators are commonly used to avoid airborne dust and many respirators capable of preventing $PM_{2.5}$ inhalation have emerged in recent years. The N95 filtering facepiece respirator is the current most commonly used $PM_{2.5}$ respirator. However, there is as yet no clear or enforced classification system for $PM_{2.5}$ respirators, with many respirators performing poorly in $PM_{2.5}$ filtration tests. Therefore, further research is required to establish high efficient filter for $PM_{2.5}$ filtration.

Fibrous filters are widely used in $PM_{2.5}$ filtration and typically outperform other filtration media. Filtration performance is most commonly measured according to the pressure drop and filtration efficiency, which are mainly determined by the filter's internal microstructure and gas–solid flow characteristics. Numerical simulations of gas–solid flow in various arrangements of fibrous media have been studied by many researchers. Most of these simulations used simple fibrous structures [4–10] and generated 2D (two–dimensional) fibrous media, while others applied heterogeneous fibrous structures [11] and generated 3D (three–dimensional) layered fibrous structures [12]. However, these fibrous models were not based on the actual fibrous media structures and the actual performance of such fibrous media remained unclear. Various novel methods for establishing realistic information about the microstructure of a fibrous media have been proposed. A useful technique was serial sectioning–imaging of the material imbedded in a polymeric resin [13]. These acquired 2D images can then be used to virtually reconstruct the original 3D microstructure [14]. Along with the above sectioning technique, X–ray microscopy was used to establish the structure and distribution of fibrous materials [15–17]. On a parallel track, Magnetic Resonance Imaging (MRI) was also used by many investigators to obtain a 3D image of porous media [18,19]. An integrated approach using automated serial sectioning technique, digital volumetric imaging (DVI), and finite volume method was presented to obtain a real fibrous media of nonwoven fabrics [20]. Using scanning electron microscopy (SEM), Zhu et al. [21] observed the microstructure of fibrous media and generated a 3D model using Matlab and Gambit. This approach was advantageous because fiber structural parameters can be numerically defined and the influence of the fiber parameters on pressure drop and filtration efficiency can be

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analyzed. In addition, a gas–solid flow model through the fibrous media was studied by combining computational fluid dynamics (CFD) with: particle trajectory simulation [4,6,7]; direct numerical simulation method [22,23]; Monte Carlo simulation [11,24]; Lattice Boltzmann modeling [24–28]; the OpenFOAM CFD package with Lagrangian tracking algorithm and a volume–of–fluid (VOF) solver [12]; ANSYS–Fluent CFD code [29,30]; or a CFD–DEM model [2,31].

However, these studies only address that the tendency of the pressure drop and filtration efficiency change with different fibrous structures, solid volume fraction, and other external factors such as face velocity and particle size. Optimized structures for particular particle sizes have not been investigated yet. In addition, all of above cited studies used a microcosmic geometry model, without considering the thickness of the fibrous media. As such, improvements in filtration efficiency are a result of increased fibrous media thickness. Beyond a certain thickness, filtration resistance and pressure drop increase rapidly, which will reduce filtration performance. Therefore, an optimal $PM_{2.5}$ filter should be characterized by a higher filtration efficiency and a lower pressure drop.

Results of pre–existing studies have some theoretical and practical significance for developing filtration theories and improving filtration performance of filters. Some researchers invented high–performance air filters on the basis of the previous study of the fibrous filtration. Liu et al. [32] developed a transparent air filter with a high filtration efficiency for $PM_{2.5}$. The filter has a specific microstructure to achieve transparent property, high air flow and high filtration efficiency. Nemoto [33] proposed a simple freeze–drying procedure to produce a nanocellulose and high–performance air filters. So the previous studies have a good application at the experimental manufacture. However, the study about the fibrous filtration is still a significative task. The more realistic computing model, more optimized microstructure, and a better way to compromise between air–flow and filtration efficiency are all need to be explored.

This work investigated the filtration performance of a multi–fiber filter. Firstly, it built three–dimensional models of the parallel and staggered filters. The models' filtration performances were compared using the commercially available software ANSYS–Fluent with a discrete phase model (DPM). In this simulation, the arrangement of fibers, fiber diameter, solid volume fraction (SVF), face velocity and particle size were considered. The staggered design was subsequently divided into three layers and optimized to achieve a higher filtration performance. The ways of optimization of the filtration performance can provide valuable advices for the production of high–performance filters.

2. Computational model of multi–fiber filter

2.1. Geometric model and simulation method

The calculation model and boundary conditions are presented in Fig. 1. The fibrous model was constructed using Gambit software, with a filtration domain length, width and height denoted by L, D and H respectively. The fibrous arrangements were either parallel or staggered. An addition 0.5 L upstream and downstream of the filtration domain was constructed, where the airflow and particles were assumed to be in an undisturbed flow field. In this simulation, L, D and H were 392, 488 and 448 μm respectively. The reference solid volume fraction (α) was defined as 5.6% [27].

The air flow was assumed to enter into the filtration domain through a velocity inlet and to leave with a pressure outlet boundary condition. The periodic boundary condition was considered for the sides of the computational domain [31]. For the fibrous surfaces, a no–slip boundary condition was assumed [2]. The air flow through the fibrous media was usually considered as a steady–state laminar flow [7,20,31]. The finite volume method by Patankar [34] was used to solve the air–flow equations. The continuity equation and the conservation of momentum equation are written as follows [20]:

$$\partial\rho/\partial t + \nabla\cdot(\rho v) = 0, \tag{1}$$

$$\rho\, dv/dt = \mu\nabla^2 v - \nabla p, \tag{2}$$

where ρ, v, p, and μ are the fluid density, velocity, pressure, and viscosity, respectively.

After the particle–free flow field was obtained, airborne particles were then introduced into the solution domain. The volume fraction of particles was less than 10%, which was regarded as the discrete phase. Combined with the obtained flow field, the force situation and trajectory of each particle were calculated by the Lagrangian method of the DPM solver, which was often used to solve multiphase flow problems [35]. The dominant forces acting on a particle are the air drag force, the Brownian forces and the gravity. The equation of motion for a spherical particle in air flow can be written as:

$$\frac{d\overrightarrow{U_P}}{dt} = \frac{18\mu}{\rho_p d_p^2 C_c}\left(\overrightarrow{U} - \overrightarrow{U_P}\right) + G_i\sqrt{\frac{\pi S_0}{\Delta t}} + \frac{\overrightarrow{g}(\rho_p - \rho)}{\rho_p}, \tag{3}$$

where $\overrightarrow{U}$ is the velocity vector of the flow filed, $\overrightarrow{U_p}$ is the velocity vector of the particle, $C_c = 1 + Kn_p(1.257 + 0.4e^{-1.1/Kn_p})$ is the Cunningham correction factor, where $Kn_p = 2\lambda/d_p$ is the particle Knudsen number, d_p is the particle diameter, ρ_p is the density of the particle, ρ is the density of the flow field, G_i is a random number chosen from a normal distribution with a zero mean and a unite variance, S_0 is the corresponding spectral intensity of the noise given by [36]: $S_0 = 216\mu kT/\pi^2 d_p^5 \rho_p^2 C_c$, $\overrightarrow{g}$ is the acceleration of gravity.

This work used the DPM model for particle motion in the fibrous filter. The DPM model supposed that particles were trapped when they touched the fiber surface, and deposited particles would not affect the flow field. So this work only considered the clean filtration stage. A more accurate model for particle motion including trapping, rebounding, interaction among particles will be considered in our future work. Finally, particles trapped by the fibers were counted to gain the filtration efficiency. In this simulation, all of the particles were modeled as rigid spheres with a uniform density of 1000 kg/m^3 [37]. They were uniformly distributed in the inlet plane and will be released from the inlet plane to the flow field.

2.2. Model validation

To validate the model, the number of mesh nodes around the fiber was increased from 10 to 40 to ensure that the calculation results were mesh–independent. A fiber diameter of 28 μm was chosen. It was a staggered model and the face velocity was 1.0 m/s. The corresponding results of mesh density analysis are shown in Fig. 2. It is found that, beyond 25, the number of nodes dose not affect the results of the pressure drop of the filter. For other fiber diameters in our simulation, the number of mesh nodes can be chosen proportionally according to above results.

For incompressible flow at very low Re (Reynold number) the air flow in the filter follows Darcy's law [20,37], which means that pressure drop is proportional to the face velocity of the entrance. Liu and Wang [38] found that the ratio of the pressure drop to face velocity is not a constant at higher Re, but rises with face velocity since a wake region is formed and additional energy is dissipated.