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Filtration of aerosol particles by clean elliptical fibers with relevance to pore size: A lattice Boltzmann-cellular automaton model

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ABSTRACT

Aerosol filtration is fundamental to environmental and industrial applications. Among several computational methods for the estimation of particle-laden flows, the lattice Boltzmann-cellular automata (LB-CA) has shown great promise. After validation, a 2-D LB-CA model is proposed to investigate the effect of pore size on particle-fiber collisions in a laminar free-stream flow over a semi-infinite array of clean elliptical fibers. The study contrasts the particle deposition characteristics of elliptical and cylindrical fibers, towards understanding the effect of ellipse eccentricity and orientation on the particle-fiber collision efficiency. Particle motion mechanisms considered comprise drag, lift, net gravitational and Brownian forces. The results show that the pore size needs to be small enough to show the significant correlation between the particle-fiber collision efficiency and elliptical fiber geometry. In the inertial impaction regime, enhancement of the particle-collision efficiency, reduction of the packing density and decreases of the pressure drop can be simultaneously achieved by employing a high-eccentricity elliptical fiber with an angle of 30° to 90° between the major axis and inflow direction. In the diffusion dominated regime, particle-collision efficiency is found to be influenced only by the fiber surface area.

1. Introduction

Aerosol particles that can be grouped into a fine mode (between 0.1 and 1 µm) and coarse mode (greater than 1 µm) are generally released into the atmosphere from vehicle engines, coal-fired power stations, oil- and wood-fired heating appliances, dust storms, and so forth. Fibrous filters, typically made of cellulose, glass or plastic, have been widely used to remove aerosol particles from carrier gases or air streams due to its simple, convenient and general features [1]. A commercial fibrous filter usually comprises a mat of uniformly distributed and randomly layered fibers in which a packing density or solidity is between 0.01 and 0.3 [2]. Important characteristics of fibrous filters include particle mass loading, packing density, mass of particles captured, particle fraction, filtration efficiency, collection efficiency and pressure drop across each layer [3]. Over the past half century, a number of theoretical and numerical methods have been employed to analyze particle-laden flows past a single fiber or fiber bundles. These general mathematical and computational tools that may speed up the design process are especially critical for manufacturers to optimize filters for a specific application.

When compared with cylindrical fibers, non-circular fibers have great potential for enhancing porosity, particle loading capacity, capture efficiency, mechanical strength and manufacturing flexibility [4]. An early experimental investigation by Lamb and Costanza [5] reported that, in comparison with cylindrical fibers, filtration performance is better with fibers having three or four lobes but poorer with fibers having two lobes. Later, Sánchez et al. [6] experimentally identified that at the beginning of filtration operations with an aerosol velocity of 0.1 m/s, collection efficiency of trilobal cross-section fibers is significantly higher than that of circular fibers. An analytical solution for flow field and pressure drop was proposed for a fiber with an arbitrary cross-sectional shape [7]. Several 2-D computational fluid dynamic (CFD) studies relevant to lobed fibers were proposed including filtration performance of multiple lobed fibers [8], a single lobed fiber operating in the slip flow regime [9], the effect of orientation angles on filtration performance of a single lobed fiber [10], and pressure drop and diffusional collection efficiency of a single lobed fiber [11]. In addition to lobed fibers, metallic fibers that are used for filtration of diesel soot generally have rectangular cross-sections with various aspect ratios. Numerous analytical or computational models for rectangular fibers have been proposed including flow field and pressure drop for a 2-D single fiber [12], filtration characteristics of 2-D staggered fibers [13,14], 3-D multifibers [15], and a 2-D single fiber [4,9-11]. Other shapes of fibers, such as triangular [10,11],

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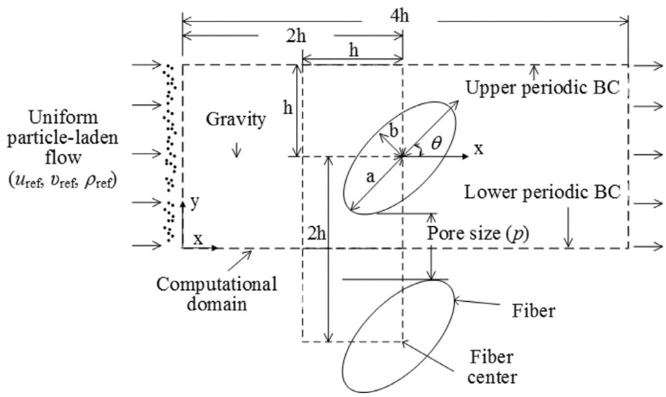

Fig. 1. Schematic of the physical model used in this study.

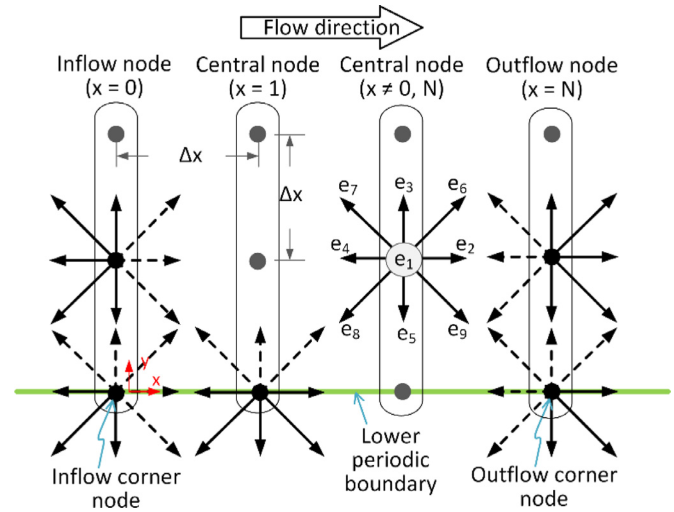

Fig. 2. Distribution functions of a 2D 9-velocity model at the inflow, outflow and lower boundary. Solid and dashed arrows are, respectively, known and unknown functions.

diamond [14], circular-arc [16], have also been studied for their filtration characteristics either by CFD or mathematical analyses.

Besides the models reviewed above, fibers with elliptical cross sections have recently drawn attention of many researchers due to their high surface area per unit volume and low drag force. Raynor [17] proposed a 2-D analytical solution for velocity fields around an elliptical fiber and aerodynamic forces of drag and lift on the fibers, where the model takes into account the influences of the fiber aspect ratio, filter solidity and fiber orientation. Later, The research group of Raynor extensively developed 2-D analytical models to study the effect of filter solidity, aspect ratio, fiber orientation and particle diameter on the interception capture efficiency [18] and diffusional capture efficiency [19] for a single elliptical fiber. Based on the models of Raynor [18,19], Wang et al. [20] further developed an analytical model to demonstrate that the interception efficiency of an elliptical fiber is higher than that of a circular fiber. Moreover, using CFD modeling, several 2-D models for the filtration characteristics of elliptical fibers have been proposed including a staggered array model [21], a single fiber operating in the slip flow regime [9], a single elliptical fiber with different orientation angles [10], and a comparative model for an elliptical and a circular fiber [22].

While a number of studies have indicated the effectiveness of elliptical fibers in improving particle-fiber collision efficiency, relatively little is known, in particular, concerning the inclusion of pore size between fibers in assessment of the filtration of aerosol particles by elliptical fibers. Addressing such issue is crucial when considering performance with respect to filtration characteristics of fibrous filter mats [23,24]. Prompted by this consideration, in the present study a 2-D computational model that is based on Lattice Boltzmann-Cellular Automata (LB-CA) is proposed to investigate particle-fiber collisions in a free-stream flow over elliptical fibers with various pore size classes. The findings of this study expand on the existing literature by identifying the operational conditions in which the use of the elliptical fibers has advantage over circular fibers.

2. Methodology

2.1. Physical model

The 2-D computational domain shown in Fig. 1 considers particle-laden flow around an elliptical fiber, where the origin of the Cartesian coordinate system is located at the bottom left corner. A centered fiber in the computational domain that consists of $4h$ in length and $2h$ in height is employed to represent a semi-infinite array of elliptical fibers in the y-direction. We fix the minimum distance ($2h$) between two centers of elliptical fibers in a plane perpendicular to the inflow. The dimensional scale h remains constant throughout this study. The pore size (p) is defined as the minimum distance between two fiber surfaces in a plane perpendicular to the inflow. In this study, the pore size is varied by changing the fiber size. a, b and θ are the major axis length, minor axis length and orientation angle, respectively.

The inflow is prescribed by a uniform velocity profile with the magnitudes of u_{ref}, kinematic viscosity of υ_{ref} and density of ρ_{ref}. Spherical particles with given size and density are injected with a random distribution at inflow boundary. The upper and lower boundaries are periodic while the standard pressure outlet condition is used at the outflow boundary.

Typical assumptions for aerosol filtration in clean fibers include aerosols with homogeneous and monodisperse spherical morphology, dilute particle-laden flow (solid volume fraction less than 10^{-6}), and one-way fluid-particle coupling without particle-particle interactions. To evaluate the particle-fiber collision efficiency, particles are removed from the flow field once they collide on the fiber surface.

2.2. Gas-phase equations

For the numerical simulations of fluid flows, the incompressible lattice Boltzmann model [25] is used. All dimensional quantities identified by a prime are nondimensionalized as follows:

$$\mathrm{u}=\frac{\mathbf{u}'}{u_{ref}},\quad \mathrm{x}=\frac{\mathbf{x}'}{2h},\quad t=\frac{t'}{2h/u_{ref}},\quad P=\frac{P'}{u_{ref}^2\rho_g},\quad \upsilon_g=\frac{\upsilon_g{}'}{2hu_{ref}},\quad \rho=\frac{\rho'}{\rho_{ref}}, \tag{1}$$

where $\mathbf{u}$, $\mathbf{x}$, t, P, υ_g and ρ are velocity, spatial coordinate, time, pressure, kinematic viscosity and gas density, respectively.

The 2-D fluid flow, solved by the D2Q9 LBM, is described by tracking the evolution of the pressure distribution function on nine-velocity square lattices, as shown in Fig. 2. The equation for the evolution of pressure distribution functions (p_α) is expressed as:

$$p_\alpha(\mathrm{x}+c\cdot\boldsymbol{e}_\alpha\cdot\Delta t,\ t+\Delta t)=p_\alpha(\mathrm{x},t)-\tau_f^{-1}\cdot[p_\alpha(\mathrm{x},t)-p_\alpha{}^{eq}(\mathrm{x},t)] \tag{2}$$

where the subscript α represents nine velocity vectors, $c=\Delta x/\Delta t$ is the streaming speed, and τ_f is dimensionless relaxation time. Δx and Δt are the lattice grid spacing and time step, respec-