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Numerical investigation of dilute aerosol particle transport and deposition in oscillating multi-cylinder obstructions

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ABSTRACT

The transport and deposition of aerosol particles through a fibrous filter is encountered in many natural and industrial processes. As the filtration performance for a stationary filter has been extensively studied in the literature, the present work focuses on the effect of fiber oscillation in a filter where the fibers are allowed to vibrate periodically. The transport and deposition of dilute aerosol particles in such a system is simulated using an efficient numerical model, where an iterative immersed-boundary lattice Boltzmann method is applied to solve the background flow with finite-size moving fibers, and the motion of aerosol particles is then tracked by a one-way coupling Lagrangian approach. In the present scheme, the no-slip boundary condition at the fiber surface can be exactly enforced with an iterative approach and the numerical stability is improved by adopting the MRT collision model. After the model validation in the two special cases of flow over an oscillating fiber in a quiescent fluid and particle capture by a stationary fiber, the filtration performance of an oscillating multi-fiber filter is investigated to study the effects of fiber number, arrangement and vibration mode. It is found that the oscillating motion of fiber has significant influence on the filtration performance. For a single fiber, with larger oscillation amplitude, the distribution ranges of the release position and impact angle of captured particles both increase. On the other hand, a larger fiber oscillation frequency tends to reduce the width of release position but increase the width of impact angle of deposited particles. Furthermore, the collection efficiency is found to be linearly related to the oscillation amplitude or frequency. For multiple fibers, the collection efficiency always increases with larger fiber number, but it is a non-monotonic function of the arrangement parameters, i.e., the longitudinal and transverse spacings, and the vibration parameters such as the amplitude, frequency and vibration mode. It is interesting to find that the in-phase mode can usually lead to excellent collection efficiency.

1. Introduction

The transport and deposition of airborne particles is encountered in a wide range of natural and industrial processes, such as the filtration, combustion and chip fabrication. In particular, one of the most attracting topics is the investigation of the fine particle removal from air [1–3]. An increasing body of works has revealed the adverse health effects of inhaled sub-micron particles [4], as a result of growing environmental concern and stricter regulatory legislation, both of which will continue to promote interest in the development of advanced particle removal technology. The commonly used dedusting methods could be roughly separated into four categories, i.e., mechanical impact from gravitational settling and cyclone separation, electrostatic precipitation, wet scrubbing and fibrous filtration [1]. Generally, filter made from the fibers with various kinds of materials is one of the most popular dedusting apparatus, due to the advantages of low cost, simple construction and high collection efficiency. For further improving the collection efficiency, there are also many new precipitators which combine the electrostatic and/or wet scrubbing technologies with the fibrous filter nowadays, such as the wet vibrating grid precipitator (WVGP) [5,6].

The flow through a fibrous filter is very complicated due to the coexistence and interactions among fluid flow, finite-size fibers, and small suspended particles. Many works have been devoted

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to study such filtration process. Brandon et al. [7] carried out numerical investigation of the particle deposition on a square cylinder placed in a channel flow. The effects of Stokes number *St*, Reynolds number *Re*, density ratio *S* (to be defined more precisely in Section 2) and the driving forces for the particle dispersion and deposition were considered. Yao et al. [8] used the spectral-element method to study the different patterns of particle dispersion in the wake of a circular cylinder. Jafari et al. [9] investigated the particle dispersion and deposition in a channel with a square cylinder obstruction using the lattice Boltzmann method. The ranges of *Re* and particle diameter d_p are, 120–200 and 0.01–10 μm, respectively. It was found that the Brownian diffusion affected the deposition rate of ultrafine particles on the front and back sides of the block, and the motion of particles behind the obstacle was greatly influenced by the vortex shedding. Haugen et al. [10] considered the particle impaction on a cylinder in a cross-flow as function of *St* and *Re*. The immersed boundary method was applied to solve the flow, and for the motion of particles only the drag force was taken into account. A new Stokes number was proposed to better scale the results. Particle impaction on the back side of the cylinder was observed, and this phenomenon was strongly dependent on the flow *Re*.

Results of the studies mentioned above have great implications both theoretically and practically for the development of high performance filter. However, it can be found that they are mostly restricted to a single fiber which may not very representative of a real fibrous filter. To overcome this defect, some researchers investigated the filtration performance of multi-fiber filter. Shou et al. [11] derived analytically the collection efficiency of filter where the fibers were distributed randomly. Liu et al. [12] studied the particle-laden flow past the multi-fiber filter and shown that the collection efficiency could not be represented by the single-fiber models. Lin et al. [13] focused on the multiple staggered fibrous filters. The influence of the fiber separation ratio in longitudinal and transverse directions on the filtration process was determined. Recently, Li et al. [14] used the numerical approach in an effort to optimize the filtration performance of a multi-fiber filter, which was composed of fibers with different diameter and structure. However, the flow *Re* in the filter was low, i.e., $Re < 1.0$ so that the inertial effect of flow could not be addressed. Shou et al. [15] also considered fibers with different sizes, and the fibers being interlaced in the filter.

Although the filtration of airborne particles by both single and multiple fibers has been studied in the past, most studies assumed that fibers are stationary. Therefore, relatively little is known concerning the influence of fiber movement on the filtration performance [16,17]. Khorasanizade et al. [18] used the smoothed particle hydrodynamics (SPH) method to study the dispersion of particles in the wake of a moving plate. For a flat plate collector, Holmes et al. [19] observed experimentally that both plunge and torsional oscillations could increase the collection efficiency. In the study of particle sampling by Price et al. [20], it was found that moving collectors could offer significant advantages over stationary one. Utilizing the fluid-structure interaction approach, Ryan et al. [21] investigated the influence of moving walls to mimic the realistic lung behavior on the deposition of respiratory aerosol. Substantial different results were obtained in comparison to those from stationary geometry with even imposed oscillating flows. Krick et al. [22] considered that the gas flow could cause the oscillation motion of a circular cylinder for higher flow *Re*. In the background of anemophilous pollination, the authors investigated the particle capture by an elastically mounted cylinder at *Re* as large as 3309 with a *St* range of 0.01–5.0. It should be noted that the flow *Re* may be too large for a fibrous filter and at the same time only one fiber is involved. Recently, Liu et al. [23] and Chen et al. [24,25] studied the performance of gas-solid separation for moving granular bed.

For the fibrous filtration, numerical approach has played an important role in solving the complicated flow resulting from blocking of fibers and resulting flow interactions. In the past few years, the lattice Boltzmann method (LBM) has been developed into a widely-used flow solver for the Navier-Stokes equations [26,27]. The method has also been applied to general particle-laden flows [28–30]. In LBM, mainly there are two schemes used to treat the no-slip boundary condition, i.e., the simple or interpolated bounce-back (BB) rule [31], and the immersed boundary (IB) method [32,33]. The flow field obtained by the BB-type method could have serious unphysical fluctuations when handling the moving boundaries [34]. This problem has been actively investigated in recent years and the sources of force oscillation have been partially identified and removed [35]. On the other hand, the IB scheme could largely avoid this problem, due to the help of local regularization or smoothing, and is therefore adopted in the present work. On the other hand, an iterative algorithm [36] is introduced into the standard IB method to solve the problem of streamline penetration [32], namely, the inaccurate implementation of the no-slip boundary condition. Furthermore, the MRT (multiple-relaxation time) collision model is adopted for substituting the commonly used LBGK (lattice Bhatnagar-Gross-Krook) model in LBM to improve the computational stability [26]. The iterative IB-LBM is then established and is to be validated in the following to have good performance in simulation of flow with moving boundaries. As for the motion of small aerosol particles, it is usually tracked by the Lagrangian approach [37].

In this work, a numerical model coupling the iterative IB-LBM for flow through fibers with the Lagrangian approach for tracking the aerosol particles is developed and used to investigate the filtration process of the oscillating multi-fiber filter. The present simulation is served as a practical analogy to the WVGP [5,6,38], where the effects of fiber number, arrangement and vibration mode are investigated. The remaining part of this paper is organized as follows. A statement of the problem is provided in Section 2. The numerical model including the lattice Boltzmann method, immersed boundary scheme, and the Lagrangian approach is introduced and validated in Section 3. In Section 4, we present the simulation results for the examination of the effects of fibers number, arrangement and vibration mode. Finally, conclusions are summarized in Section 5.

2. Problem description

The geometric model of the present fibrous filtration system for airborne particles is sketched in Fig. 1. The gas has a temperature *T*, density ρ_f and dynamic viscosity μ, and entrains a dilute concentration of particles with the density ρ_p and diameter d_p. The flow is assumed to be not affected by the aerosol particles due to the assumption of very low mass loading; Only the trajectories of the aerosol particles are driven by the flow (i.e., one-way coupling); Particle-particle interactions are also neglected (Those assumptions may generally hold for mass loading less than 8‰ [28]). The particle-laden flow is fed towards an array of oscillating finite-size circular fibers. The flow Reynolds number *Re* is fixed at 100, defined as $Re = \rho_f U_0 D/\mu$ where U_0 is the velocity of free stream, and *D* is the diameter of fiber. Hence, the present model falls into the range of inertial fibrous filters [2]. The physical and corresponding computational parameters of the gas, particle and fiber are given in Table 1. It is known that the deduced stream velocity, U_0, is high (up to tens of m/s) which is an important feature for the inertial fibrous filters [2,39,40]. The fibrous filter is semi-infinite in the *y*-direction. Therefore, to decrease the computational effort in simulations, it is reasonable to make use of the periodic boundaries to just consider a row of fibers [13], as shown