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Numerical investigation on non-steady-state filtration of elliptical fibers for submicron particles in the "Greenfield gap" range

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ABSTRACT

While noncircular fibers (especially elliptical fibers) have demonstrated significant advantage of high collection efficiency for fine particles, only a few investigations have yet been conducted to study the non-steady-state filtration performance of noncircular fibers during the particle deposition process. In this work, we utilize a lattice Boltzmann-cellular automata (LB-CA) probabilistic model to investigate the growing process of particle dendrites on elliptical fibers. The transient pressure drop and collection efficiency are analyzed. For the deposition of sub-micron particles (0.3–0.5 μm in the "Greenfield gap" range) which are dominated by the diffusion and interception mechanism, the captured particles distribute relatively uniformly around elliptical fibers (the equivalent diameter d_f of 22.8 μm and the packing density of 5% in this work) at the initial stage of loading process. The deposited particle leads to the formation of complicated dendrites, expanding the filtration area and thereby altering the flow field. Then particles will mostly deposit on the windward of the elliptical fibers (especially on the both ends of the elliptical long axis) at the complete dendrites capture stage. Various operation conditions (inlet flow velocity of 0.1–0.3 m/s, particle diameter of 0.3–0.5 μm, aspect ratio of elliptical fibers of 2–4, orientation angle of 30°~60°) are simulated. It is found that the pressure drop of dust loaded elliptical fibers normalized by the corresponding pressure drop of clean elliptical fibers increases almost exponentially with the mass of captured particles; and the normalized collection efficiency of elliptical fibers is approximately a linear function of the deposit mass when the increase rate of the normalized efficiency is stabilized.

1. Introduction

Fine particles suspended in the air cause adverse impact on the environment, climate and human health, which is one of the largest environmental problems. Fibrous filters are widely used in coal-fired power plants, chemical engineering processes, heating and semiconductor industries because of the advantages of low price, high collection efficiency of fine particles and simple construction for filter regeneration. The filtration process of fibrous filters contains complicated flow-particle-fiber interactions. Brownian diffusion, interception and inertial impaction are three basic mechanisms that lead to an aerosol particle deposits on a neutral fiber (Ramarao, Tien, & Mohan, 1994). In the present work, the deposition process of sub-micron particles (diameter of 0.3–0.5 μm in the "Greenfield gap" range (Greenfield, 1957)) is considered, and the effect of inertial impaction can be neglected while diffusion and interception are the dominant filtration mechanisms.

Classical fibrous filtration theories, which were based on a numerical or an exact solution of the velocity distribution of the flow

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around a circular fiber in a two-dimensional configuration, were originally developed for clean media. Based on these theories, a number of expressions for calculating the pressure drop and collection efficiency of fibrous filters have been proposed (Brown, 1993). However, the clean condition only exists in the initial stage of the filtration process for a short time, which can be regarded as the steady-state filtration. As for the real fibrous filtration process, when particles move to the surface of fibers, they may deposit on the fiber, increasing the collection area and thereby altering the flow field. The formation of particle dendrites will exert significant effects on the capture efficiency and pressure drop.

It has been identified in previous studies that the formation of dendrites follow three stages of dendrite formation—initial fiber collection, interim fiber-dendrite collection, and complete dendrite collection (Li & Marshall, 2007). However, simulation of this dynamic process is still difficult for several reasons: particle dendrites growth on dust loaded fibers is complicated and does not follow simple geometrical patterns; the shape of particle dendrites changes depending strongly upon the dominant capture mechanism; the growth of particle dendrites will change the boundary conditions for flow field and the flow field around the fiber needs to be recalculated after particle deposition.

Billings (1996) was probably the first to perform a systematic investigation of particle accumulation on individual fiber. He calculated the single fiber efficiency from SEM micrographs taken at regular time intervals. Payatakes and Tien (1976) studied the formation of dendrites on fibers uniformly placed within a Kuwabara cell in the interception regime. Payatakes and Gradoń (1980) expanded this model to simulate the filtration process of fibers in the diffusion and inertial impaction regimes. Kanaoka, Emi, and Myojo (1980) studied the growing process of particle dendrites on a fiber and the time dependency of single fiber collection efficiency utilizing Monte Carlo simulation technique. They found that the ratio of collection efficiency under dust loading (η) to that of the clean fiber (η_0) is approximately linear with the mass of deposited particles (m): $\eta/\eta_0 = 1 + \lambda m$, where λ is the increase rate of the normalized collection efficiency. Then, Myojo, Kanaoka, and Emi (1984) experimentally confirmed the theoretical investigations of Kanaoka et al. (1980) in the region of inertial and interception mechanisms, and found that the collection efficiency is more sensitive to Stokes number than interception parameter. In addition, Kanaoka and Hiragi (1990) proposed a model to predict the pressure drop of dust loaded filter based on the direct microscopic observation of particle attachment processes. Zhao, Tardos, and Pfeffer (1991) experimentally studied both the pressure drop and collection efficiency in dust loaded electrostatically filters by replacing the fiber diameter and packing density with the equivalent values. Thomas et al. (1999), Thomas, Penicot, Contal, Leclerc, and Vendel (2001) proposed a new model to give a quantitative prediction of pressure drop increase during filter clogging through dividing the filter into various slices in which two kinds of particle collectors coexist. Based on these researches, many numerical simulations (Przekop & Gradoń, 2008; Przekop, Moskal, & Gradoń, 2003) and experimental measurements (Kasper, Schollmeier, Meyer, & Hoferer, 2009; Kasper, Schollmeier, & Meyer, 2010) were conducted to investigate the dust loading problems.

With the fast development of manufacturing technology and materials science, fibrous filters composed of noncircular fibers have been used in practical applications to meet different requirements. A series of noncircular fibers have been commercially produced for high performance specialty nonwoven fabrics (*e.g.*, spun-bonded trilobal fibers with the brand name REEMAY registered by BBA Fiberweb). Having the advantage of larger specific surface area than traditional circular ones, the noncircular fibers demonstrate great potential to make fibrous filters at advantages of collection efficiency, particle loading capacity, manufacturing flexibility and mechanical strength. Many researchers have investigated the filtration performance of elliptical fibers (Raynor, 2002; Wang, Zhao, & Wang, 2014) and of rectangular fibers (Adamiak, 1999; Fardi & Liu, 1992; Ouyang & Liu, 1998; Zhu, Lin, & Cheung, 2000). The other kinds of noncircular fibers with triangle and trilobal cross-sections have also been studied (Fotovati, Tafreshi, & Pourdeyhimi, 2011; Inagaki, Sakai, & Namiki, 2001; Lamb & Costanza, 1980; Sanchez, Rodriguez, & Alvaro, 2007). There are some articles focusing on comparing the filtration performance of fibers with different cross-sections (Hosseini & Tafreshi, 2011; Huang, Wang, & Zhao, 2016; Wang & Zhao, 2015). In our recent work (Huang et al., 2016), diffusional capture efficiency of four kinds of noncircular clean fibers in filtration was quantitatively investigated. It turns out that elliptical fibers demonstrate higher diffusional collection efficiency than the other kinds of noncircular fibers with the same specific surface area. Nevertheless, neither of the above works investigated the non-steady-state filtration processes of noncircular fibers. Our extensive literature search resulted only a few articles (Cheung, Cao, & Yan, 2005; Sanchez et al., 2007) studying the particle loading process of noncircular fibers. The non-steady-state deposition of particles on noncircular fibers is not well understood.

Among different numerical simulation method, lattice Boltzmann method (LBM), which is used to simulate the flow fields, is considered as a very promising approach to treat irregular and dynamic geometrical boundaries like the captured particles forming dendrites here. Filippova and Hänel (1997) used the lattice Boltzmann method to simulate the gas-particle flow and growth of particle dendrites. Their work has taken a significant step towards simulating this complex process. Lantermann and Hänel (2007) used the lattice Boltzmann method to calculate the flow field and electrical potential field and particle Monte Carlo method to study the morphology of deposited particles.

As well-known, very fine particles (< 0.1 μm) and very coarse particles (> 5 μm) can be collected by fibers very efficiently, mainly due to Brownian diffusion and inertial impaction respectively; however, intermediate particles (*e.g.*, 0.3–0.5 μm in diameter) are hardly removed by fibers because the two important filtration mechanisms, Brownian diffusion and inertial impaction, have the minimum effect on these particles and the contribution of interception mechanism on capture efficiency is generally weak. Considering the outstanding performance of elliptical fibers on the effective removal of fine and intermediate particles, our idea is to utilize the elliptical fibers to improve the filtration efficiency of sub-micron particles (0.3, 0.4, and 0.5 μm as representative). In order to attain optimal filtration performance of elliptical fibers with respect to sub-micron particles in the "Greenfield gap" range, it is essential to deeply investigate the loading behavior of elliptical fibers. In the present study, the growing process of particle dendrites on a dust loaded elliptical fiber and the dynamic evolution of both pressure drop and collection efficiency are investigated using a lattice Boltzmann-cellular automata (LB-CA) probabilistic model, which has been already successfully applied by our group (Wang,

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