Powder Technology 292 (2016) 232–241

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Numerical study of pressure drop and diffusional collection efficiency of several typical noncircular fibers in filtration

Haokai Huang, Kun Wang, Haibo Zhao *

State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan, 430074, Hubei, China

ARTICLE INFO

Article history:
Received 10 November 2015
Received in revised form 2 February 2016
Accepted 5 February 2016
Available online 9 February 2016

Keywords:
Lattice Boltzmann method
Noncircular fiber
Fitting expression
The Levenberg–Marquardt algorithm

ABSTRACT

Noncircular fibers have larger specific surface area compared to the circular cross-section fiber with the same volume fraction and may perform higher collection efficiency of submicron particles. In this article, we use a lattice Boltzmann-cellular automata (LB-CA) probabilistic model to simulate the particle filtration processes of four kinds of noncircular fibers with rectangular, trilobal, quatrefoil and triangular cross-sections at low Reynolds number (less than 1). The pressure drop and collection efficiency for the diffusion dominant regime, where the Peclet number ranges from 235 to 1000, are investigated. By normalizing the pressure drop and collection efficiency of noncircular fibers with those of the circular fiber, which can be calculated from the existing classical expressions developed in the past, the corresponding ratios are gained. Then the Levenberg–Marquardt algorithm is used to obtain the fitting expressions of the above ratios. The proposed easy-to-use fitting expressions can be used to calculate the pressure drop and diffusional collection efficiency of noncircular fibers under different operation conditions, when the fiber volume fraction is 5%–10%. The results show that the pressure drop of noncircular fibers is dependent on the orientation angle and the aspect ratio. The diffusional collection efficiency is almost independent of the orientation angle but proportional to the aspect ratio for all the noncircular fibers.

1. Introduction

Fibrous filters are widely used to remove particles from particulate laden flow due to their advantages of low price, simple construction for filter regeneration and high collection efficiency, which make them popular in heating, ventilating, air-conditioning (HVAC) industries. In addition, fibrous filters can be described as mats of randomly arranged fibers where most of the fibers are roughly perpendicular to the air flow through the filter. The collection of particles from flow streams by fibrous filters is mainly due to the combined effects of Brownian diffusion, interception and inertial impaction. In the present case of the collection of very small particles, the effects of interception and inertial impaction can be neglected and Brownian diffusion becomes the dominant mechanism for particle filtration. Though a real filter consists of lots of fibers, the study on a single fiber is the basis of the research on the real filters. The comprehensive study on the single fiber is essential because the collection efficiency of a real clean filter medium is closely linked to the single fiber capture efficiency [1]. The steady-state particle capture process occurs only in the early stage of the real filtration. However, many researchers consider that the collection efficiency of a clean fiber with the steady-state filtration process (η_0) is dependent of the efficiency increase with particle loading of the real filtration [2–4]. Understanding and modeling the kinetics of dust filtration on the basis of the classical clean single fiber theory is an effective method.

Davies [5] and Hinds [6] reviewed the development of fibrous filters in details. The particle-flow-fiber interactions in fibrous filtration are very complicated and many researchers have studied the filtration processes through numerical simulation, theoretical analysis and experimental measurements [7–9]. At the early stage, almost all the researches focused on circular fibers. Kuwabara [10] solved the two-dimensional velocity field of viscous flow transverse to randomly arranged cylinders. Happel [11] obtained similar results in the same year independently. Since then, many researchers studied fibrous filtration based on Kuwabara or Happel flow field. For examples, Lee and Liu [12] investigated the collection efficiency of circular fibers due to diffusion and interception mechanisms by using the Kuwabara flow field. Brown [13] proposed an expression for the drag force on a circular fiber with the 2-D cell model of Kuwabara.

With the fast development of filter manufacturing technology, fibers with elliptical, rectangular, and wedge-shaped cross-sections are available [14] and the researchers show a growing interest in noncircular fibers. Having the advantage of larger specific surface area than traditional ones, the noncircular fibers have great potential to make fibrous filters with increases in collection efficiency, mechanical strength, porosity, particle loading capacity, and manufacturing flexibility [15]. An example of noncircular fibers is a family of Spun-bonded trilobal fibers produced by BBA Fiberweb, which are sold under the brand name REEMAY [16]. There are already some studies on the noncircular fibers with rectangular and elliptical cross-sections. Fardi and Liu [17,18] investigated the

---

* Corresponding author.
E-mail address: klinsmannzhb@163.com (H. Zhao).

http://dx.doi.org/10.1016/j.powtec.2016.02.012
0032-5910/

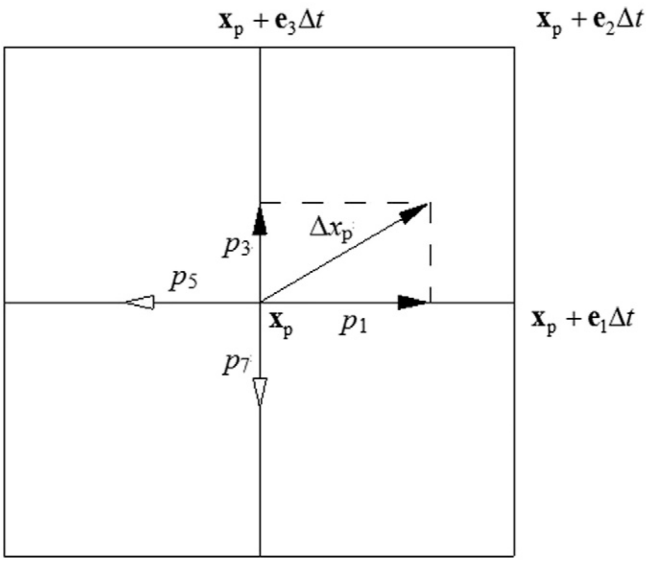

Fig. 1. Particle transport rule in the CA probabilistic model.

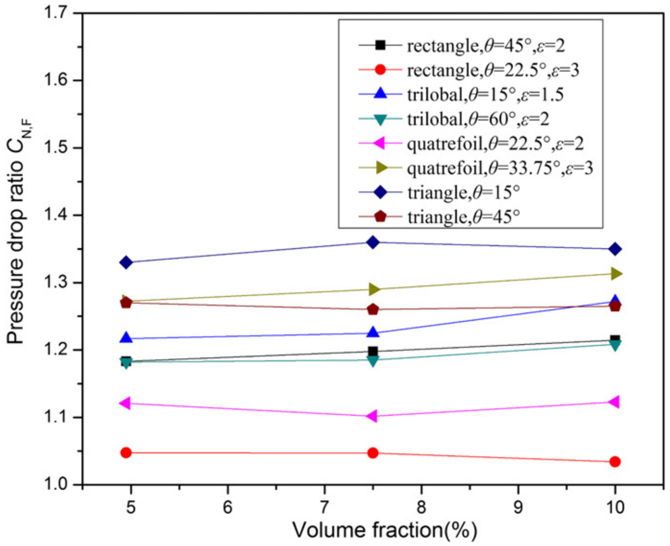

Fig. 3. Pressure drop ratio $C_{N,F}$ vs. volume fraction.

pressure drop and diffusional collection efficiency of rectangular fibers for the first time. Wang [19] studied the flow fields around multilayer rectangular fibers and put forward an empirical expression to calculate the pressure drop of a single square fiber. Ouyang and Liu [20] studied the flow fields and pressure drop of rectangular fibers with different aspect ratios and volume fractions but with the same orientation angle. Adamiak [21] investigated the motions of particles in an electric field and the collection efficiency of square fibers by using the finite element method. Zhu et al. [15] analyzed the filtration process of rectangular fibers due to the inertial impaction mechanism. Cheung et al. [22] investigated the collection efficiency and filtration process of electrets split type rectangular fibers. As for elliptical fibers, Raynor [23] investigated the drag force of the elliptical fiber and obtained an empirical formula based on the Kuwabara flow field. Then Regan and Raynor [24] studied the collection efficiency dominated by the diffusion mechanism and found that the diffusional collection efficiency of the elliptical fiber is higher than that of the circular fiber, independent of the orientation angle and proportional to the aspect ratio. Raynor [25] also proposed an empirical formula for interceptive efficiency of a single elliptical fiber. Wang et al. [26] in our group studied the flow around an elliptical fiber and the collection efficiency dominated by various collection mechanisms. There are also a few studies dealing with other kinds of noncircular fibers. Such studies include, but not limited to, numerical simulation of Fotovati et al. [16], Hosseini and Tafreshi [27], Inagaki et al. [28], Wang et al. [29] as well as the experimental work of Lamb and Costanza [30], and Sanchez et al. [31]. However, our extensive literature search resulted only in a very few of the mentioned works comparing the performance of filters made of different kinds of noncircular fibers [27,29]. To the best of our knowledge, the influence of fiber cross-sectional shape and orientation angle on the filter collection performance is not well understood.

In the present study, the performance (i.e. the pressure drop and diffusional collection efficiency) of four kinds of noncircular fibers with rectangular, trilobal, quatrefoil and triangular cross-sections for the diffusion dominant regime is investigated using a Lattice Boltzmann-Cellular Automata (LB-CA) probabilistic model proposed previously [32,33]. The motions of particles under the combined effects of Brownian diffusion and drag force are quantitatively obtained by computing the probability of motions of particles. The flow fields are obtained using the Lattice Boltzmann method (LBM). LBM has some outstanding advantages including its simple and clear physical pictures, inherent parallelism, and high capability to address complex boundary conditions compared with some traditional numerical methods, making it particularly suitable to study the filtration of noncircular fibers with, for example, a quatrefoil cross-section. As for the fibrous filtration, the pressure drop and collection efficiency are two of the most important parameters. Not only noncircular fibers may perform higher collection efficiency due to their larger specific surface area than the traditional circular ones but also exhibit larger pressure drop because of their worse streamlined shapes. So these two parameters must be considered together. Then the Levenberg–Marquardt algorithm (LMA) [34] is used to obtain the fitting expressions of the correction ratios, which are gained by normalizing the pressure drop and collection efficiency of

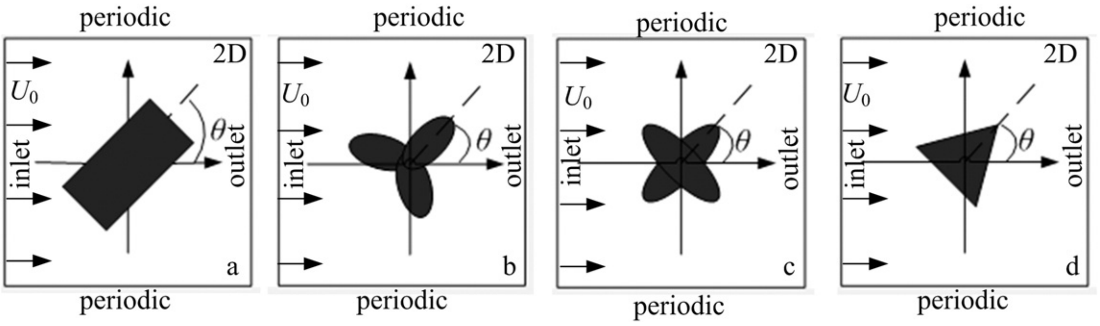

Fig. 2. Computational domain for simulating flow fields around noncircular fibers: (a) rectangular fiber; (b) trilobal fiber; (c) quatrefoil fiber; (d) triangular fiber.