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Experimental-computational study of fibrous particle transport and deposition in a bifurcating lung model

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ABSTRACT

Experiments carried out using a lung model with a single horizontal bifurcation under different steady inhalation conditions explored the orientation of depositing carbon fibers, and particle deposition fractions. The orientations of deposited fibers were obtained from micrographs. Specifically, the effects of the sedimentation parameter (γ), fiber length, and flow rate on orientations were analyzed. Our results indicate that gravitational effect on deposition cannot be neglected for $0.0228 < \gamma < 0.247$. The absolute orientation angle of depositing fibers decreased linearly with increasing γ for values $0.0228 < \gamma < 0.15$. Correspondence between Stokes numbers and γ suggests these characteristics can be used to estimate fiber deposition in the lower airways. Computer simulations with sphere-equivalent diameter models for the fibers explored deposition efficiency vs. Stokes number. Using the volume-equivalent diameter model, our experimental data for the horizontal bifurcation were replicated. Results for particle deposition using a lung model with a vertical bifurcation indicate that body position also affects deposition.

Introduction

Man-made inhalable fibers may cause detrimental health effects, as in the case of asbestos, as well as carbon and vitreous fibers (Blake et al., 1998; Cavallo et al., 2004; Champion & Mitragotri, 2006; Hodgson & Darnton, 2000; Kulkarni, Baron, & Willeke, 2011; LeMasters et al., 2003; Marsh et al., 2001; Mossman & Churg, 1998). Alternatively, they can be used for treatment, as in the case of therapeutic drug particles (Simone, Dziubla, & Muzykantov, 2008). Thus, computational and experimental analyses of the transport and deposition of non-spherical aerosols in models of the human lung are of great interest. For example, Myojo (1987) experimentally examined fiber deposition in a single-bifurcation airway, and qualitatively stated that the deposited fibers traveled parallel to the carrier-fluid flow. Furthermore, Myojo (1990) investigated the effects of fiber length and diameter on fiber deposition. Myojo and Takaya (2001) proposed an empirical correlation to estimate the deposition fraction (DF) of fibrous particles linked to impaction and interception. Sussman, Cohen, and Lippmann (1991) studied the effects of asbestos fiber length and flow rates on deposition efficiency (DE) in a tracheobronchial airway. Marijnlssen, Zeckendorf, Lemkowltz, and Bibo (1991) analyzed the deposition of nylon fibers in an upper airway, and concluded that the deposition hot spot of nylon fibers at the carina is similar to that of spherical particles. Su and Cheng (2005) investigated fiber deposition in the human nasal airways at different flow rates. Their results indicated that the dominant mechanism was impaction, and that fibrous particles could pass through the nasal cavity more easily than spherical ones. Su and Cheng (2006) emphasized the effect of impaction in experiments on deposition of fibers in an airway replica, comprising an oral cavity, pharynx, larynx, and pulmonary bifurcations. Further experimental observations (Zhou, Su, & Cheng, 2007) showed that fibers could penetrate the upper respiratory airways and enter lower lung regions more easily than spherical particles having the same volume. Wang, Hopke, Ahmadi, Cheng, and Baron (2008) analyzed the influences of fiber length, flow rate, and airway geometry on particle deposition in nasal cavities. Examples of recent numerical analyses of fiber deposition in

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Nomenclature

d_{ae}	fiber's aerodynamic equivalent diameter
d_p	diameter of fibrous particle
d_{ve}	fiber's volume equivalent diameter
d_*	dimensionless particle diameter
D	inlet tube diameter
DF	deposition fraction
Fr	Froude number
g	gravitational acceleration
$m_{deposit}$	particle mass deposited on the inner airway surfaces
m_{exit}	particle mass which had exited the airway model
L	length of the airway tube
l_p	length of fibrous particle
St	Stokes number
U	mean air velocity at the inlet
v_*	dimensionless terminal velocity
$v_{setting}$	settling/terminal velocity of the particle
Greek letters	
β	aspect ratio of fiber
γ	sedimentation parameter
κ	dynamic shape factor
$\kappa_{\parallel}$	dynamic shape factors of the fibers oriented parallel to the flow
$\kappa_{\perp}$	dynamic shape factors of the fibers oriented perpendicular to the flow
θ	orientation angle of deposited fiber
$\lvert\theta\rvert$	absolute value of the orientation angle
$\lvert\bar{\theta}\rvert$	average of the absolute orientation angle
μ	dynamic viscosity of air
ρ_f	density of fluid
ρ_p	density of fiber
ρ_0	density of water
φ	inclination angle measured relative to the horizontal
ϕ	particle sphericity

realistic nasal cavities include simulations by Inthavong, Wen, Tian, and Tu (2008) and Shanley, Ahmadi, Hopke, and Cheng (2009); the latter group compared fibrous particle DEs to those of spheres. Tian and Ahmadi (2013) analyzed the flow field, fiber trajectory, and DE in an asymmetric, generation G0–G3 lung bifurcation model. Feng and Kleinstreuer (2013) investigated ellipsoidal particle transport in Poiseuille flow, which resulted in a revised Stokes-equivalent-diameter for ellipsoidal particles. They compared their simulations to measured data sets for ellipsoidal particles to predict the DEs in subject-specific airways from the oral cavity to a G3 lung model. Kleinstreuer and Feng (2013) reviewed spherical and non-spherical fluid-particle dynamics, and discussed different numerical methods for non-spherical particle simulations.

Nevertheless, the behavior of fibrous particles in deeper lung regions is still unclear, especially when the effect of gravitational sedimentation on deposition becomes a factor. For example, Sakai, Watanabe, Sera, Yokota, and Tanaka (2015) carried out deposition experiments in nasal cavities with large particles (i.e., lycopodium powder, with an average diameter of 32 μm and density of 1.05×10^3 kg/m^3), and showed that DE is about 15–25% higher than the experimental correlation proposed by Kelly, Asgharian, Kimbell, and Wong (2004) for 1- to 10-μm-sized particles undergoing sedimentation. Kleinstreuer, Zhang, and Kim (2007) simulated spherical micron-sized particle deposition in a G6–G9 airway, taking into account inertial impaction and sedimentation. Their results also showed that gravitational sedimentation becomes locally significant in some lung airways, influencing deposition patterns as well as DEs, especially under slow inhalation conditions. Hofmann, Balásházy, and Koblinger (1995) simulated spherical particle deposition in a single-bifurcation G15–G16 airway under different gravity angles, using a Monte Carlo method. The simulations showed that deposition was greatly affected by the angle between the parent tube axis and the gravitational vector; horizontally placed bifurcations yielded the highest DEs. Sedimentation is more complicated for fibers than for spherical particles, because their motion is influenced by their orientation in the fluid flow field. For example, the settling velocity of a high-aspect-ratio fiber released parallel to the gravitational vector is about twice that attained when descending perpendicular to gravity (Herzhaft & Guazzelli, 1999).

The goal of our study is to investigate fiber deposition in a bifurcating lung model to obtain quantitative data on the orientation of fibrous particles during transport and deposition. Using steady air-fiber flow in a single-bifurcation airway model, following the geometry of Weibel (1963), the DEs of fibrous particles were acquired under different flow rates. Images of local particle deposition were captured using a microscope and analyzed to obtain fiber orientations. Stokes number and sedimentation parameters were calculated to evaluate the behavior of these fibrous particles in the lower airway. Our data provide new insights into fiber behavior that can be used for computer modeling of the transport and deposition of fibrous particles with a lung model.

Method

Fiber characteristics

Black carbon fibers were used in experiments of this study, provided by Corker, Inc. (Hangzhou, China). Carbon fibers provide a high contrast to the system background, ideal for imaging. The fibers were monodisperse in diameter, but polydisperse in length. Fiber length and diameter distributions shown in Fig. 1 were obtained by measuring fibers ($N > 200$) on SEM images. Their count median diameter (CMD) was 7.34 μm and the geometric standard deviation of the diameter was 1.07. Their count median length (CML) was 22.97 μm, and the geometric standard deviation of the length was 1.81. The density of the fiber was 1780 kg/m^3.

Experimental setup

The G0–G1 bifurcating model shown in Fig. 2 was reproduced from Weibel's 23-generation pulmonary airway model (Weibel, 1963) using a 3D printer (ZBuider, Zcorp, Burlington, USA). The rectangles in Fig. 2 show the positions selected to observe the orientations of deposited fibers using a microscope. The interval between neighboring observation points was 10 mm. Position 11 (P11) was omitted to facilitate discussion of results for G0 and G1 model sections. Physical parameters of our model are listed in Table 1. The orientation angle θ is defined as the angle between the axial directions of the tube and the deposited fiber, as illustrated in Fig. 2. The inner surface of our airway model was coated with a sodium polyacrylate solution to cause fibers to adhere to its surface.

Fig. 3 illustrates the experimental setup of our fiber deposition experiments under steady inhalation conditions. The experimental system consists of a fiber generator, a mixing chamber, the airway model, filter units, two flow meters, and a vacuum pump. Fibers were delivered into the mixing chamber by air from the generator, dispersed in the mixing chamber before moving into the airway model under inspiratory flow. Because image processing was used to identify the lengths of deposited fibers, a differential mobility analyzer was not employed. Fibers were randomly

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