Journal of Aerosol Science 117 (2018) 149–163

Contents lists available at ScienceDirect

Journal of Aerosol Science

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

Deposition of glass fibers in a physically realistic replica of the human respiratory tract

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ARTICLE INFO

Keywords:
Fiber deposition
Human respiratory airways
Glass fibers
Experiments
Deposition measurement

ABSTRACT

Regional deposition of glass fibers was investigated in a physically realistic, human respiratory tract replica. The replica begins with the oral cavity and includes the airways up to the 7th generation of the tracheobronchial tree. Uniform diameter glass fibers were classified by length using a dielectrophoretic classifier and introduced into the replica at three steady-state flow rates (15, 30, and 50 LPM). A novel automatic image processing method was utilized to speed up the sample analysis and make it more reproducible. Fractional deposition was high in the oral cavity and the upper respiratory airways. Deposition density was higher in the first few generations of the tracheobronchial tree. Deposition efficiencies were compared with published data and good agreement was obtained. Our data confirmed that the deposition efficiency increased with increasing Stokes number indicating that impaction was the main deposition mechanism. The experimental data were used to propose new empirical models predicting fiber deposition in the tracheobronchial tree.

1. Introduction

Since the discovery of the toxicity of asbestos, there has been ongoing interest in inhalable fibers (Baron, 2001). The use of asbestos has been strictly regulated or banned altogether in the past. However, these restrictions led to increased production of substitute materials, such as man-made vitreous fibers (MMVFs). MMVFs have some physical similarities to asbestos that provide them with comparable aerodynamic characteristics and thus, the ability to penetrate into the human respiratory system. This capability naturally raised the question of their toxicity. Although the International Agency for Research on Cancer has classified glass, rock, and slag wool as non-carcinogenic to humans, and ceramic fibers as possibly carcinogenic to humans (IARC, 2002), MMVFs remain a concern. Recommended occupational exposure limits (OEL) of 1 fiber/ml have been established in the countries of European Union (SCOEL, 2012).

Most prior studies regarding particle transport and deposition in human respiratory airways involved spherical particles (Chan & Lippmann, 1980; Lizal, Belka, Adam, Jedelsky, & Jicha, 2015; Zhou & Cheng, 2005). However, it is not possible to extrapolate these results to fibrous aerosols. Fibers exhibit different aerodynamic behavior than spherical particles, causing different deposition patterns. This difference occurs because of the complicated motion of fibers that undergo both translation and rotation. After inhalation, fibers tend to align with the air stream causing their effective aerodynamic diameter to closely approximate its diameter with length having a negligible influence (Baron, 2001). During translation motion, fibers occasionally rotate, which temporarily changes the

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https://doi.org/10.1016/j.jaerosci.2017.11.006
Received 3 February 2017; Received in revised form 16 October 2017; Accepted 15 November 2017
Available online 21 November 2017

particle's drag force (Kleinstreuer & Feng, 2013). The frequency of fiber rotation in the flow depends on the fiber aspect ratio and the position in the airways. Fibers rotate more frequently with a decreasing aspect ratio, and near the walls in high shear flow (Feng & Kleinstreuer, 2013; Tian, Ahmadi, Wang, & Hopke, 2012).

Only a few studies of fiber deposition in human respiratory airways have been reported. Controlled experiments on human subjects are potentially hazardous and thus, unethical. Therefore, experimental methods using airway replicas and numerical simulations are required. Myojo and coworkers (Myojo & Takaya, 2001; Myojo, 1990) experimentally investigated glass fiber deposition in bifurcating airway models. The two models consisted of single bifurcations from the 2nd to 3rd and the 3rd to 4th generations of tracheobronchial branching of a Weibel A lung model (Weibel, 1963), respectively. Preferred sites of deposition or "hot spots" were found around the carinal ridges, and the orientation of deposited fibers was parallel to the air stream. Sussman, Cohen, and Lippmann (1991) performed experiments with an upper tracheobronchial tree replica to study the influence of fiber length and diameter on deposition distribution. A mechanical larynx was connected to the model to simulate the influence of upper respiratory airways. Deposition hot spots were identified around carinas as well as on the upper dorsal wall of the trachea. Deposition in the trachea was caused by a jet that formed at the larynx constriction and directed the air towards the trachea wall (Chan & Schreck, 1980). Su and coworkers (Su & Cheng, 2006a, 2006b, 2009) and Zhou, Su, and Cheng (2007) experimentally studied fiber deposition in two realistic replicas consisting of human airways from the oral cavity to the 4th branch generation. Various fiber types with different densities were employed including carbon, TiO_2, and glass fibers. High inertia fibers deposited extensively in oropharynx and larynx in both the replicas. However, low inertia fibers mostly traversed the replicas. Comparing the two replicas, the exact location of deposition hot spots differed slightly indicating that the differences in geometry caused small changes in the flow field and the resulting changes in deposition.

Computational studies of particle deposition in realistic human airway models are difficult because the underlying physics that must be captured is highly complex. Moreover, the complex coupled rotational and translational fiber motion must be addressed. Therefore, many studies have been conducted on idealized geometries using simplified cases where an analytical solution was employed or simple shear flows were used. For example, Cai and Yu (1988) predicted fiber deposition in bifurcating airways. Fan and Ahmadi (1995) presented fiber equations of motion in a sublayer model evaluating the fiber deposition in turbulent streams. Zhang, Asgharian, and Anjilvel (1996) studied the fiber deposition numerically in an equal diameter bifurcating airway model for various fiber sizes and bifurcation angles. Balashazy, Martonen, and Hofmann (1990, 2005) tested an equivalent diameter concept and predicted fiber deposition in the bifurcating model for the three fiber orientations; parallel, perpendicular and random with respect to the streamlines.

Recently, numerical simulations of fiber deposition in realistic geometries have been reported. Tian et al. (2012) introduced a computational model for predicting the fiber transport and deposition in low Reynolds number flows. Later, Tian and Ahmadi (2013) employed the model to study fiber deposition in bronchial airways from the trachea to the 3rd bronchial generation. The absence of a larynx was addressed by prescribing turbulence intensities at the trachea inlet. The results showed that turbulence enhances deposition, emphasizing the importance of larynx and upper respiratory airways for a proper study of deposition patterns. Feng and Kleinstreuer (2013) investigated transport and deposition of ellipsoidal particles in a similar geometry of human respiratory airways as those used by Su and Cheng (2006b). The deposition efficiencies in these studies were compared and acceptable agreement was found. Deposition of particles with various aspect ratios was then studied. It was observed that the particles with higher aspect ratios have higher probabilities of penetrating deeper into the lungs compared to lower aspect ratio particles, e.g. spherical particles. Additionally, the deposition efficiency per generation of these high aspect ratio fibers increased slightly from trachea to the fourth generation, indicating interception driven by secondary flows can influence the deposition in higher branch generations. Inthavong, Mouritz, Dong, and Tu (2013) studied the transport of airborne fibers through the nostrils into the respiratory system using empirically defined drag coefficient for the fiber motion. Dastan, Abouali, and Ahmadi (2014) extended the work of Fan and Ahmadi (1995) and employed the equations for fiber motion to study fiber deposition in human nasal cavities. Shanley and Ahmadi (2011) developed a computational model to account for the motion of ellipsoidal particles in viscous shear flows. Shanley, Ahmadi, Hopke, and Cheng (2016) employed this model to numerically analyze fiber deposition in human nasal cavity.

The use of proper computational models that account for the fiber motion in conjunction with the computational fluid dynamics methods is essential in fiber deposition studies. The crucial step on the way to routinely and reliably use CFD calculations is a proper validation with experimental data, either acquired in vivo or on human replicas. However, the number of experimental data regarding fiber deposition is rather sparse. That is the reason why we experimentally investigated glass fiber deposition in our human airway replica. The replica geometry extends from the oral cavity to the 7th bronchial generation (Lizal, Elcner, Hopke, Jedelsky, & Jicha, 2012). The fibers were classified using dielectrophoresis to yield uniform length particles. A novel automatic image processing method was utilized to speed up the sample analysis, make it more convenient and more reproducible (Belka et al., 2016). The results of this study also provide the first measurements of deposition beyond the 4th generation. The current replica has been employed in other experimental works (Jedelsky, Lizal, & Jicha, 2012; Lizal et al., 2015; Nordlund et al., 2017) and thus, the results on fiber deposition presented in this paper further extend the data set for experimental validation. Recent progress in simulations performed on the current replica has been documented by Koullapis et al. (2017) and Frederix et al. (2018). The digital geometry of the airways is available upon request.