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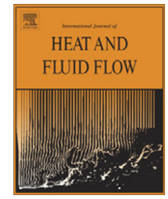

Characteristics of turbulent particle transport in human airways under steady and cyclic flows

Jan Jedelsky *, Frantisek Lizal, Miroslav Jicha

Faculty of Mechanical Engineering, Brno University of Technology, Technicka 2896/2, 61669 Brno, Czech Republic

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Motion of monodispersed aerosol particles suspended in air flow has been studied on realistic transparent model of human airways using Phase Doppler Particle Analyser (P/DPA). Time-resolved velocity data for particles in size range 1–8 μm were processed using Fuzzy Slotting Technique to estimate the power spectral density (PSD) of velocity fluctuations. The optimum processing setup for our data was found and recommendations for future experiments to improve PSD quality were suggested. Typical PSD plots at mainstream positions of the trachea and the upper bronchi are documented and differences among (1) steady-flow regimes and equivalent cyclic breathing regimes, (2) inspiration and expiration breathing phase and (3) behaviour of particles of different sizes are described in several positions of the airway model. Systematically higher level of velocity fluctuations in the upper part of the frequency range (30–500 Hz) was found for cyclic flows in comparison with corresponding steady flows. Expiratory flows in both the steady and cyclic cases produce more high-frequency fluctuations compared to inspiratory flows. Negligible differences were found for flow of particles in the inspected size range 1–8 μm at frequencies below 500 Hz. This finding was explained by Stokes number analysis. Implied match of the air and particle flows thereby indicates turbulent diffusion as important deposition mechanism and confirms the capability to use the P/DPA data as the air flow velocity estimate.

1. Introduction

Transport and deposition of aerosol in human airways has been of research interest for several decades. Main present motivation for elucidation of related phenomena is the increasing tendency of therapeutical drug application in the form of the inhaled aerosol (Azarmi et al., 2008). Aerosol deposition in the human airways is also extensively studied in many industrial hygiene related researches (Kleinstreuer et al., 2008; Sosnowski et al., 2007; Su and Cheng, 2009 and others).

Published works show that the air flow in the multiple-bifurcating airway system is a very complex phenomena showing turbulent, transitionary and laminar behaviour depending on breathing conditions, morphology and position in the airways (Cohen et al., 1993; Guan and Martonen, 2000; Ramuzat and Riethmuller, 2002; Martonen et al., 2002; Kleinstreuer and Zhang, 2003; Fresconi et al., 2003; Li et al., 2007). Transitionary and turbulent flows often occur in the mouth–throat and upper conducting airways while laminar flow controls transport beyond approximately the 9th generation of the bronchi. Within this wide range of conditions, fate of the inhaled particles depends on their size in conjunction with the local flow dynamics. Aerosol deposition may occur due to impaction, sedimentation, diffusion, and turbulent dispersion.

The occurrence of upstream turbulent flows may influence both the inlet velocity and particle profiles entering the bifurcation and may enhance deposition within the model (Longest and Holbrook, in press). The turbulence induced by the laryngeal jet significantly affects airway flow patterns as well as tracheal wall shear stress (Lin et al., 2007) and is responsible for increased local particle deposition (Gemci et al., 2002; Chan et al., 1980). Kleinstreuer and Zhang (2003) demonstrated the importance of transitional and turbulent flows on particle deposition throughout an oral-trachea airway model. They reported enhanced particle deposition in the trachea near the larynx due to turbulence and throughout the airway mainly for small particles ($Stk < 0.06$) due to turbulent dispersion. Sosnowski et al., 2007 used CFD modelling to study behaviour of aerosol particles with size 0.3–10 μm in the oro-pharynx under unsteady air flow and found higher deposition efficiency for smaller particles due to strong effects of turbulent diffusion. Kleinstreuer et al., 2008 modelled deposition of micron-size particles in pulmonary airway replicas and located particles mainly around the carinal ridges deposited due to inertial impaction but some particles also landed outside the vicinities of the cranial ridges due to secondary flows and turbulent dispersion. Cheng

* Corresponding author.
E-mail addresses: jedelsky@fme.vutbr.cz (J. Jedelsky), lizal@fme.vutbr.cz (F. Lizal), jicha@fme.vutbr.cz (M. Jicha).

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et al. (1997) used oral airway replicas and found that turbulent diffusional deposition is the dominant deposition mechanism of ultrafine particles (<0.1 μm).

Turbulence in the respiratory tract is generated by several mechanisms. Primary source of turbulence is often the inhaler, which delivers particles into the mouth producing high momentum turbulent spray jet. A high-speed laryngeal jet is formed as the flow passes through the glottis; this jet induces turbulent flow in the trachea. Lin et al. (2007) found out that regions of maximum local turbulence in the trachea are associated with Taylor-Görtler-like coherent vortical structures in the supraglottis and the subglottis. Hiemenz flow (characterised by transition to turbulence at low Reynolds numbers (250) (Obrist et al., 2011)) at the carinal ridges can be related to the increased turbulence in daughter branches during inspiration. Overall fluid motion in curved airway tubes has helical character (Guan and Martonen, 2000); the vortices formed contribute to turbulence. It was confirmed in the left curved bronchus by Große et al. (2007). Mixing of streams from daughter branches is a source of turbulence for expiratory flows. Complex flow structures containing different types of vortices, flow detachment, wakes, simultaneous bidirectional flow, recirculation zones and velocity oscillations observed particularly for cyclic breathing as described in a number of papers (brief review in Jedelsky et al., 2010a) contribute to the turbulence as well. The turbulence in airways is generally strongly anisotropic with major part of turbulent kinetic energy (TKE) contained preferably in axial direction of the flow (Longest and Holbrook, in press).

Turbulent flow contains unsteady vortices which appear on many different length scales and interact with each other. Most of the kinetic energy of the turbulent motion is contained in the large-scale structures generated by the flow. These energetic structures transform to smaller-scale vortices by an inertial and basically inviscid mechanism. Smaller and smaller structures are produced until they are small enough for molecular diffusion to become important and viscous dissipation of energy finally takes place. This process known as the energy "cascade" leads to essentially continuous frequency spectrum of TKE. The largest eddies appear at low frequencies and are followed by energy containing eddies that are characterised by maximum amplitude at the spectrum. Inertial subrange, at higher frequencies, shows decreasing TKE tendency with frequency and successive dissipation subrange at the highest frequencies shows even faster TKE decay with frequency. The TKE spectrum can be estimated using time-resolved measurement of velocity of particle laden turbulent flows by laser-Doppler techniques such as P/DPA. Fate of airborne particles in turbulent flows depends on their *Stk*. Very small particles ($Stk \ll 1$) follow the fluid motion, while larger particles ($Stk \sim 1$) tend to be centrifuged toward the peripheries of the vortical structures. For $Stk \gg 1$ the particles move essentially independent of the fluid (Crowe et al., 1998). Small *Stk* particles, transported by turbulent eddies, can deposit if forced by these eddies towards the airway wall. Particles with $Stk \sim 1$, concentrated at the peripheries of turbulent structures (Zhang and Kleinstreuer, 2002), can deposit as well. Turbulent dispersion is therefore responsible for increased deposition efficiency.

Continuous movement from simple airway models and steady flows to realistic models and lifelike cyclic flow regimes is seen on present CFD simulations and experimental studies. Realistic, CT based, lung models were proved to be a must for valid results of flow and particle transport. Several works report significant quantitative and qualitative differences between aerosol transport/deposition characteristics under steady flows, most frequently studied in the past, and lifelike oscillatory flows (Lieber and Zhao, 1998; Zhang and Kleinstreuer, 2004; Zhang et al., 2001).

Several methods have been applied for flow studies in airway models. Intrusive Hot Wire Anemometry (HWA) was used for in vitro air flow measurements in the past while optical methods prevail today. The most common is Particle Image Velocimetry (PIV). Laser Doppler Anemometry (LDA) (Corieri and Riethmuller, 1989; Lieber and Zhao, 1998; Tanaka et al., 1999; Corcoran and Chigier, 2000) and P/DPA (Gemci et al., 2002) are less frequent. Complex design of realistic models hampers application of optical methods for aerosol transport studies. PIV, in realistic models, requires application of a liquid with refraction index equal to the one of the model walls instead of air, as the real breathed fluid, or usage of simple models with cylindrical walls if air used. LDA (or P/DPA), as point-wise technique is more suitable for measurements in the composite optical system of transparent model with flowing air. This method moreover allows direct particle flow measurement with high spatial resolution and high data rate. Aside basic flow characteristics as mean and rms velocities also spectral flow properties could be estimated therefore. Estimation of PSD from Laser-Doppler based data faces a problem of irregular time sampling. A number of different techniques was developed to treat this problem; it was formerly solved using analogue filters of the velocity signals or by equidistant time re-sampling. Scott (1974) derived an expectation of the spectrum on the basis of a Slot Correlation technique (SC) which remains even today one of the most viable means for PSD estimations. Large group of estimators is based on the concept of signal reconstruction and re-sampling at equal time intervals. The most common reconstruction is zeroth-order interpolation or sample and hold (S+H) method. Other spectral estimator for LDA data, introduced by Nobach et al. (1996), was based on one-point reconstruction techniques employing a refinement which accounts, in a statistical manner, for the velocity change between a particle arrival and the sample instant. The most reliable spectral estimation techniques are explained in detail by Benedict et al. (2000).

In this work, we have focused on description of the turbulence in frequency domain for the case of the complex flow in the multiple bifurcating airways, which is not sufficiently studied topic so far. We have processed exemplary P/DPA data acquired during our earlier study[1] with the aim to document spectral properties of turbulent particle transport in human airways. Brief description of our experiment and measured data is made first. Kern software program (Nobach, 2002) is used for estimation of PSD of particle velocity fluctuations. Setup of the program has been optimised for our data and several P/DPA data sets are processed. Arbitrary PSD plots are shown to describe nature of the particle-air flow. Differences between steady and cyclic flows at several positions of the airway model and the influence of the flow regime and particle size on the PSD are discussed. Several recommendations for future to improve the PSD estimations are given.

2. Experimental apparatus

Our experimental device (Fig. 1) uses a computer controlled motor (6) which drives piston through pneumatic cylinder (5) as a source of oscillating air flow. Steady air flows were maintained using a downstream suction source – vacuum air pump. Three steady breathing regimes (15, 30 and 60 l/min) and three corresponding cyclic sinusoidal breathing regimes were used (tidal volume 0.5 l and breathing period 4 s, 1 litre & 4 s and 1.5 litre & 3 s). Monodispersed aerosol particles of di-2-ethyl hexyl sebacate (DEHS) ranging from 1 to 8 μm are generated by condensation generator (4). One-half of the particles is mixed with the air in a chamber (3) using static mixer and flows into the airway model (Fig. 1).

[1] This study of transport of monodispersed micron-sized liquid particles dispersed in air was made in realistic transparent human airway model for a range of steady and cyclic flows and particles of various sizes. P/DPA was used to acquire time-resolved data of particle velocity (Jedelsky et al., 2010a).