Experimental investigation of aerosol deposition in alveolar lung airways

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Small particles, called aerosols, reaching the gas-exchange surfaces in the alveolar regions of the lower pulmonary airways are known to cause or exacerbate pulmonary diseases. In medical research, pulmonary drug delivery can serve as a systematic treatment in the diagnosis, prevention and control of such diseases. The importance of, and the mechanism governing the transport of these particulates is not yet fully understood. Studies related to aerosol deposition in the alveolar pulmonary airways have been mostly restricted to numerical studies, which require further experimental validation. Few experimental studies have been performed extracting quantitative data due to the involved complexity accompanying the extremely low Reynolds-numbers (in the order of 0.01) encountered in the lower lung airways.

The article presents measurements of both fluid velocity and aerosol trajectories conducted in a curved pipe with cylindrical cavities representing the alveolar structures in the 21st generation in the Weibel model (Fig.1). These can later be used in the validation of numerical codes.

It turned out to be impossible to model simultaneously Reynolds, gravitational and inertial similarity for the aerosol particles. As one of the main objectives was to act as a benchmark test for numerical codes rather than to accurately simulate the conditions encountered in the alveoli, iron particles of 1.2mm in diameter were chosen for, representing aerosols with in-vivo diameters of 12.8µm. Silicone oil served as carrier fluid allowing flow rates of 0.84ml/s corresponding to Reynolds numbers of 0.07. The experimental model was casted in a silicone block. The difference in refractive index between model and fluid was negligible, reducing refracting originating from the curved surfaces. Using iron particles of 20µm as tracers, PIV experiments were conducted to extract the steady flow velocity distributions while a time-resolved tracking algorithm allowed the extraction of the particle positions from the digitally recorded images.

Background subtraction was applied to improve the image quality. An existing cross-correlation algorithm was elaborated to include ensemble correlation. As such the negative influences of poor image quality and low seeding could be lessened. The former incorporates window distortion and reduction of the interrogation windows within an iterative structure. The adapted algorithm allowed the extraction of valuable velocity information with relatively high spatial resolution, even in regions of poor image quality and low seeding. A time tracking algorithm extracted the time-resolved particle positions from digitally recorded images. Incorporated in the algorithm was the four-frame tracking method, followed by a linear extrapolation of previous determined particle locations to serve as predictor for the next position.

A curvilinear separation streamline at the alveolar openings characterized the flow field and indicated little convective change with the lumen flow. Tubular vortices were found in the corners of the outer radius of the bend which then merged into a larger vortex when reaching the inner radius (Fig.2). The velocity inside the alveoli was about two orders of magnitude smaller compared to the mean lumen velocity. Through the advanced interrogation methodology, allowing correlation windows of 20 20 pixels, even slow rotating fluid elements located at the center of each cavity could be properly identified. None of the injected aerosols were able to follow the tube geometry perfectly (Fig.3). All aerosol trajectories showed a curvilinear behavior indicating gravity as the dominating deposition mechanism. The Stokes number along the particle trajectories was in the order of 10^{-4} proving viscous forces to overrule the inertial forces.

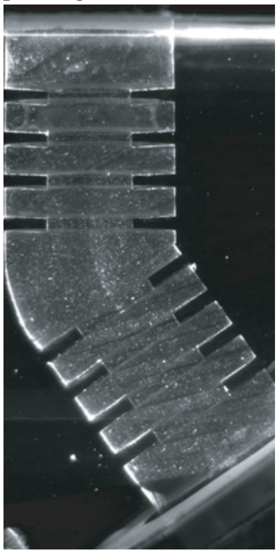

Fig. 1

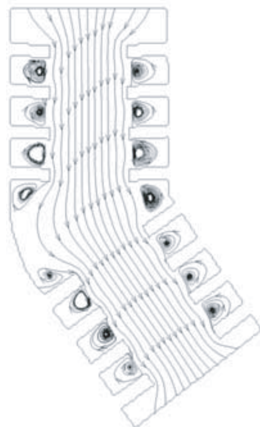

Fig. 2

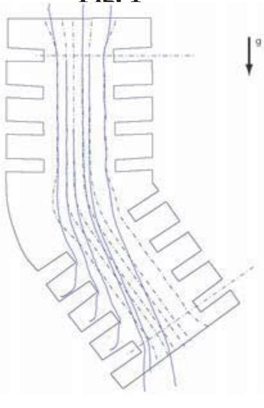

Fig. 3