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Numerical simulation of a turbulent oscillatory pipe flow

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Introduction

High-frequency oscillatory ventilation is an artificial respiration technique employing high "breathing" frequencies ω and low tidal volumes. Fig. 1 depicts, that the oscillatory flow in the multi–bifurcating geometry of the human airways imply a wide range of the key dimensionless parameters, i.e. the Reynolds and the Womersley number, respectively, defined as

$$Re = \frac{\hat{u} \cdot D}{\nu} \quad \text{and} \quad Wo = \frac{D}{2}\sqrt{\frac{\omega}{\nu}}\,, \tag{1}$$

where D is bronchi diameter and ν the viscosity. The flow in the upper generations occasionally implies relatively high Re, at least when peak velocities $\hat{u}$ occur. In this context, findings from Eckmann & Grotberg (1991) and Trukenmüller (2006) indicate, that the respiratory flow might not sustain laminar behaviour throughout the complete oscillation

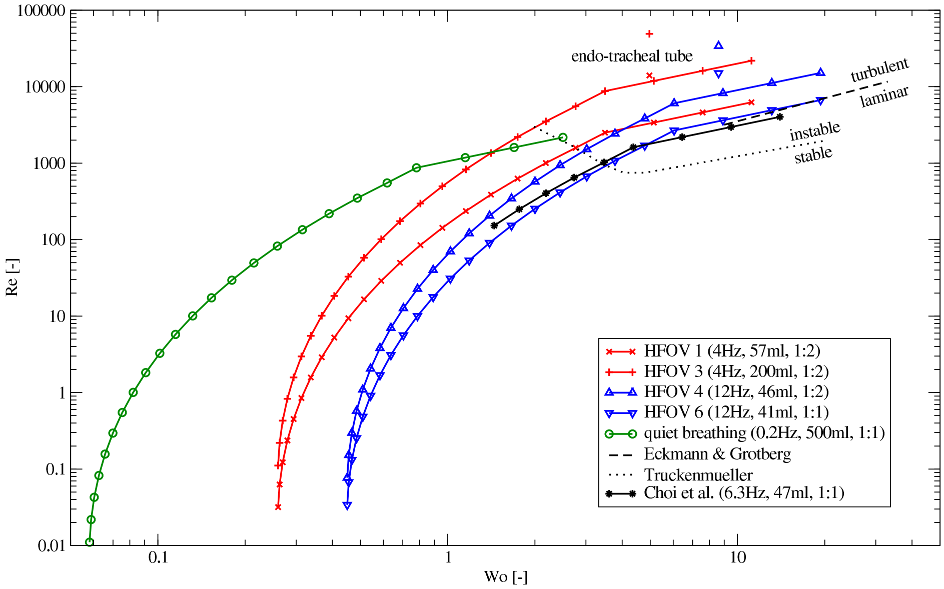

Figure 1: Parameter range in the bronchial tree (Weibel (1963)) under several respiratory conditions (graphs) at every bronchial generation (symbols), from trachea (top right) down to the terminal bronchioles (bottom left) and the corresponding endo–tracheal tube (ETT, single symbols). The frequency and the tidal volume of each scenario according to Hager *et al.* (2007) are given in parentheses.

cycle. To gain more insight regarding the flow structures and its impact on gas transport for these Re–Wo–combinations, we perform an implicit LES in a straight pipe.

Numerical method

We solve the unsteady, incompressible Navier–Stokes equations using an unstructured finite volume method. For temporal integration an implicit second–order backward differencing scheme is used, while the spatial discretisation is handled by an unbounded second–order central differencing scheme. The solver takes advantage of the PISO method for the pressure–velocity coupling and the resulting linear systems for the momentum equation and the Poisson equation are processed with a preconditioned bi–conjugate gradient solver and a generalised geometric–algebraic multi–grid solver, respectively. The boundary conditions for pressure and velocity are strictly periodic in axial direction and a sinusoidally oscillating source term is used as driving force. The variable time step was chosen to follow a Courant number of at least $Co \leqslant 0.3$ throughout the whole oscillation cycle.

Numerical results

We present first results for the case of HFOV 1 at the ETT, i.e. $Re = 1.8 \times 10^4$ and $Wo = 5$ from fig. 1. The grid resolution was chosen to fulfil at least $\Delta x^+ = 14$, $r^+ \cdot \Delta\phi = \Delta r^+|_0 \leqslant 4.5$ as well as $\Delta r^+|_{D/2} = 0.82$ resulting in about 6.5×10^6 cells. Here, $^+$ denotes wall units and the friction velocity u_τ within one cycle was a priori estimated by finding the maximum wall–normal velocity gradient of the analytical solution for laminar flows according to Womersley (1955). Thus, we get $Re_\tau = 462$ and fig. 2 presents instantaneous flow fields at the medial cross–section of the ETT, comprising turbulent expiration, re–laminarisation and large–scale instabilities during the flow reversal as well as re–establishing turbulence.

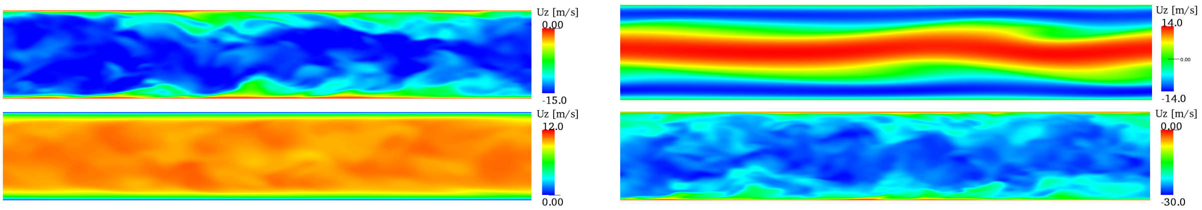

Figure 2: Instantaneous axial velocity fields at late expiration (t.l), early inspiration (b.l.), flow reversal (t.r.) and early expiration (b.r.). Note the different scaling.

References

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