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Simulation of Microfluidic Mixing using Artificial Cilia

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Introduction

In Lab-on-Chip devices, mixing of fluids or reagents is often a big challenge. By mimicking natural cilia (Fig. 1), integrated on the floor of the micro-channel, den Toonder et al. [1] quite unexpectedly achieved good mixing. Cilia are the beating hairs on the outside of micro-organisms.

Fig. 1 (a) Paramecium a micro-organism covered with cilia. (b) Micrograph of artificial cilia, length L of a cilium is 100µm.

Objective

Determine the reason for the highly efficient mixing in the micro-mixer based on artificial cilia.

Numerical Model

A cross-section of the original micro-channel has been modelled, see Fig. 2. The fluid is assumed Newtonian and incompressible with density $\rho$ and viscosity $\eta=1\text{ mPas}$, the solid Neo-Hookean, incompressible and inertialess with modulus $G=1\text{ GPa}$. The interaction between the cilia and the fluid is captured using the fictitious domain method [2].

Fig. 2 Computational domain $W=1\text{ mm}$, $H=0.5\text{ mm}$ and $D=L/\pi=32\text{ µm}$. Five cilia are placed on the channel floor.

The cilia unroll due to an applied body force and recover elastically. One full cycle is simulated using a finite element method, thereafter passive particles are tracked for 50 cycles using this velocity field. To study the effect of fluid inertia, the Reynolds number $Re=\frac{UL}{\eta}$ is varied from 0 to 10 by changing the density, where $U$ is the typical velocity being $O(1\text{ m/s})$.

Experiments

The simulated particle positions are compared to experimental Optical Coherence Tomography data (OCT), which are recorded at the same cross-sectional plane. In OCT a laser illuminates suspended particles and the scattered light patterns are recorded.

Results

The simulated particle distributions after 50 cycles are given in Fig. 3. For $Re=0$ the motion is clockwise and for $Re=10$ the motion is counter clockwise. The latter is in accordance with experiments, indicating that inertia controls the flow direction even at these low Reynolds numbers.

Fig. 3 (a) Simulated particle positions after 50 cycles for $Re=0$ and (b) $Re=10$.

The OCT data at three sequential frames and the simulated particle positions at three times are shown in Fig. 4.

Fig. 4 (a) OCT data at three sequential times and (b) simulations for $Re=10$.

The simulated particle motion at $Re=10$ agrees well with the experimental data, hence inertia causes good mixing in this micro-mixer.

Conclusion

A model has been developed which predicts the flow and mixing of a micro-mixer based on artificial cilia. The simulations and experimental data show surprisingly good agreement for $Re=10$. Therefore fluid inertia is the reason for the efficient mixing in this device.

References


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