

# SIMULATION OF MICROFLUIDIC FLUID MIXING USING ARTIFICIAL CILIA

M.G.H.M. Baltussen<sup>1</sup>, J.M.J. den Toonder<sup>1,2</sup>, F.M. Bos, P.D. Anderson<sup>1</sup>

<sup>1</sup>*Technische Universiteit Eindhoven, THE NETHERLANDS, and*

<sup>2</sup>*Philips Research Laboratories, THE NETHERLANDS*

## ABSTRACT

In previous work we developed a micro-mixer based on artificial cilia, that was experimentally proven to be very effective. Here, we present numerical simulations of the mixing process carried out using an advanced numerical tool, in combination with OCT experiments, that explain the observed effectiveness. As opposed to what was expected, fluid inertia was found to be the key ingredient for effective mixing.

**KEYWORDS:** micro-mixing, optical coherence tomography, FEM simulation

## INTRODUCTION

An important tool in clinical diagnostics is the biochemical analysis of biofluids. By miniaturization of analysis devices, such that channel dimensions are only millimeters or smaller, the amount of required fluid is lowered and diagnostic time is shortened. A typical operation during analysis is the mixing of two reactants. Since diffusion alone is too slow, and the flow is far from turbulent, special micro-mixers have been developed which lead to efficient chaotic mixing at these length scales.

One of these micro-mixers is an active micro-mixer based on artificial cilia [1]. Cilia are the periodically moving hairs on the outside of micro-organisms, used for propulsion, see Fig 1. This device consists of rows of cilia which are attached to the bottom of the channel. The motion cycle of a cilium consists of two parts, the first where an electrostatic force is applied and the cilium rolls out onto the bottom wall, and the second where the cilium recovers elastically to its original shape. The cycle frequency is about 100 Hz. These devices showed good mixing over length scales much shorter than expected for microfluidic flows in the low Reynolds regime. The reason for this high efficiency is explained in this paper.

## MODELLING & METHOD

In order to explain the highly efficient mixing reported in [1], a 2D model has been developed. A cross-section of the original channel has been modelled, see Fig. 1, and the mass and momentum equations for both the fluid and the solid (cilia) are solved. Both fluid and solid are assumed to be incompressible and the solid is also inertialess. The interaction between fluid and solid is modelled with the fictitious domain method and implemented as was done by Khatavkar *et al.* [2]. The electrostatic actuation force is modelled as a body force that increases quadratically with the vertical distance between the cilium and the lower wall. This force is turned off when the cilium is rolled out, *i.e.* is fully parallel to the wall, after which the cilium recovers elastically. The resulting set of equations is solved with a finite element method (FEM) for different Reynolds numbers (Re), which quantifies the influence of inertia with respect to viscous forces.

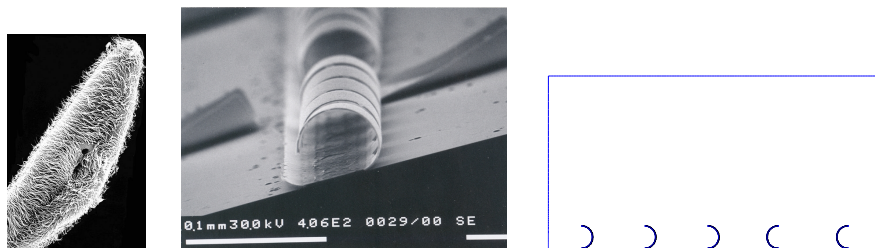


Figure 1: Left: *Paramecium*: a micro-organism that makes use of beating cilia on its surface for propulsion. Its cross section is about  $40\ \mu\text{m}$ . Middle: picture of the developed artificial cilia; their length is about  $100\ \mu\text{m}$ . Right: schematic cross section of the mixing channel, with five artificial cilia, represented as semi-circular structures, located on the floor. Three are unrolling to the right when actuated, the other two to the left. The channel height is  $0.5\ \text{mm}$ , the width  $1\ \text{mm}$  and the length of the individual cilium is  $100\ \mu\text{m}$ . This is a cross-section of the device used in [1].

Next, the positions of a group of passive particles is tracked for 50 cycles of cilia oscillations, using the computed velocity field. The obtained particle positions are compared with optical coherence tomography (OCT) data, which are recorded in the same cross-sectional plane as the simulations.

## RESULTS

The rotation of the left part of the flow is found to be clockwise in the  $Re = 0$  case, in which inertia is not playing any role and only viscous effects can be observed. In the  $Re = 10$  case, on the other hand, in which inertia does play a part, the rotation direction is found to be precisely opposite, see Fig. 2. This counterclockwise flow is also found in the OCT experiments, as shown in Fig. 3. Moreover, the particle distribution of the  $Re = 10$  case matches the particle distribution in the experiments. Therefore inertial forces play an important role in the flow behaviour of this mixer. By changing the actuator velocity, which controls the Reynolds number for a given system, the rotation of the fluid can be controlled. The  $Re = 10$  case also show better distributive mixing than the  $Re = 0$  simulations, indicating that inertia enhances mixing even at these low Reynolds numbers.

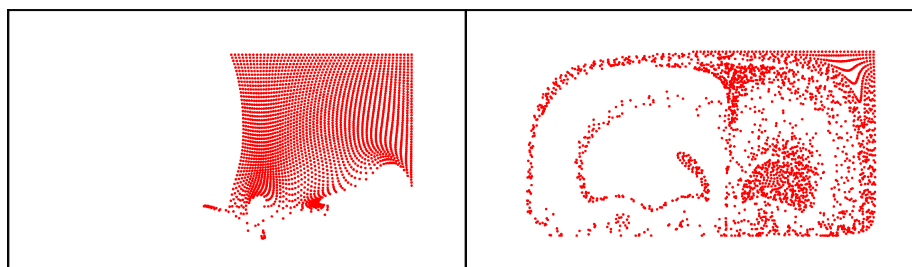


Figure 2: The difference in simulated flow direction for  $Re=0$  (left) and  $Re=10$  (right) for the configuration of Fig. 1 after 50 cilia oscillations.

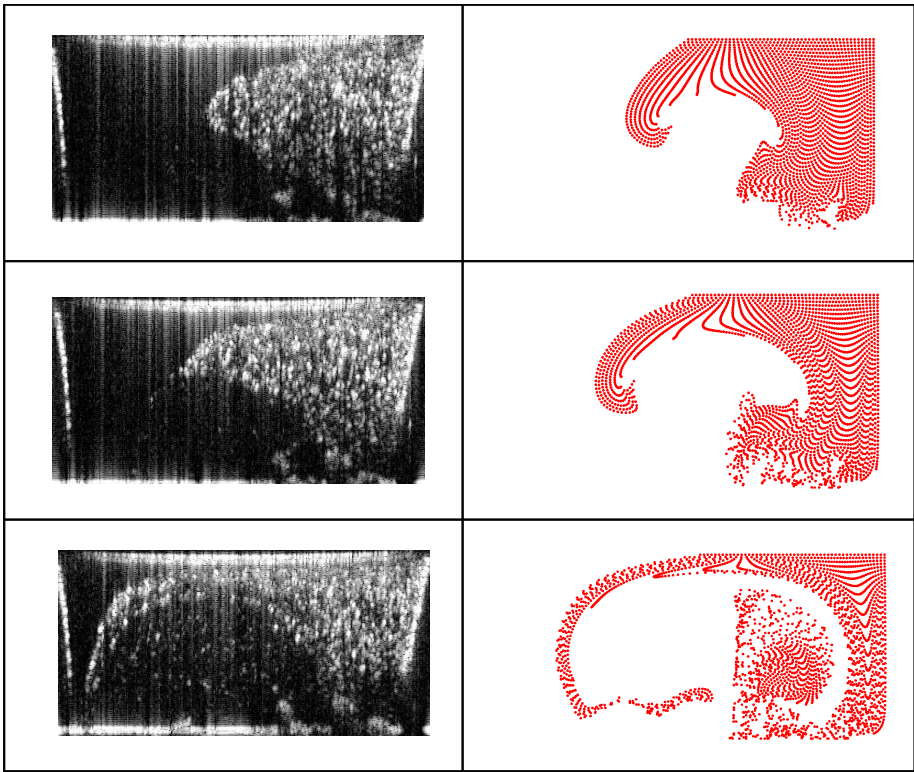


Figure 3: Cross-sectional views of the tracer particles in OCT experiments (left) and simulation (right) at different time-scales for the configuration in Fig. 1. The time scales of the simulations correspond to 6, 10, and 22 oscillations of cilia motions.  $Re=10$  in the simulations.

## CONCLUSIONS

A model has been developed which can predict the mixing evolution for a micro-mixer based on artificial cilia. A comparison of the numerical results with experiments proves that, unexpectedly, the observed effectiveness of the mixing is due to inertial flow effects. Hence, even though the artificial cilia are very small, low Reynolds number theory does not suffice to explain the observed flow.

## ACKNOWLEDGEMENTS

This work is part of the European project 'Artic' (Framework 6, STRP 033274).

## REFERENCES

- [1] J.M.J. den Toonder, F.M. Bos, D.J. Broer, L. Filippini, M. Gillies, J. de Goede, G.N. Mol, W. Talen, J.T.A. Wilderbeek, V. Khatavkar and P.D. Anderson, *Artificial cilia for active micro-fluidic mixing*, Lab Chip, **8**, 533-541, 2008.
- [2] V. Khatavkar, P.D. Anderson, J.M.J. den Toonder, H.E.H. Meijer, *Active micromixer based on artificial cilia*, Phys. Fluids, **19**, 083605, 2007.