A CORIOLIS-BASED SPLIT-AND-RECOMBINE LAMINATOR FOR ULTRAFAST MIXING ON ROTATING DISKS

J. Ducrée, T. Brenner, T. Glatzel and R. Zengerle

IMTEK, University of Freiburg, Georges-Köhler-Allee 103, D-79110 Freiburg, Germany, ducree@imtek.de, phone: +49/761/203-7324, FAX: -7322

We for the first time present a concept to substantially speed up mixing of laminar flows through generic radial microchannels on a rotating disk. Our experiments and simulations reveal that transversal flow patterns are generated by the pseudo-Coriolis force. By optimizing the channel geometry and the speed of rotation as the key impact parameters, the induced convection can be utilized to stir and even reverse the alignment of two parallel flows. These findings lead to a novel split-and-recombine laminator constituted by a simple arrangement of rectangular, low-aspect-ratio microchannels yielding, drastically reduced mixing times.

centrifugal microfluidics, Coriolis force, mixer, split-and-recombine

Introduction

In all microchannels, the laminar flow conditions impose severe limitations on the speed of merely diffusion-driven processes such as mixing and subsequent chemical reactions. Since the early days of microfluidics up to now, many concepts to enhance mixing have been elaborated which involve active elements (piezos, heaters, external pumps) or passive, 3-dimensional microstructures (caterpillar structures, etc.) which are complex to fabricate with standard equipment. These requirements are apparently not compatible with typical technological and economic constraints, in particular for disposable devices in many life science applications.

In this paper we present a novel method for the rapid mixing of laminar flows in simple, 2.5-dimensional microchannels on a disk rotating at the angular frequency ω (Fig. 1) [1,2]. In the rotating frame of reference, the liquid experiences two types of forces. The centrifugal force scales with ω^2 and the apparent Coriolis force $\propto \vec{v} \times \vec{\omega}$ with the flow velocity $\vec{v}$. In a radial channel, $\vec{F}_{\text{Coriolis}}$ is perpendicular to $\vec{F}_\omega$ and the ratio of the force densities amounts to $\varrho \Delta x^2 \omega / 4\eta \approx 10^{-2}\omega$ for the density ϱ of water and a channel radius $\Delta x = 200\,\mu\text{m}$. To induce transversal mixing by means of the Coriolis force, we go beyond the ω-threshold of about $100\,\text{rad}\,\text{s}^{-1} \approx 1000\,\text{rpm}$ where the Coriolis force prevails over the centrifugal force!

Single-Channel Mixer

Experiments and accompanying simulations to resolve detailed mixing patterns of two flows contacted in a rectangular channel at different positions are displayed

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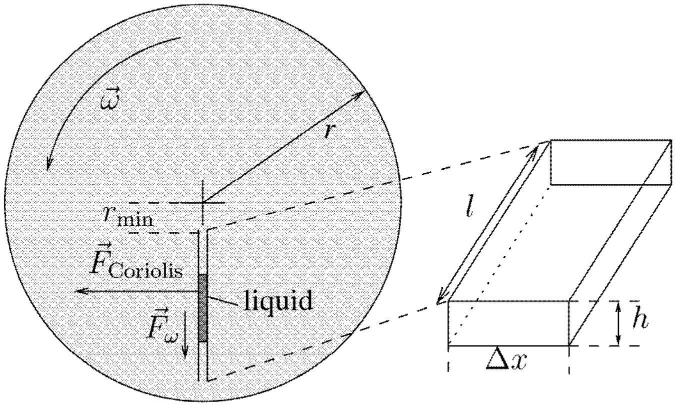

Figure 1: Geometry and forces on a disk spinning at the angular velocity $\vec{\omega}$ pointing out of the paper plane. The radial channel of length l, width Δx and height h starts at a distance $r = r_{\text{min}}$ from the center. The liquid traveling at a speed v is exposed to the centrifugal force $|\vec{F}_\omega| \propto \omega^2$ and, in the non-inertial rotating frame, to the (apparent) Coriolis force $\vec{F}_{\text{Coriolis}} \propto \vec{v} \times \vec{\omega}$.

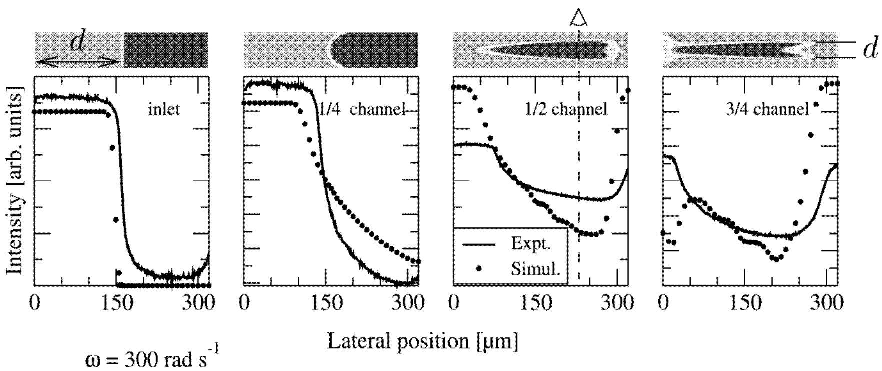

Figure 2: Experiments and simulation of Coriolis-induced mixing in a radial channel of length $l = 2\,\text{cm}$, starting at a radius of 2 cm from the center and rotating at $\omega = 300\,\text{rad}\,\text{s}^{-1}$, at different downstream positions. The intensities represent the integral concentration accumulated along the dashed line.

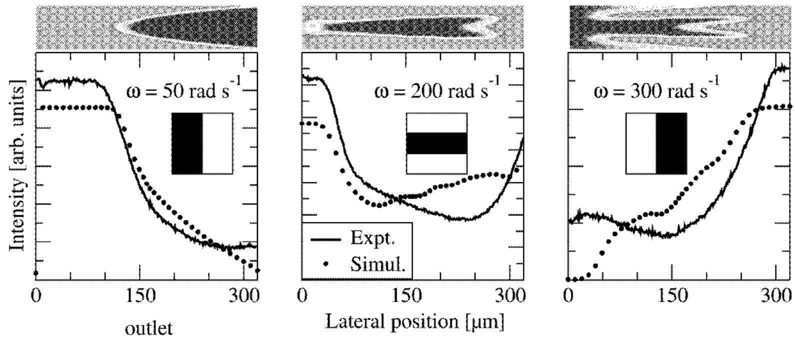

Figure 3: Experiments and simulation of flow profiles at the outlet of the 2-cm channel. At $\omega = 50\,\mathrm{rad\,s^{-1}}$, the flow is still widely undisturbed by F_{Coriolis}. Proceeding to $\omega = 200\,\mathrm{rad\,s^{-1}}$, a vertical stacking takes place. Reaching $\omega = 300\,\mathrm{rad\,s^{-1}}$, the order of the two flows is flipped and a large contact surface forms. This evolution is impressingly observed in the videos taken from the experiments.

in Fig. 2. Under the impact of F_{Coriolis}, the initially undisturbed flow pattern is increasingly deformed in downstream direction. At 3/4 of the channel length, the blue liquid has protruded far into the other liquid. In this vertical stack of thin liquid layers, the characteristic diffusion length d has been reduced by a about a factor of three to cut down diffusion times $t_D \propto d^2$ by a factor of nine in an ordinary, straight microchannel! It is obvious that this effect is even more pronounced towards decreasing (!) aspect-ratios which can easily be manufactured. Note the good qualitative agreement between the measurement and corresponding simulations.

Flipping and Laminating

Fig. 3 investigates the flow patterns recorded at a fixed location near the outlet as a function of ω. This way we can identify the channel length, its aspect ratio and the rate of rotation as the decisive impact parameters governing the Coriolis-induced reshaping of the contact surface. Based on these findings, we designed a novel split-and-recombine laminator by means of a simple microchannel geometry (Fig. 4). The two flows are initially split into three parallel subchannels to enable flipping at the end of the central channel. As the channels rejoin, an alternating ABAB pattern builds out which is immediately distorted by the strong Coriolis force. By cascading a series of n (e.g. 3) congruent laminators, it is obvious that the maximum layer thickness d (e.g. $100\,\mu\mathrm{m}$) is reduced by a factor of 2^{-n} (8) to accelerate mixing time t_D by a factor of 2^{-2n} (64)!

In conclusion, we have shown by simulations and experiments that switching,

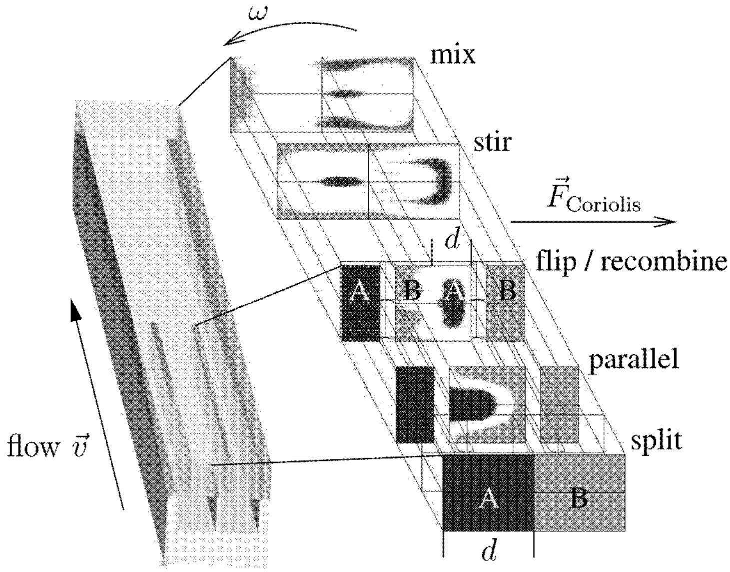

Figure 4: Split-and-recombine laminator (axial and transversal direction not to scale). The flows are divided into three parallel subchannels. The inversion of the flow pattern in the central channel leads to an ABAB alignment to increase the speed of subsequent mixing $t_D \propto d^2$ by a factor of four. To avoid high-aspect-ratio fabrication, the width of the fins can be extended without interfering with the mechanism of lamination.

lamination and substantially accelerated mixing of flow can be realized in simple 2.5-dimensional microchannels. This novel actuation scheme is based on the apparent Coriolis force which is inherent to centrifugal microfluidics. The components presented in this paper will play an important role for non-hydrophobic flow control on a novel lab-on-a-disk platform [3].

[1] G Ekstrand *et al.* In *Proc. μTAS 2000*, p. 311–314. Kluwer, The Netherlands.

[2] M J Madou and G J Kellogg. In *Proceedings of SPIE*, v. 3259, p 80–93, 1998.

[3] *Bio-Disk project* – WWW.BIO-DISK.COM, June 2003.