A FLOW SWITCH BASED ON CORIOLIS FORCE

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Abstract

This paper shows for the first time a flow switch which is controlled by the Coriolis force on a centrifugal „lab-on-a-disk" platform. The Coriolis switch consists of an inverse Y-structure with one common upstream channel and two symmetric outlets. Above a certain threshold frequency ω_0, the Coriolis force becomes dominant to direct nearly 100% of the flow in one of the outlets which is selected by the direction of rotation. The threshold frequency has been measured to be 350 rad s^{-1} for a channel width of 360 µm and a depth of 125 µm. The results are supported by extensive CFD simulations.

Keywords: centrifugal microfluidics, Coriolis force, flow control, switch

Introduction

Rotating disks have been introduced as convenient platforms which allow flow control based on centrifugal forces [1,2]. The centrifugal force creates an artificial gravity pointing in radial direction (Fig. 1). Flow control on these platforms is, for instance, achieved by capillary-burst valves which are hydrophobic patches blocking a flow until a specific angular speed is reached. So far, the impact of the pseudo Coriolis force has not been considered for those platforms despite the fact that the Coriolis force can prevail over all other forces beyond a certain speed of rotation. The effect is employed to realize a novel flow switch which is solely controlled by the Coriolis force.

Coriolis Force

In the Navier-Stokes equation describing the hydrodynamics of the fluid on the disk, the centrifugal term $\vec{f}_\omega = -\rho \cdot \vec{\omega} \times (\vec{\omega} \times \vec{r})$ represents the force density experienced by a liquid plug of density ρ within a channel in radial r-direction on a disk spinning at ω. The maximum velocity

$$v_{max} = \frac{\rho \cdot \omega^2 \cdot \bar{r}}{2 \cdot \eta} \cdot x_0^2 \qquad \text{with} \qquad \bar{r} = \frac{1}{2} \cdot (r_> + r_<)$$

of the centrifugally-driven flow results from the balance of viscous and centrifugal forces. The inner and outer spacings of the liquid plug from the center of rotation are denoted by $r_<$ and $r_>$. In order to allow a simple analytical treatment, a gap of a width $\Delta x = 2 \cdot x_0$ instead of a rectangular channel is assumed. η denotes the viscosity of the liquid. When the

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resulting flow is observed from a frame rotating at ω, i.e. with the disk at rest, an additional Coriolis force component $\vec{f}_{Coriolis} = -2 \cdot \rho \cdot \vec{\omega} \times \vec{v}$ appears in the non-inertial frame of reference. This force acts perpendicular to the plane spanned by the velocity $\vec{v}$ and the frequency of rotation $\vec{\omega}$.

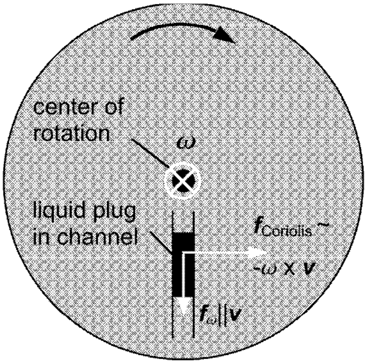

Fig.1: Forces acting on a liquid plug on a disk spinning at the frequency of rotation ω.

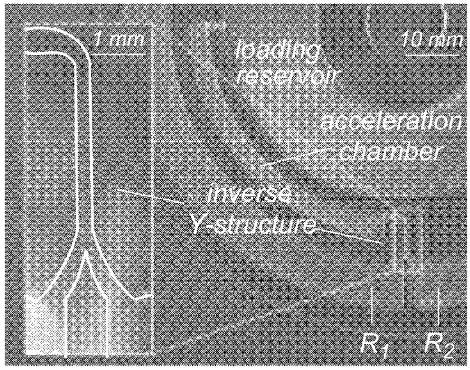

Fig.2: Sector of the test structure milled in a PMMA disk. The inverse Y-structure is zoomed out.

The ratio

$$\frac{|\vec{f}_{Coriolis}|}{|\vec{f}_\omega|} = \frac{\rho \cdot \Delta x^2 \cdot \omega}{4 \cdot \eta}$$

compares the centrifugal force in radial direction to the transversal Coriolis force. For the characteristics of water and a channel $\Delta x = 200$ µm, the ratio roughly amounts to $10^{-2}\omega$. This shows that for frequencies ω beyond 100 rad s^{-1} (≈ 1000 rpm), the Coriolis force prevails over the centrifugal force!

Experiments

The Coriolis effect is demonstrated by a switch that splits a flow through a radial channel via an inverse Y-structure into two reservoirs R_1, R_2 (Fig. 2). If Coriolis effects did not exist, 50% of the flow would be evenly distributed among the two outlets. However, a dominating Coriolis force would direct the flow into one addressed outlet. The influence of the Coriolis force can be measured by recording the filling heights in each reservoir which represent the integral over the flow. Potential effects resulting from the acceleration of the disk are ruled out by an acceleration chamber. This chamber which is situated downstream the loading reservoir fills during the acceleration phase of the disk. After steady state conditions have been reached, it overflows into the switch structure. The structures are fabricated in PMMA disks of standard CD-format by CNC milling and sealed by adhesive tape covering the full disk. Width and depth of the incoming channel have been determined to be 360 μm and 125 μm. The reservoirs and the acceleration chamber measure a depth of 900 μm. The filling heights in the outlets are observed under rotation by a sequence of captured images. A fast shutter camera (*PCO Sensicam*) is triggered by the zero crossing signal of the rotating disk and periodically records the flow into the outlets.

Simulations

To investigate the impact of the Coriolis force on the switching behaviour, extensive numerical simulations have been carried out using the commercial code ACE+ (*CFD-GUI Revision* 2002.2.16, *CFD-ACEU solver* Revision 2002.0.40) from *CFDRC*. The mere inverse Y-structure without any reservoirs is simulated in a reference frame rotating at the same speed as the disk, i.e., with the channels remaining at rest. The 3-dimensional simulations are carried out under steady-state conditions with fixed-pressure boundary conditions and no-slip condition at the walls.

Results and Discussion

The experiments clearly show that above a threshold frequency $\omega_0 = 350$ rad s^{-1}, the entire flow is diverted into one designated outlet channel defined by the direction of rotation (Fig. 3). This can also be seen by the velocity profile resulting from the simulations as depicted in figure 4. Since acceleration effects are ruled out, the switching of flow solely results from the transversal Coriolis force.

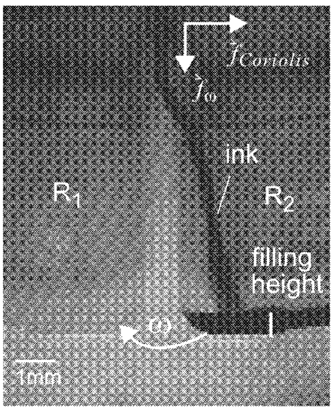

Fig.3: *Switched flow at* $|\omega|=350$ rad s^{-1}. *Ink solely streams into reservoir 2* (R_2) *by Coriolis force.* R_1 *remains unaffected.*

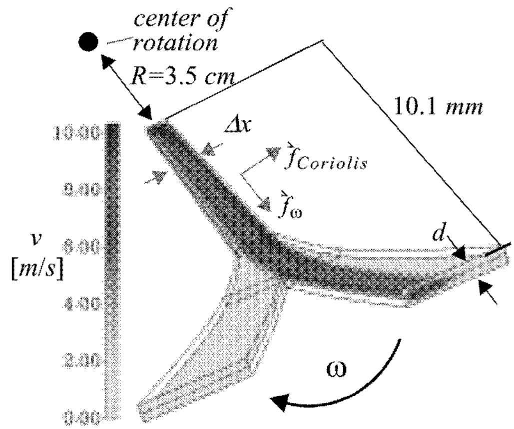

Fig.4: *Simulated flow in the inverse Y-structure* (Δx=360 μm, *depth* d=125 μm) *by Coriolis force at* $|\omega|=350$ rad s^{-1}.

In order to quantify the effect below the threshold frequency ω_0, the ratio of the filling heights γ is measured at different frequencies between 75 rad s^{-1} and 350 rad s^{-1} (Fig. 5). At frequencies below 75 rad s^{-1}, the Coriolis force is neglegible and the flow rates and filling heights are nearly equal ($\gamma \approx 1$). Towards higher frequencies, the filling heights change according to the increasing force $\vec{f}_{Coriolis}$ until the complete flow is diverted into one channel above 350 rad s^{-1}. Changing the direction of rotation fills up the other reservoir. The experimental filling ratios are in excellent agreement with simulated flow ratios of the outlets. However, small deviations at low frequencies are related to small asymmetries of the inverse Y-structure resulting from tolerances in the micromilling process. Simulations show that the threshold frequency ω_0 strongly depends on the channel depths d, since the velocity profile and thus $\vec{f}_{Coriolis}$ scales with d^2 (Fig. 6). An increase of d shifts ω_0 towards smaller values.

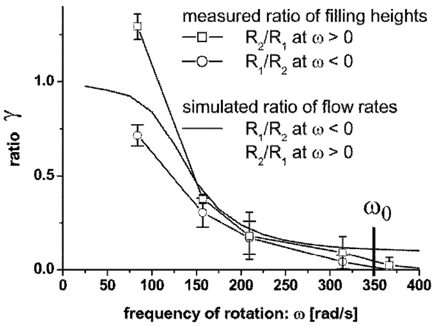

Fig.5: Ratios of measured filling heights and simulated flow rates at the outlets over frequency of rotation ω in both directions.

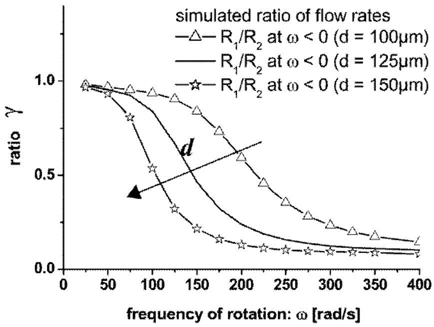

Fig.6: Simulated ratio of flow rates over frequency of rotation ω at different channel depths d (channel width Δx=360µm).

Conclusions and Outlook

The Coriolis force is the major force in rotating microchannels beyond a characteristic angular frequency depending on the channel geometry. The effect is used to switch a radial flow between two reservoirs. We currently work on implementing the hydrodynamic patterning of flow induced by the Coriolis force for realizing other on-disk flow control elements with simple 2.5-dimensional microstructures.

References

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