

Methods of energizing micro flows by acoustic and electric fields

F. Schönfeld*, D. Dadic*, J. Pinzón*, F. Schmitz**, M. Weniger*

* Institut für Mikrotechnik Mainz –(IMM), Carl-Zeiss-Str. 18-20, 55129 Mainz, Germany, schoenfeld-, dadic-, pinzon-, weniger@imm-mainz.de

** micromotive GmbH, Carl-Zeiss-Str. 18-20, 55129 Mainz, Germany, schmitz@imm-mainz.de

ABSTRACT

Generally, flow rectification of oscillating excited flows may occur when the governing equations show a substantial non-linearity. This can be exploited for pumping or micro mixing. The present work discusses two phenomena which show the above mentioned non-linear behavior: induced-charge electroosmosis and acoustic streaming. A particular variant of the latter relying on oscillating air slugs is investigated in close detail. First, a FEM-based model is developed to study the interplay between oscillating air and the adjacent liquid. Second, a simple experimental realization is presented which allows to achieve efficient mixing of continuous liquid streams and more important minute liquid slugs. The chosen approach allows to realize active micro mixing in disposable fluidic chips attached to a sound generator.

Keywords: Micro mixing, Flow rectification, Acoustic streaming

1 INTRODUCTION

Pumping and mixing of liquids are paramount tasks in the development of μ -TAS and Lab-on-a-chip (LOC) systems as well as in micro chemical process engineering [1]. Although, in case of mixing, various favorable passive μ -fluidic concepts have been developed in the past showing a logarithmic dependence of the mixing length on the Peclet number due to the induced chaotic flow, smart, simple and compact solutions are still lacking for many practical applications. Typical biological LOC applications require the mixing of minute liquid slugs. However, common droplet-based mixing methods such as utilizing meandering channels for slug flows which induce a kind of baker's transformation (see e.g. [2]), are adversarial. Due to the intense sample-to-wall contact, inevitable in this approach, unwanted binding of sample molecules to the wall may occur. Moreover, many passive mixing concepts do not ensure a complete drainage of the channel structures when finite liquid slugs are processed.

Active mixing concepts have the potential to overcome these drawbacks. In this regard - as with respect to μ -fluidic pumping - the question arises how to couple 'external' energy or momentum into the liquid. Here we present two different concepts which rely on the coupling of electromagnetic or acoustic energy into liquid. To begin with, what do these seemingly rather different approaches

have in common? In both cases we are faced with alternating fields – voltage and pressure, respectively. In order to induce a *directional averaged* flow by means of the oscillating fields essential non-linearities in the governing equations are exploited. In case of electromagnetic energy input, such a non-linearity comes into play due to the so-called induced-charge (IC) electroosmotic flow (EOF) [3]. Here, ICEOF and a possible realization is only very briefly discussed (sect. 2). Section 3 is dedicated to acoustic energy input, where the simulation approach, experimental results and possible further applications are discussed in detail. We conclude with a summary and outlook in sect. 4.

2 INDUCED-CHARGE EOF

An electrical field applied to an immersed conducting body surrounded by an electrolyte causes accumulation of charges at the liquid/solid interface leading to a dipolar charge distribution. Within the conductor the external field is compensated due to its polarization. The polarization charges at the end faces cause double layer formations of respective counter charges. Thus the induced ζ -potential has opposite sign at the surfaces facing the anode and cathode, leading to opposing EOF velocities at both sides (see [3] and references therein). The induced EOFs show a quadratic dependence on the applied field. In particular the flow direction is independent of the field polarization and thus leads to a rectification in case of AC EOF.

Here, we investigate a circular bypass geometry shown in Fig. 1 [4]. The bottom face comprises two conducting segments which are not electrically contacted to the exterior for the induced ζ -potential to develop. Within an external field the conducting segments are polarized and surface charges accumulate. This leads to EOFs which are locally opposed to the global EOF direction.

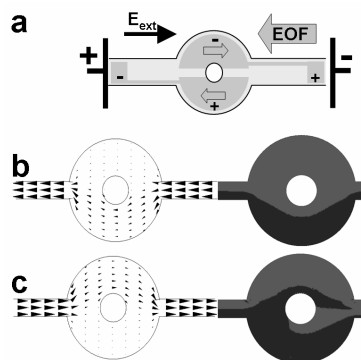


Figure 1: a: circular bypass for the induction of a vortex flow; conducting elements at the bottom side of the channel are shown in dark gray; b,c: ICEOF induced slip velocities and concentration fields indicating the vortex.

Since the local ICEOFs depend on the squared external potential, the corresponding flow direction remains unchanged if the voltage is reversed. Thus, for an alternating voltage the global EOF averages out, while the circulating flow survives. Respective FEM simulations are shown in Fig 1 [4]. Corresponding experiments are currently undertaken.

3 ACOUSTIC STREAMING

Acoustic streaming relies on the fact that periodic motion is rectified by the inertial non-linearity of the governing Navier-Stokes equations. In order that the non-linear terms have an effect in a microfluidic system, the small feature size must be ‘compensated’ by sufficiently high frequencies (see [3] and references therein). In the following subsection we discuss the numerical simulation of such scenarios. Subsequently, experimental set-ups and results are discussed utilizing similar approaches for continuous mixing and mixing within finite slugs.

3.1 Theory and Simulation

One, especially simple appealing realization of such an acoustic pump has been presented, by Dijkink et al. [5]. The basic working principle relying on the asymmetry of flow exiting and entering a tube is shown in Fig. 2. For not too low Re the liquid exits the tube as a jet while it enters almost isotropic from the half solid angle. Thus, averaging over a cycle of an oscillating flow one finds a net momentum input from the tube into the liquid.

Utilizing acoustics, i.e. an oscillating pressure field, for the flow generation one has to assure that a sufficiently large amplitude is provided. This can be readily achieved by exciting a gas volume with an oscillating pressure close to its resonance frequency. Fig. 3 shows a FEM model of the realization presented in [5]. Basically the model represents a Helmholtz resonator [6], where the oscillating mass is approximately given by the liquid volume confined

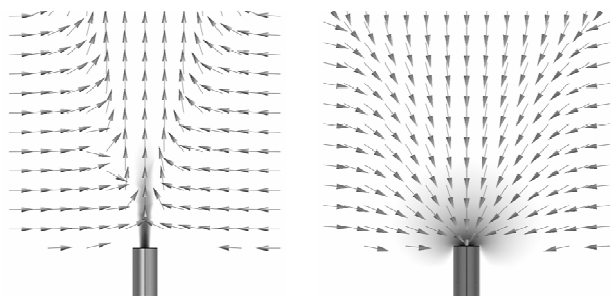


Figure 2: FEM simulation of steady flow fields exiting and entering a capillary. The Reynolds number related to the capillary diameter is 75. Arrows denote the normalized velocity field. The velocity magnitude is grayscale encoded.

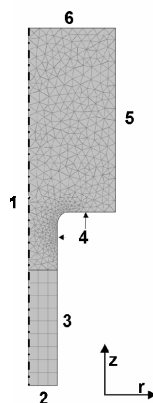


Figure 3: FEM model for simulation of fluid dynamics induced by an oscillating air bubble. The upper part (unstructured mesh) represents the liquid domain while the lower part (structured mesh) describes the compressible gas. Boundary conditions are applied as follows: 1 radial symmetry; 2 fixed; 3 free along z-direction, r fixed; 4 no-slip; 5,6 pre-defined oscillating pressure

in the tube and the confined gas volume is excited by an alternating pressure field. In order to facilitate the simulation we employ the fluid-structure interaction module implemented in COMSOL [7]. For the structural part (lower part with regular mesh in Fig. 3) to resemble entrained air the Young module was set to $1.18 \cdot 10^5$ Pa and the Poisson ratio was set to zero. So the solid material is defined as fully compressible with a speed of sound equaling $c_{\text{air}} = 344$ m/s. Water like fluid properties have been applied in the upper part of the model. The coupling between both domains occurs via the moving boundary which models the interface between water and air. A possible deformation of the interface or advanced models for resolving the viscous stress singularity at moving contact lines are not taken into account. Within the given framework structural properties as well as the dynamics of the flow field was analyzed. Exemplarily, typical flow fields and a resonance curve are shown in Fig. 4. The left hand side of the figure shows snapshots of the velocity fields within an oscillation cycle. The right hand side shows data of the oscillation amplitude as function of the excitation frequency. A Lorentz fit (dashed line) yields a resonance frequency of 1076 Hz. Within the simplified model of a Helmholtz resonator one finds a resonance fre-

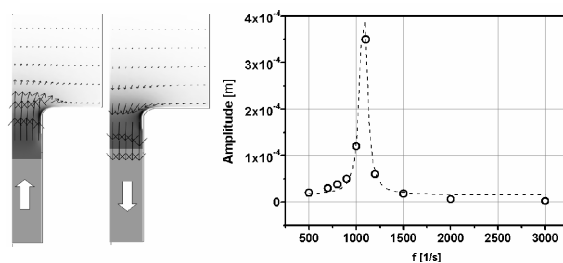


Figure 4: Fluid-Structure interaction simulation results of the model shown in Fig. 3. The tube and bubble lengths are, 3 mm and 2 mm, respectively, the tube diameter was set to 1 mm. Left: Flow fields arising from an expanding and contracting bubble as denoted by the open arrows. The grayscale denotes the velocity magnitude. Right: Simulated resonance curve (circles) and fit of a Lorentz curve.

quency of about 1300 Hz, which reduces to about 1170 Hz if an effective slug length is introduced adding an extra length of 0.6 times the tube radius to the geometric liquid slug length in the tube. As a further benchmark the force on the bottom boundary (2 in Fig. 3) was computed and compared to experimental values given in [5]. Here, the FEM model reproduces the experimental results within the scatter of the data. From both validations we conclude that the physics is covered with a sufficient accuracy in the numerical model. Hence, the simulation approach is appropriate to design more complex resonant-bubble devices, which is the subjected to future work.

3.2 Experiments

Several acoustic-driven micro mixers have been reported so far (see e.g. refs. given in [5]). Yet, especially in the case of acoustic actuation in polymer μ -fluidic systems the transducer/liquid coupling is not trivial due to impedance mismatches and among others relative complex set-ups have been reported. Here, we aim at a simple and yet reliable set-up which allows the use of disposable polymer chips in combination with a piezo actuator to be mounted in the respective LOC handling system. Fig. 5 shows the set-up as used in the preliminary experiments of the present study for continuous mixing and for mixing of finite slugs.

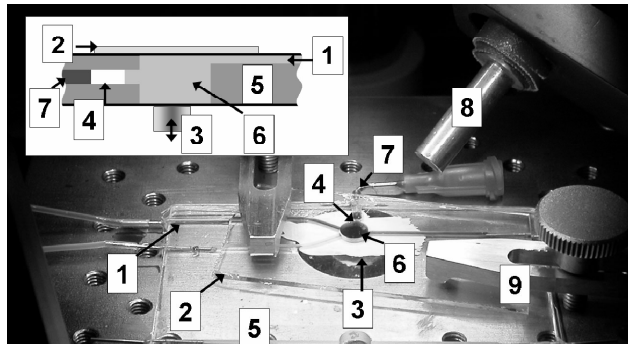


Figure 5: Experimental set-up. The inset shows a schematic of the cross section. 1 inlet channels; 2 glass cover plate; 3 piezo actuator; 4 air entrainment; 5 COC chip with polymer membranes bonded on both sides; 6 mixing chamber; 7 sealing to keep and adjust the air entrainment; 8 light source; 9 fastener.

Continuous mixing: To begin with, mixing experiments with continuous feeding of liquid streams have been conducted. Using blue and yellow dyed liquid streams mixing was analyzed by monitoring the color intensity in the mixing chamber. Fig. 6 shows a series of consecutive snapshots. The shown mixing chamber has a diameter of 5 mm and a height of 2 mm. Following the approach in [5] an air slug (length about 3 mm) was confined in a Teflon tube (4 mm length, $d_i = 0.25$ mm).

The piezo actuator (Physik Instrumente (PI) GmbH & Co. KG, Germany) was driven with voltage and frequency of 20 V and 700 Hz, respectively. The time span between subsequent images was 50 ms and the total applied flow rate was 0.05 ml/min. From the micrographs shown in Fig. 6 a characteristic mixing time below about 100 ms can be read off. Moreover, the momentum input of the oscillating slug is clearly visible in the upper right image. Thus, the observed mixing is solely induced by the oscillating bubble and not by spurious acoustic streaming effects which are expected to arise mainly at higher frequencies. Finally we note that the shown recirculation could be readily repeatedly induced after e.g. interchanging the polymer chip and reassembling the set-up. A fine tuning of the system parameters such as the frequency is not required, as long as the applied frequency lies between about 500 Hz and 1500 Hz.

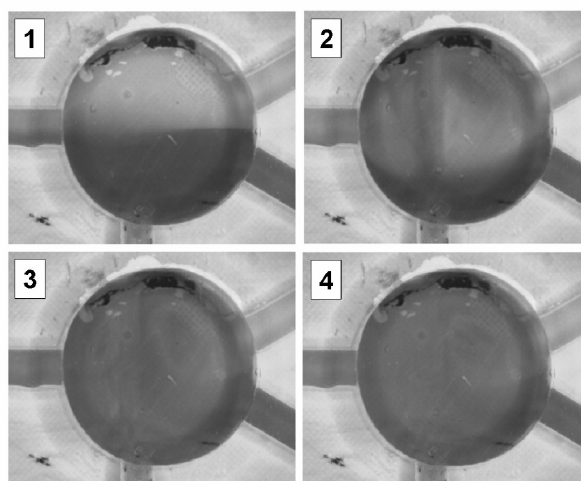


Figure 6: Consecutive micrographs showing the formation of oscillation-induced recirculation fields and corresponding mixing of continuously fed liquid streams. The time span between subsequent images is 50 ms. The air entrainment (not visible) is confined in a tube shown at the lower part of each image. The flow direction is from right to left.

Mixing of liquid slugs: While, a huge number of mixing concepts have been developed for continuous liquid streams (see e.g. [1]) fast mixing of finite slugs still remains challenging. This is especially true in cases where the mixture to wall contact has to be minimized, such as in case where a PCR master mix is to be mixed with a sample containing only a few amplifiable strands. If the sample slug has to be pushed through a long channel to achieve a sufficient mixing the risk of unspecific binding of sample molecules to the wall is increased. In contrast, by means of oscillation-induced vortices sample and PCR mix can be stirred right after contacting. Fig. 7 (left) shows one of the channel geometries used in corresponding experiments. A liquid volume of about 30 μ l is placed in the bulged channel section kept in place by means of smooth channel constriction at both sides. In the present experiment two air

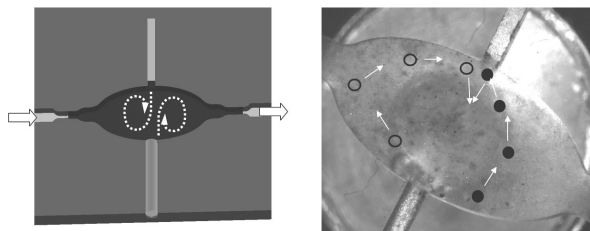


Figure 7: Left: Sketch of the polymer chip used for the experimental investigation of oscillation-induced vortices in liquid slugs. The slug volume (black) is about 30 μl and the depth of the bulged channel is 1 mm. Right: Characteristic recirculating particle trajectories derived from a video. Two air entrainments confined in a rectangular channel (lower vertical lines) and in a circular hole (upper vertical lines) have been used.

volumes were simultaneously utilized both contained in dead-end channels of rectangular (lower vertical line in Fig 7) and circular (upper vertical lines in Fig 7). Here, graphite particles suspended in water have been used to visualize the flow field. Fig. 7 depicts characteristic particles trajectories which are clearly visible in the video recorded during the experiment. The quantification of the induced mixing by means of a chemical reaction is subjected to future work.

4 SUMMARY AND OUTLOOK

Oscillating fields can induce a directed time averaged motion due to rectification by non-linearities in the governing equations. The present work highlights two possible physical mechanisms for flow rectification: ICEOF and acoustic streaming. The former is exemplified by FEM simulations taking a circular bypass channel geometry as an example. Corresponding experiments are yet to be performed. The main part of the presented work focuses on flow rectification caused by the non-linear inertial term in the Navier-Stokes equation. Motivated by the pumps mechanisms investigated in [5] oscillating air slugs are considered to develop a simple and yet reliable realization of an active disposable micro mixer.

Using, the fluid-structure coupling provided by the commercial FEM solver COMSOL a simulation approach has been implemented and validated. The numerical simulation reliably predicts resonance frequencies, damping and momentum input in the studied models. Next, experiments with respect to continuous mixing and mixing of minute sample plugs have been conducted, proving that fast and thorough mixing is achieved in a simple set-up featuring a direct coupling of a disposable polymer LOC system and the piezo actuator. Future work is dedicated to quantitative evaluation of the approach using chemical reactions, to miniaturization and to integration of the approach into complex disposable LOC systems.

Finally, we mentioned that a miniaturized analogue of a magnetic stirrer could be realized based on the above mentioned principle. Since the magnetic force scales with

the characteristic volume, such stirrers become inefficient within microfluidic systems. Moreover, the required external magnetic field renders its use in context with handling of magnetic bead suspensions impossible. By contrast, consider a section of a tube as shown in Fig. 8. The tube contains an air slug (not shown), which arises naturally if a poor wetting wall material is chosen and the tube is immersed in a liquid. Alternatively the tube may contain two such slugs separated by a wall in the centre. If the immersed tube experiences an acoustic field (oscillating pressure) it will spin due to the inclination of the both faces at its ends. The spinning could be utilized for mixing the same way magnetic stirrers are used for mixing of macroscopic batch systems. The investigation of this approach is subjected to future investigations.

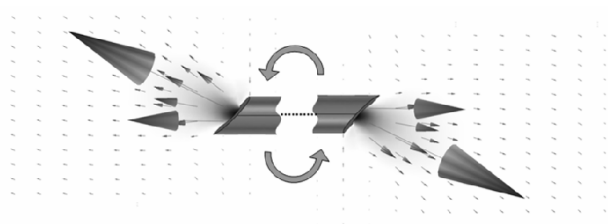


Figure 8: Sketch and preliminary simulation of an acoustic stirrer. As above, an oscillating air bubble induces a flow field which is rectified due to the asymmetry between exiting and entering fluid flow. The inclined end faces lead to an off-axis momentum input causing the tube to spin.

ACKNOWLEDGEMENTS

This paper partly describes work undertaken in the context of EC IST project 027652 MASCOT. The IST programme is partially funded by the European Commission. The authors would like to acknowledge the contributions of the consortium participants (<http://www.imec.be/mascot>). Moreover, FS acknowledges financial support by the DFG-Forschergruppe FOR 516/1

REFERENCES

- [1] S. Hardt, K.S. Drese, V. Hessel, F. Schönfeld, *Microfluidics Nanofluidics* 1 (2), 108 – 118, 2005.
- [2] H. Son, D. L. Chen and R.F. Ismagilov, *Angew. Chem. Int. Ed.* 45, 7336-7356, 2006.
- [3] T.M. Squires, S. Quake, *Rev. Mod. Phys.* 77, 977-1025, 2005.
- [4] F. Schönfeld and S. Hardt, *Proc. Micro TAS 2005*, Boston, MA, 581-583, 2005.
- [5] R.J. Dijkink, J.P. van der Dennen, C. D. Ohl, A. Prosperetti, *J. Micromech. Microeng.* 16, 1653-1659, 2006.
- [6] <http://www.phys.unsw.edu.au/jw/Helmholtz.html>
- [7] www.comsol.com