EFFECTIVE MIXING OF LAMINAR FLOWS AT A DENSITY INTERFACE BY AN INTEGRATED ULTRASONIC TRANSDUCER

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ABSTRACT
An acoustic mixer for glass channel microfluidic systems is presented. An acoustic standing wave, perpendicular to the fluid flow, is generated by the excitation of a miniaturized piezoelectric transducer operated around 10 MHz. The mixing occurs at a fluid-fluid density interface due to the acoustic radiation force; an analytical expression is derived to qualitatively describe this phenomenon. Only a density difference in the range of 2-5 % is required to achieve effective peak broadening of a fluorescent sample between sheath flows.

KEYWORDS: Mixing, Density difference, Acoustic, Transducer

INTRODUCTION
Microfluidic systems with channel dimensions from a few microns up to several hundreds of microns possess the property of having complete laminar flows, due to low Reynolds number. Laminar flows are mostly considered advantageous and constitute an important cornerstone within microfluidics, since this makes it possible to predict in a very precise manner where molecules are transported within the system. In the absence of specially designed mixing structures, mixing in these laminar-based flow systems is only accomplished by passive interdiffusion between the fluids. However, many reactions and analyses require well-mixed fluids and to reduce the analysis time of a miniaturized system, the mixing becomes a key unit operation. On-chip applications include e.g. enzyme reactions, cell lysis, immunoassay interactions and hybridization reactions.

The system evaluated here utilizes the acoustic radiation force on an interface between two liquids with different density and this interface is oriented parallel to the wave propagation in a standing wave cavity operated around 10 MHz. At this operation frequency, viscous absorption losses in the fluid are small and the frequency enables resonance in the fluid. Resonance in the fluid generates high acoustic amplitudes that are useful in employing acoustic forces in general. The lateral dimensions of the transducer (900*900 µm) enable local activation in a small area of the channel, thereby allowing the handling of small sample volumes with small dead volume.

THEORY
A theoretical description of the radiation force has earlier been presented by Rozenberg, however for a density interface perpendicular to the wave propagation direction. In analogy, we have derived an expression for the present system, i.e. where the radiation force acts on an interface parallel to the direction of the wave propagation, between liquids of different density. In summery, the maximal radiation force
on an interface of fluid 1 and fluid 2 parallel to the wave propagation may be expressed as

\[
\frac{F_{r_{1-2}}}{A} \bigg|_{\text{max}} = \frac{Q_{SW} \langle P_{a1}^2 \rangle_{\text{max}}}{2 \rho_{01} c_{01}^2} - \frac{Q_{2} \langle P_{a2}^2 \rangle_{\text{max}}}{2 \rho_{02} c_{02}^2} = \frac{v_r^2}{2} Q_{SW} \left( \rho_{01} - e^{-\frac{-(f_2 - f_{SW})^2}{4 \ln 2}} \rho_{02} \right)
\]

for the case where the fluid 1 is supporting the standing wave. \(Q_{SW}\) is the Q-value supporting the standing wave, \(P_a\) the pressure amplitude due to the acoustic field, \(\rho_0\) the density of the medium, \(c_0\) the speed of sound, \(v_r\) the velocity at the transducer-fluid interface and \(f\) the channel frequency. Viscous forces were ignored for simplicity.

**EXPERIMENTAL**

A schematic view of the device is shown in Figure 1a and 1b. Miniature single layer PZT-ultrasound transducers, 900×900×200 µm, were integrated into the bottom channel wall. The channel-reflector structure was fabricated by wet etching borosilicate glass wafers to a reflector thickness of 923 µm and 71 µm channel depth. The glass-PCB device was sandwiched between two brass plates and pressure sealed by screwing the upper and lower plates tightly together.

![Figure 1. Schematic image and photo of the device having three integrated acoustic transducers for fluid mixing.](image)

**RESULTS AND DISCUSSION**

A typical intensity profile for a set-up with lower-density middle flow and the mid-channel transducer is displayed in Figure 2a. The middle fluid is fluorescently labeled with Rhodamine B. The transducer was run with a driving frequency of 10.3 MHz and the system had a total fluid flow of 3 µL min\(^{-1}\) (0.7 mm s\(^{-1}\)). A mixing sequence above the transducer is shown in Figure 2b with 60 ms between the images, the fluids entering the system from the right. It is evident that the mixing starts from...
the interface surfaces and moves the lower-density fluid into the higher-density fluid, in agreement with the proposed theory, provided that the channel is matched for the lower-density fluid. The fluid convection of the lower-density fluid is fastest at four positions on either interface, Figure 2bii, which corresponds to the spatial pattern of the pressure amplitude in the acoustic near field. At the next stage, Figure 2biii, the fluid moves in the direction normal to the interface created by the initial mixing movement. The convective motion proceeds until the density difference is equalized, Figure 2bvi. Analyzing the mixing speed at a position 500 µm downstream the transducer, the main part of the mixing, 80%, occurred within 0.36 s and the mixing was completed after additional 0.72 s.

CONCLUSIONS

We present an effective mixing device for microfluidic applications. It is shown that the acoustic radiation force generated by an integrated piezoelectric transducer acts on the fluid density interface parallel to the wave propagation direction. A density difference between the sample and sheath fluids of 4.5 % yields a mixing efficiency of 400 % peak broadening for the case of a lower-density middle flow. For this standing wave mixer, no acoustic streaming was observed. Compared with mixing induced by acoustic streaming it is advantageous that this mixing is not caused by acoustic absorption losses, especially when temperature increase in the channel is critical.

REFERENCES