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ACTIVE MANIPULATION OF INHOMOGENEOUS MISCIBLE FLUID INTERFACES USING ACOUSTICAL TWEEZERS

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ABSTRACT

The manipulation of immiscible fluids at microscales has paved the way for a wide range of applications and technologies. In particular, ultrasounds serve as versatile tools for manipulating dispersed immiscible droplets. By shaping the acoustic field, droplets can be sorted, divided, merged, selected, and positioned. Typical approaches involve standing waves to attract and trap droplets at fixed pressure nodes/antinodes or traveling waves to displace droplets in the direction of the ultrasound wave propagation. Recent advancements have enabled precise manipulation of selected droplets using selective acoustic tweezers based on focused beams, or acoustical vortices. However, the ultrasound-based manipulation of miscible fluids has only recently been demonstrated theoretically by Karlsen, Augustsson, and Bruus [1]. In this case, the manipulation results from an acoustic force density appearing due to the inhomogeneity in density and sound speed between the two fluids. In this work, we experimentally demonstrate the application of acoustic tweezers to pattern, trap, and displace high-concentration miscible-fluid islands (Ficoll-PM400) within a lower-concentration medium (water) using ultrasounds. This research establishes the basis for ultrasound-based drug and chemical manipulation, with diverse applications in biology and medicine.

Keywords: *Microfluidics, Acoustofluidics, Acoustic vortices, Acoustic tweezers, Miscible fluids.*

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1. INTRODUCTION

Acoustic tweezers have risen to prominence as a highly effective means for the accurate and selective manipulation of microparticles and microorganisms [2, 3], capitalizing on two non-linear physical phenomena: acoustic radiation pressure and acoustic streaming [4]. These tweezers provide considerable benefits compared to optical and magnetic alternatives, including the generation of substantial forces [5] without causing harm to the biological cells under investigation [6]. Owing to ultrasonic sources that cover a wide frequency range from kilohertz to gigahertz, acoustic tweezers are increasingly favored for their ability to manipulate, separate, trap, and sort particles and cells [7]. The versatility of acoustic tweezers has motivated researchers to explore their applicability in controlling fluids within microfluidic systems. Recent investigations have emphasized the proficiency of ultrasonic waves in carrying out an array of droplet manipulation techniques, encompassing droplet manipulation [8], micropumping [9], jetting [10], mixing [11], and atomization [12]. In addition, researchers have delved into the deformation of immiscible fluid interfaces [13, 14]. Manipulating miscible fluid interfaces remains an unsolved challenge, despite the significant advances in microfluidics. While the active manipulation of immiscible fluids has led to the development of digital microfluidics [15],

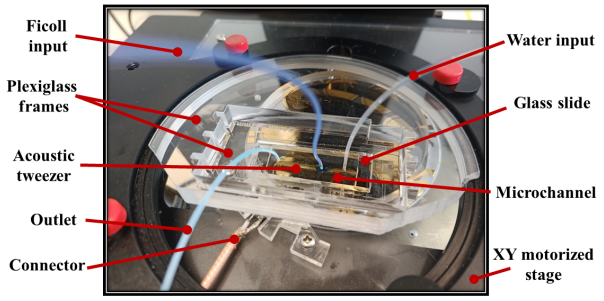

Figure 1. Microchannel positioned on top of an acoustical tweezer. The microchannel is fixed in a plexiglass holder and can be moved with a motorized stage.

there is a need for a new tool to enable active manipulation of miscible fluids. If such a method were to be established, it could open up new possibilities in microfluidics for applications.

In this study, we experimentally demonstrate the capability of acoustic vortices in patterning, trapping, and displacing high-concentration miscible-fluid islands (Ficoll-PM400) within a lower-concentration medium (water).

2. METHODS

2.1 Experimental setup

The key components of our experimental setup described in Fig. 1 are a microchannel and our custom acoustical tweezers. The microchannel can be moved with respect to the tweezers using a highly accurate (100 nm) XY Thorlabs motorized stage. The complete experimental setup is integrated onto a (Nikon Ti2E) optical microscope, as sketched in Fig. 2. Videos are recorded with a sCMOS Prime-BSI photometric camera at a rate of 20 frames per second. The start of the recording triggers (via the intermediate of a single-channel (Tektronix AFG 30516) signal generator generating a 20 s square signal) an IFR 2023A frequency generator, which operates at an amplitude of 5dBm and driving frequency of 17.3 MHz. The signal is further amplified by an (AR50A250 150 W) amplifier leading to a substrate vibration of amplitude of 5 nm, and thus a maximum pressure magnitude of the order $\sim$ 0.8 MPa (estimation provided with the plane wave approximation).

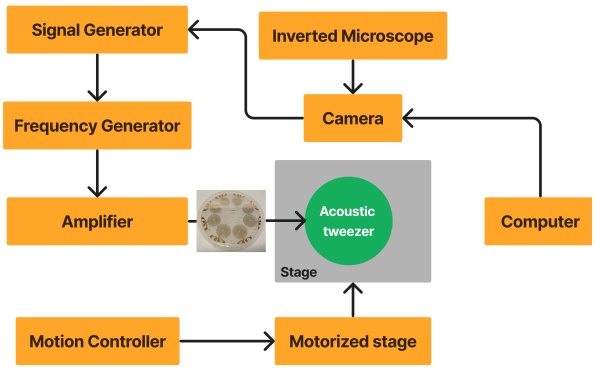

Figure 2. Diagram of the different components of the experimental setup.

2.2 Acoustic tweezers & microchannels fabrication

The 17.3 MHz tweezers feature spiralling metallic electrodes patterned on a 0.5 mm thick, 3-inch lithium niobate piezoelectric substrate with photolithography and metal sputtering. The photolithographic technique involves cleaning the substrate, applying an adhesion promoter (HMDS) and negative photoresist, curing, and transferring the tweezers' patterns using an optical mask and UV aligner. After developing, the wafer is coated with titanium and gold layers, followed by a lift-off process. A borosilicate glass wafer is attached to the piezoelectric substrate using optically transparent epoxy glue (EPOTEK 301-2). Chromium markers are deposited on the glass wafer for vortex center localization.

The 40 µm thick microchannels were fabricated in PDMS with classic photolithographic technics using SU8 2035. The microchannel features two distinct inlets, with one being designated for the introduction of Ficoll and the other for water, alongside a single outlet for the resultant fluid mixture. Notably, the channel width at the location of tweezer activation measures 1.5 mm.

2.3 Experimental procedure

A solution of 20% (w/w) Ficoll PM400 in water is prepared and dyed using Methylene blue. Using syringe pumps, the Ficoll solution is injected into the microfluidic chip in co-flow with pure water. As soon as a straight and stable line of Ficoll inside the water phase is created (see Figure 3 A), the syringe pumps are stopped and the camera and acoustical tweezer are actuated.

2.4 Post-processing

Before post-processing, we have conducted supplementary experiments to establish a correlation between the Ficoll concentration and the image gray value. We have then translated the recorded gray color images into concentration percentage images. This allowed us to compare the Ficoll concentration at the center of the tweezer to the Ficoll concentration on a ring around the center (placed at about the first pressure maximum); see also Fig. 3.

3. RESULTS

3.1 Patterning concentration fields

The activation of the acoustic tweezer system generates patterns at the interface between the 20% Ficoll solution and pure water as illustrated in Figure 3. Our experimental observations reveal that the denser fluid is drawn towards the acoustic field's minima, while the lighter fluid accumulates at the maxima. This behavior is also predicted numerically using a height-averaged 2D model of the system, based on Karlsen and Bruus [16], thus confirming that our experimental outcomes using tweezers with topological order $l = 1$ align with theoretical predictions.

To investigate the distribution of concentrations during the pattern formation process, we calculate the concentration differences between the Ficoll center and a circular region of the first pressure maximum. As expected, the concentration difference increases upon activation of the tweezer (panels B, C, D), signifying the redistribution of water to pressure nodes and Ficoll to pressure antinodes. After reaching a fully formed pattern (panel E), a gradual decrease in concentration difference is observed, indicating the inevitable process of diffusion (panel F). Panel G displays the time-evolution of the concentration difference between the central point and the average concentration surrounding the first pressure ring, as deduced from panels A to F. The plot, furthermore, includes the time-evolution of the concentration difference for a corresponding numerical simulations, which is confirming the experimental trend.

3.2 Translation of a local high-concentration region

Karlsen et al. [16] investigated numerically the feasibility of capturing and manipulating a localized high-concentration area using an acoustic vortex of topological charge $l = 1$. In these simulations, a 30% iodixanol high-concentration region could be moved within a 10%

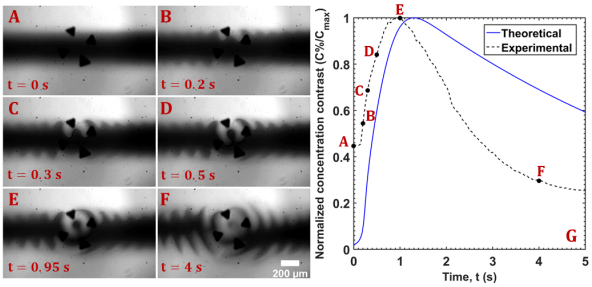

Figure 3. Acoustic patterning of dyed Ficoll PM400 and water, observing the evolution of the interface from stage A to stage F at 4 seconds. Panel G demonstrates the normalized concentration variation.

iodixanol lower-concentration medium for about 0.9 seconds before diffusion effects take over. In our research, we experimentally demonstrate that trapping and manipulating a highly concentrated region (20% Ficoll solution) in a low concentration solution (water) is indeed possible, see Fig. 4. Upon activating the acoustical tweezers, we moved the microchannel using an XY motorized platform, allowing the trapped Ficoll solution to move simultaneously. Panel D effectively portrays the shifted Ficoll phase in the center of the tweezer, while E emphasizes the considerable influence of diffusion on the trapped region. The entire procedure, leading to total dissolution, spanned approximately t= 5.8 seconds.

4. CONCLUSION

This work showcases the ability of acoustical tweezers to pattern and manipulate miscible fluids. The patterning corresponds to the relocation of the concentration field according to the ring patterns of the pressure field. For the manipulation, we have showcased the possibility of capturing a high Ficoll concentration area and temporarily transferring it to a lower concentration medium before diffusion occurs in the trapped region. This research holds promise for various fields, such as enhanced drug delivery systems, biotechnology, and artificial fertilization.

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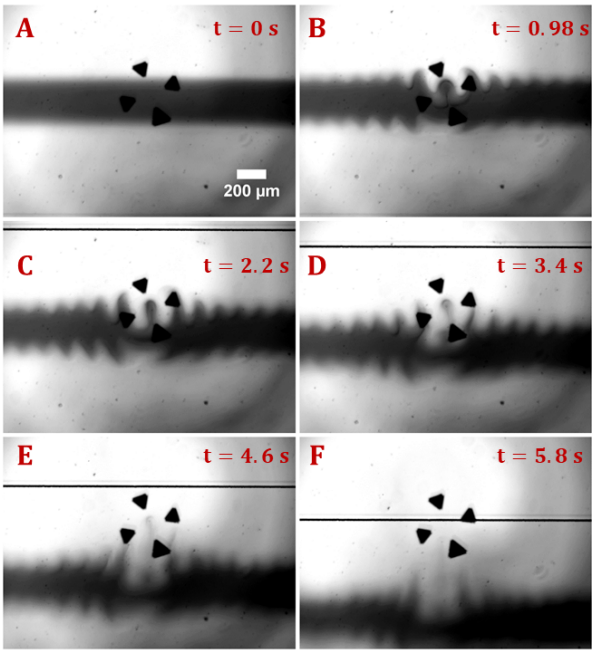

Figure 4. Trapping (A-B) and translational movement (C-F) of Ficoll 20% through water.

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