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Controlling the acoustic streaming by pulsed ultrasounds

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ABSTRACT

We propose a technique based on pulsed ultrasounds for controlling, reducing to a minimum observable value the acoustic streaming in closed ultrasonic standing wave fluidic resonators. By modifying the number of pulses and the repetition time it is possible to reduce the velocity of the acoustic streaming with respect to the velocity generated by the continuous ultrasound mode of operation. The acoustic streaming is observed at the nodal plane where a suspension of 800 nm latex particles was focused by primary radiation force. A mixture of 800 nm and 15 μm latex particles has been also used for showing that the acoustic streaming is hardly reduced while primary and secondary forces continue to operate. The parameter we call "pulse mode factor" i.e. the time of applied ultrasound divided by the duty cycle, is found to be the adequate parameter that controls the acoustic streaming. We demonstrate that pulsed ultrasound is more efficient for controlling the acoustic streaming than the variation of the amplitude of the standing waves.

1. Introduction

Particle manipulation by using ultrasonic standing waves (USWs) in microfluidic devices is ubiquitous in bioseparations, characterization and analysis of micron-sized species. A great number of publications have been highlighted the utility of USW by showing how particles, cells, bacteria and other non-colloidal materials can be affected by acoustic radiation forces in very different manners [1–10]. Primary radiation forces generate levitation of species at the nodal plane in a resonator; inhomogeneity of the transversal energy distribution and non-idealities in geometry of the resonator may lead particles to agglutinate at the nodal plane [10–12]. Secondary Bjerknes forces may keep aggregates consolidated and stable [13,14]. Finally, acoustic streaming may generate clumps and recirculation of particles at nodal planes [15–19]. Aggregation of cancer cells for instance, can be generated in cylindrical resonators in order to study physiological cell interactions [20]. Acoustic focusing in microfluidic channels allows generating separations in function of size and acoustic impedance [3,5,10] and acoustic levitation has demonstrated the possibility of enhancing spore capture into an immune-coated surface [21].

It is well known that species bigger than 2–3 μm are easily trapped by an USW namely, can be focused at the nodal plane of the standing wave and kept closely immobile [22]; isolated particles, as well as 2D and 3D aggregates, can be kept in stable levitation [23]. When species become smaller than ~1 μm, Brownian agitation becomes not negligible and acoustic and thermodynamic forces enter in competition for establishing a steady state after a relaxation time. Nevertheless, the well-known phenomenon called acoustic streaming (AS), in this study we are dealing with Rayleigh streaming [19,24], becomes visible when a suspension is composed of sub-micronic particles, thus displacements of fluid may drag the species over the whole volume of the resonator modifying thereby the thermodynamic equilibrium. Several works have been devoted to the observation and description of the acoustic streaming in microfluidic devices [15,25–27].

AS is always present when the acoustic radiation pressure generated by USW is operating, but primary radiation forces veil it when micron-sized species are manipulated. Several works have visualized the AS by using particle image velocimetry, (PIV) [15,27,28], showing that the flow velocity generated by the streaming is strong enough for making the manipulation of sub-micronic species extremely difficult. Manipulation means generating relative displacements between particles and the surrounding fluid under the action of ultrasonic radiation forces in order to induce separations, aggregation or other transport processes. It has been observed that AS concentrates sub-micronic particles in stream-lines forming clumps, leading to configurations that may depend on the acoustic energy distribution, but also on the competition between radiation forces and diffusion [27].

In this work, we experimentally demonstrate the possibility of controlling the AS by using a pulsed ultrasound technique. Thus, species in Brownian motion can be focused close to a nodal plane in a resonator generating a steady concentration profile, and at the same time, AS can be systematically reduced to a minimum

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detectable, keeping secondary forces strong enough for generating aggregates of micron-sized species. We demonstrate in this study that the pulsed ultrasound is more efficient for controlling the acoustic streaming than the technique consisting in reducing the amplitude of the acoustic waves. By using the technique we propose, new applications in colloid sciences requiring aggregation and separation should be possible.

2. Acoustic streaming and sub-micronic species

The term streaming generally describes the flow induced by any force acting upon a fluid and dominated by its fluctuating velocity components. The AS is induced by the non-uniformity of the acoustic field and/or by the energy dissipation at the boundary layer at the vicinity of the interface fluid–solid wall of the resonator. The AS is so far a well understood non-linear phenomenon; many papers and books have been thoroughly reviewed the different types of streaming and analyzed its effects in particle and cell manipulation [18,19,27,29,30]. The AS may be visualized using μPIV taking sub-micronic particles as seeds following the streamlines [31–34]. AS in microfluidic channels has been visualized with flow velocities spanning from tenths to hundreds of μm/s [15,27]. It has been demonstrated that micron-sized particles, cells and even bacteria [35] can be trapped by primary radiation forces, but are not affected by the streaming. Let's note that the acoustic primary force and the streaming force are proportional in theory because both are proportional to the acoustic energy density [15,36], but the relationship between them is difficult to establish experimentally, for that purpose, a thorough study beyond of this work would need to be conducted.

3. Pulsed ultrasound technique

We have recently demonstrated that micron-sized species $d \geqslant 10$ μm, latex particles and cancer cells, can be manipulated by using pulsed ultrasounds [37]. We demonstrated that the aggregation rate and the configuration 3D or 2D could be controlled in a very precise way. In that aggregation process the AS was not playing any roll even though the observed weak rotation or vibration of a whole aggregate could be attributed to the AS. Pulsed ultrasound technique consists on sending a group of N of pulses or periods denoted by $T_p = N/f$, with f the driven frequency, separated by repetition time T_r. Therefore, species undergoing the optimum or maximum force migrate at a maximum velocity during short periods T_p separated by times of rest T_r called, leading to an average velocity smaller than that corresponding to continuous mode ultrasound.

4. Experimental section

4.1. Experimental set-up

Experiments have been conducted in two different chambers in order to show that the control of the streaming is independent of the resonator geometry. The first ultrasonic resonator UR1, was a Hele-Shaw cell of 4 cm length, 5 mm wide and 280 μm thickness, composed of 2 mm thick stainless steel plate and 1 mm glass plate separated by a polyimide Kapton® tape spacer assembled in sandwich with neoprene glue. The second ultrasonic resonator UR2, was a cylinder of 5 mm diameter and 180 μm thickness composed of a 2 mm stainless steel plate and 180 μm thick glass slide, separated by polyimide Kapton® tape. The transducer was glued with conductive epoxy (Chemtronics ITW, Kennesaw GA, USA) behind the metal plate in both chambers. Ultrasounds have been generated by 100 MHz dual channel arbitrary wave generator (5062 Tabor Electronics, Israel), the signal was amplified by a dual differential wide band 100 MHz amplifier (9250 Tabor Electronics, Israel) and the signal was visualized with a digital storage oscilloscope (IDS 8064 60 MHz ISOTECh, Hanan–Israel). We employed 800 nm latex particles (Fluorescent particles, Polysciences Inc., Warrington PA, USA) of concentration less than 0.1%; some experiments have been performed with a mixture 800 nm and 15 μm latex particles (Micromod Rostock-Warnermunde, Germany). All the experiments have been performed in steady state. The suspension has been observed by a reflecting Olympus epi-fluorescence microscope with magnifications 10X and 20X, provided with a high resolution camera DCU223 M ThorLabs (Hans-Brocker, Dachau Germany) and recorded in a PC computer.

4.2. Experimental results and discussion

We perform several experiments in both resonators: UR1 parallel plate channel at resonance frequency 2.63 MHz, and UR2 cylindrical shape at resonance frequency 4.12 MHz. The maximum amplitude applied in both resonators was $13V_{p-p}$. Both resonators present one pressure node close to the mid distance between the walls.

4.2.1. Evidence of the acoustic streaming control

The acoustic streaming was first studied in UR1 device. When the acoustic was off, 800 nm particles showing Brownian motion, were initially distributed in the whole channel thickness. Once the acoustics applied, the nano-metric-sized particles were both, focused by the primary radiation force around the nodal plane and dragged out by the AS. After a period of relaxation, a quasi-steady state was observed into the microscope field of view, which was 210×157 μm^2 at 10X magnification. The quasi-steady state was identified when the streaming velocity and the thickness of the layer formed by focused particles reached constant values; that relaxation time was estimated less than 45 s in our specific experimental conditions. The focus of the microscope in the thickness was fixed at the nodal plane, previously determined by the equilibrium position reached by 15 μm latex particles when the ultrasounds were acting at maximum amplitude. The concentration profile showed an apparent higher nanometric particle concentration at the nodal plane. We determined the layer thickness by fixing the positions of the firsts and the last particles with the focus of the microscope. The precision of the measurement was relatively low in continuous mode at maximum amplitude because of the presence of the AS. We reach better precision in pulsed and continuous modes when the AS was the minimum observable; we shall discuss this aspect later on.

Structures already reported [26,27] have also been observed in our resonator namely, the agglutination of particles and recirculation forming stretched clouds, as shown in Fig. 1. These structures more or less stable have been formed several minutes after the acoustic force was applied. The meaning of "stable" is that the structure remains more or less unchanged even though particles continue to move agglutinating and following the streamlines in closed trajectories. The explanation of those structures is related to the energy distribution in the resonator and on other resonances generated by geometrical factors [38]. We fixed the observation zone where the particle flux was roughly constant and the streaming velocity throughout the horizontal plane did not vary more than 20%; the streaming velocity considered was an average of particle velocities determined at three different points in the plane field of view. Let's note that when ultrasounds were turned off, the flow stops instantly while when the acoustics was turned on, the streaming takes some seconds to be established. The AS characteristic velocity has been determined by tracking both, individual particles and small aggregates composed of a few particles,