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Review

Microstreaming and Its Role in Applications: A Mini-Review

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Abstract: Acoustic streaming is the steady flow of a fluid that is caused by the propagation of sound through that fluid. The fluid flow in acoustic streaming is generated by a nonlinear, time-averaged effect that results from the spatial and temporal variations in a pressure field. When there is an oscillating body submerged in the fluid, such as a cavitation bubble, vorticity is generated on the boundary layer on its surface, resulting in microstreaming. Although the effects are generated at the microscale, microstreaming can have a profound influence on the fluid mechanics of ultrasound/acoustic processing systems, which are of high interest to sonochemistry, sonoprocessing, and acoustophoretic applications. The effects of microstreaming have been evaluated over the years using carefully controlled experiments that identify and quantify the fluid motion at a small scale. This mini-review article overviews the historical development of acoustic streaming, shows how microstreaming behaves, and provides an update on new numerical and experimental studies that seek to explore and improve our understanding of microstreaming.

Keywords: cavitation microstreaming; microfluidics; particle image velocimetry; acoustics

1. Introduction

To appreciate the origin of microstreaming and its role in applications, it is useful to first establish the historical development of acoustic streaming as a whole. The study of acoustic streaming has a rich history that dates more than a hundred years back to Rayleigh [1]. Though there is a substantial amount of theoretical work available now, experiments were carried out to study such phenomena long before that. From among the very first experimenters, Faraday [2] conducted an experiment with a vibrating plate, arranged as in Chladni's experiments [3], in 1831. He explained the formation of a boundary layer by the interaction of vibrations of the plate with the air at the surface. Dvořák [4] also observed air currents corresponding to the formation of dust figures. Although these individuals had observed the air motion due to vibration phenomena, there had been no mathematical explanation offered. The first theoretical description was given by Rayleigh in his book *Theory of Sound* [5]. Lord Rayleigh gave the first thorough theoretical description of streaming in a Kundt's tube in 1883, where he explained the origin of streaming for a standing wave between two parallel walls. His analysis showed that the motion of air was caused by a nonlinear second-order effect [1]. This type of streaming owes its origin to shear viscosity in the thin Stokes boundary layer in the vicinity of a solid boundary and is referred to as "Rayleigh streaming".

Rayleigh streaming, or "outer streaming", is the streaming in the main bulk of the fluid outside the boundary layer. There is another type of streaming cell inside the boundary layer called "inner streaming". In his analysis, Rayleigh [1] did not include the details of inner acoustic streaming that drives the outer streaming. Schlichting [6] gave the first mathematical model for inner streaming, which he explained as a steady boundary layer vorticity, known as "Schlichting streaming". This powerful inner boundary layer streaming flow then generates counter rotating streaming vortices within the main body of the fluid, accordingly named outer streaming, as already defined. This concept of combined inner and outer streaming in an incompressible flow was given by Stuart [7] (termed "Stuart streaming" by Lighthill [8]).

Lighthill [8] classified streaming into two kinds of streaming: acoustic streaming induced by standing waves and microstreaming resulting out of the oscillations of a solid body in the fluid. Here, the mechanism of generation of the former streaming is the attenuation of sound waves owing to fluid viscosity, while for the latter, it is the friction at the boundary of the solid. Both these types of streaming have been extensively reviewed by Riley [9] and Nyborg [10].

Streaming observed in the main body of the fluid, when it is penetrated by an ultrasonic sound beam with a high amplitude, is termed the "quartz wind". This time-averaged flow is caused by the dissipation of acoustic energy in the fluid owing to its viscosity. Although earlier observations of the quartz wind were made by Meissner [11] in liquid and Walker and Allen [12] in air, Eckart was the first one who gave a mathematical analysis for the quartz wind. Eckart [13] showed that the quartz wind is caused by viscous attenuation. "Eckart streaming" can be generated both in standing and travelling waves.

Following Rayleigh and Lighthill, Riley [14] gave a theoretical description of time-averaged streaming flows in incompressible fluids. In order to incorporate flows in incompressible fluids, the assumption was made that particle size has to be very small in comparison to the wavelength of the sound applied. The term "steady streaming" was first coined by Riley [9,14,15], who noticed that the origin of streaming in both cases (a) and (b) described in Section 2 was attenuation. Riley [9] clarified the need for a term in place of acoustic streaming, as it is used for cases with a certain degree of compressibility of the fluid. He kept the term steady streaming for the time-averaged, incompressible flow above and beyond the Stokes drift velocity.

Microstreaming specifically refers to the streaming flow of fluid around an oscillating object such as a gas bubble. The fluid flow is generated from the vorticity caused by the oscillation of the boundary layer surrounding, for example, an oscillating cavitation bubble. Due to the importance of cavitation bubbles in sonochemistry/sonoprocessing and microscale geometries present in microfluidic applications, cavitation microstreaming plays a major role in a number of applications.

Previous reviews on the topic of acoustic streaming [9,16–18] have covered most of the different types of streaming flows in microfluidic and non-microfluidic devices in great detail. While microstreaming has been discussed in these reviews, there is yet to be a review that compiles recent advances and highlights the importance of microstreaming in the context of its range of applications. The aim of this mini-review is thus to provide a snapshot of recent advances made in the understanding of microstreaming. Prior to delving into recent experiments and numerical developments, a basic overview of the numerical origin of microstreaming is provided in the following section together with a map of the relevant parameter spaces in which studies have been performed.

Numerical Origin of Microstreaming

The origin of microstreaming can be mathematically derived from a fluid mechanics perspective. Firstly, assume a Newtonian fluid that behaves as a continuum containing an incompressible sphere and is subject to a stationary acoustic wave. If the size of the sphere immersed in this fluid is very small in comparison to the wavelength of the stationary acoustic wave, then the fluid around the sphere can be assumed incompressible. Since the wavelength of the applied acoustic wave is large compared to the particle size, this can also be seen as an oscillation being applied in the far field of the fluid. On the surface of particles, a no-slip boundary condition is applied. Such a flow can be modelled mathematically by the equation of continuity and the Navier–Stokes equation for conservation of mass and momentum, respectively, in Cartesian coordinates given as

$$\nabla.\boldsymbol{u} = 0$$

$$\rho\{\boldsymbol{u}t + (\boldsymbol{u}.\nabla\boldsymbol{u})] = -\nabla p + \mu\Delta\boldsymbol{u} \tag{1}$$

where $\boldsymbol{u}$ is the velocity vector, ρ is the density, and p is the pressure of the fluid with a kinematic viscosity, μ. Note that there is a quadratic nonlinearity present on the left-hand side in Equation (1) as a product of velocity and velocity gradient $\boldsymbol{u}.\nabla\boldsymbol{u}$. This nonlinearity can be produced in two ways: either the velocity $\boldsymbol{u}$ has to be large or the gradient of velocity $\nabla\boldsymbol{u}$ is large. The time average of this product is nonzero. It is this nonlinear term that is responsible for microstreaming in the fluid.

The relevant parameter space for microstreaming can be effectively categorised by the Stokes number, defined below. Firstly, let

$$\epsilon = \frac{U}{\omega D} \text{ and } Re = \frac{UD}{\nu} \tag{2}$$

where ω is the frequency, U is the velocity amplitude, D is the diameter of the sphere, and ν is the kinematic viscosity. A ratio of Re (the Reynolds number) and ϵ is also introduced as $\Omega = \omega D^2/4\nu$, which is known as the Stokes number. These terms are dimensionless and can be usefully used to categorise the parameter spaces for which different studies on microstreaming have been performed in past studies (see Figure 1).

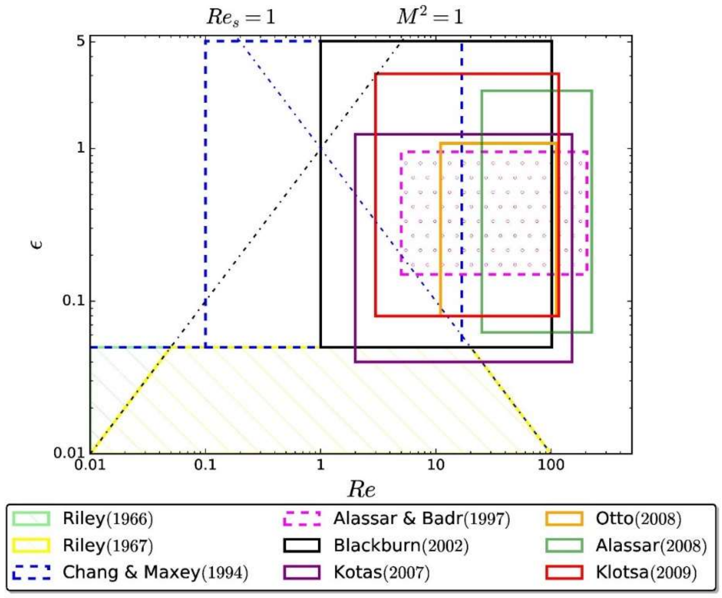


Figure 1. Parameter spaces for various studies ([13,19–26]) conducted for microstreaming flows around a single sphere, where the entire domain shown is the parameter space used in Jalal [27]. Re_s is the product, and M^2 is the ratio of dimensionless parameters Re and ϵ, respectively. The shaded regions for Riley (1966, 1967) depicts a region where $\epsilon \ll 1$.

2. Role of Microstreaming in Applications—Recent Developments

Microstreaming plays an important role in various applications, ranging from sonochemistry and sonoprocessing in large systems to acoustophoresis in microfluidic lab-on-a-chip systems [18]. In the following section, we overview some recent experimental developments in cavitation microstreaming, microstreaming that occurs specifically in microfluidics, and microstreaming in the context of particle separation and manipulation.

2.1. Cavitation Microstreaming

Cavitation microstreaming is the streaming induced by a bubble undergoing oscillations due to the influence of an acoustic field. This type of streaming plays an important role in both microfluidic-based applications and sonochemistry-type applications, where the production and collapse of bubbles is an important driving mechanism for efficient performance. This is because the streaming created may influence the growth of bubbles in an acoustic field (i.e., via rectified diffusion) and/or influence the location of nearby bubbles within the sound field itself.

Tho et al. [28] used micro-PIV (particle image velocimetry) measurements and streak photography to study the flow field around both single and two oscillating bubbles that were resting on a solid boundary. They investigated several different modes of oscillation and, interestingly, found that the mode of oscillation varied primarily with the applied acoustic frequency. Translating modes were also observed to occur in a sequential order, changing from a translation along a single axis to an elliptical orbit and finally to a circular orbit. In regards to the streaming patterns, patterns ranging from symmetrical flow structures containing four vortices and circular vortexes centered on a bubble were observed.

Leong et al. [29] used the techniques established by Tho et al. [28] to relate the streaming velocities around cavitation bubbles to the enhancement in bubble growth rate within an acoustic field by a process known as rectified diffusion [30]. As described by Church [31] and Gould [32], microstreaming around an oscillating bubble enhances the mass transfer effects and hence bubble growth rate. In the presence of different types of aqueous surfactant solutions, the authors [29] found that different types of surfactants offered different magnitudes of streaming velocity enhancement depending on the electrostatics, head group size, and chain length. One interesting observation was the effect of surface oscillations, which were promoted by the presence of surfactant molecules. Surface oscillations resulted in a more chaotic type flow and produced streaming velocities that were orders of magnitude faster (see Figure 2) than in the absence of surface oscillations.

Using microscopic observations, Marmottant et al. [33] were able to capture details of the bubble motion during an ultrasound cycle. Fast frame recordings of a tracer particle embedded in the liquid around the particle enabled full resolution of the acoustic streaming flow induced by the bubble oscillation. When attached to a wall, the bubble is found to provide high efficiency as a "liquid pump" that drives and propels liquid with a characteristic velocity proportional to the square of the vibration amplitude. Interestingly, the viscosity of the fluid provides an important role in triggering a larger phase shift between the oscillation and translation, which is in contrast to more conventional consideration of streaming flows where velocities are assumed to be independent of viscosity.

As noted in some of the above studies, the confinement of cavitation bubbles, either attached to or between walls, enables more effective study of the microstreaming. Mekki-Berrada [34] was able to analyse the microstreaming flow generated around either an isolated or a pair of interacting bubbles that were confined between two walls of a silicone microchannel that were anchored on micropits. Whilst isolated bubbles induce short-range microstreaming in the channel gap, a pair of bubbles were found to produce long-range microstreaming and large recirculatory motion that can be elegantly described as a butterfly-like shape (Figure 3). By adjusting the distance between these bubbles, different streaming shapes could be observed.

High-intensity focused ultrasound (HIFU), whereby a sound field is established such that there is the formation of an intense cavitation focal point, is commonly used in sonochemistry applications. One interesting phenomenon observed in studies is that the sonochemiluminescence at the focal point of HIFU devices is actually lower than expected. Uemura et al. [35] studied the influence of acoustic streaming on the generation of acoustic cavitation by analysing the flow in the sound field using PIV. Interestingly, it was found that acoustic cavitation bubbles in the focal area of a HIFU field become carried away by acoustic streaming as soon as they were generated in the focal area. This is the key reason as to why the sonochemiluminscence intensity is diminished in HIFU systems at the focal point. PIV can also be used to characterise acoustic streaming in focused fields, and Slama [36] evaluated the effects of using different seeding particle sizes (5, 20, and 50 µm) to observe the behaviour. Larger particles are dominated by radiation forces, and streaming effects are not effectively characterised. Contrarily, smaller particles produce velocity measurements consistent with Computational Fluid Dynamics (CFD) simulations.

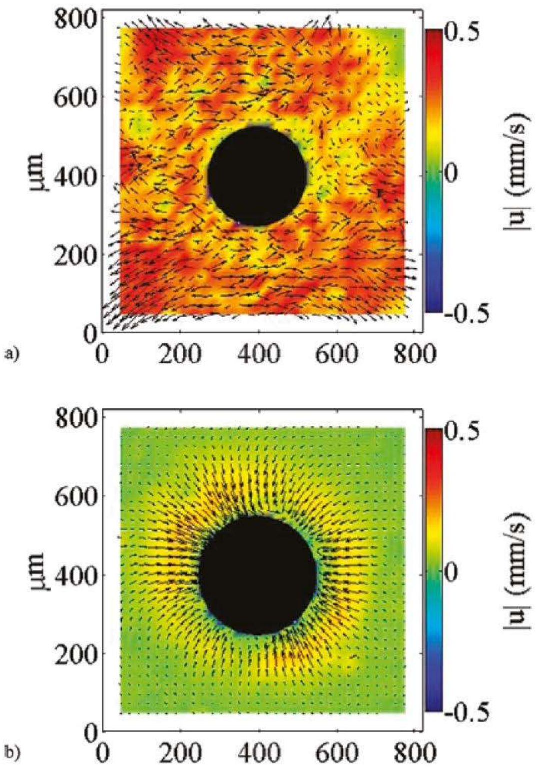


Figure 2. Particle image velocimetry (PIV) velocity fields for (**a**) cavitation bubble with surface oscillations resulting an observed chaotic flow and (**b**) without surface oscillations and ordered flow. Reproduced with permission from [29].

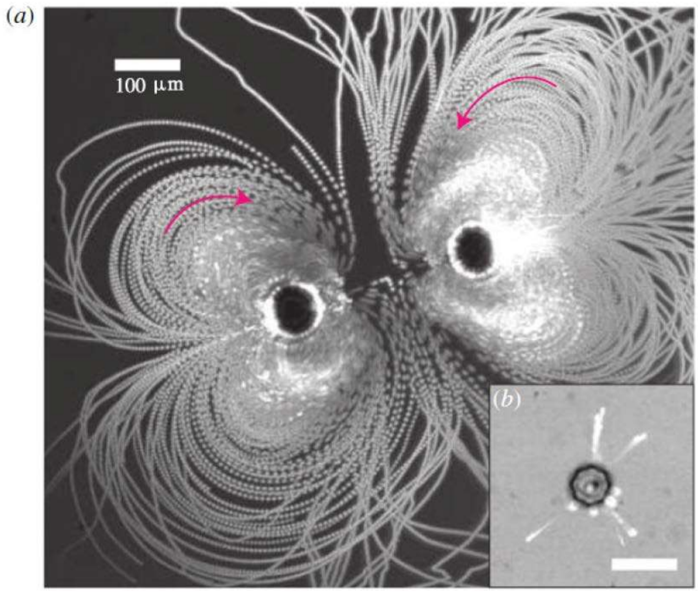


Figure 3. Microstreaming generated by (**a**) a bubble pair and (**b**) a single bubble driven at an acoustic frequency of 104 and 148 kHz, respectively. Reproduced with permission from [34].

One of the most widespread and important uses of microstreaming currently in industry today is for the semiconductor industry. Particulate contaminants are deposited on silicon wafer surfaces by cleanroom personnel or equipment during production. These particles can cause critical defects if not removed. One of the main mechanisms for particle removal is acoustic streaming and microstreaming. However, despite this wide use of megasonics in the semiconductor industry, the physics of megasonic particle removal remains largely unexplained [37]. Microstreaming in particular is of interest, as it is extremely powerful and generates strong localised currents that aid cleaning efficiency. The currents are most pronounced near bubbles that undergo volume resonance and/or are located along solid boundaries. The acoustic streaming patterns in sonic cleaning baths can be visualised using Ar-ion laser sheets directed into a tank to illuminate the air bubbles in the flow. Particle removal experiments have shown that wafers are cleaned due to both a combination of stable cavitation events (e.g., shock wave) and associated cavitation microstreaming motion that aid the detachment of contaminant particles from the wafer. Bulk acoustic streaming, in addition to microstreaming, provides an efficient transfer mechanism of detached particles away from the wafer surface through the creation of strong currents and boundary layer thinning.

Microstreaming in the context of large-scale systems is rather difficult to study due to the random and chaotic nature of the flow and interference caused by the presence of multiple bubbles. Instead, most studies to date are considered within a microfluidic regime, which is discussed in the next subsection.

2.2. Microstreaming in Microfluidic Applications

2.2.1. Particle Separation and Manipulation

In microacoustofluidic applications, the typical dimensions result in two acoustic effects of main importance, these being the acoustic radiation force, which influences the movement of particles towards either nodes or antinodes within the chamber, and microstreaming, which imparts motion to the entire fluid.

A numerical study of the microstreaming that occurs around spheres (single and double) within an oscillatory flow was performed recently by Jalal [27] to understand the effects of microstreaming on particle manipulation and separation in an acoustic field. For high amplitudes (i.e., $1 < \epsilon < 5$), direct numerical simulation (DNS) data showed the presence of a flow regime that had not been observed or discussed in the literature previously for the single particle case (Figure 4). The DNS was also capable of capturing the nonsymmetric nature of the sizes of the inner vortices. However, DNS is limited to steady flows around a single sphere unless fully three-dimensional simulations are conducted, which is very expensive computationally.

It was concluded that for high frequencies, the spheres tend to realign themselves into the only stable configuration (i.e., lateral configuration) before attracting each other. This implies that, in any situation with a nonuniform distribution of particles, particles of larger sizes ($\Omega \geq 20$) will attract each other. In the context of particle separation and manipulation, this is critically important. For example, the separation of fat in milk systems, whereby large milk fat globules (i.e., $\Omega \geq 20$) collect together and rise to form cream, whereas the smaller ones ($\Omega < 5$) remain suspended in the milk, confirming some of the conclusions of experiments conducted by Leong et al. [38]

The relative motion of two particles owing to the mutual induction of microstreaming was also calculated in a parameter range for the first time by Jalal [27]. It was found that spheres of sufficiently large size or high frequency (i.e., $\Omega \geq 10$) touch each other in a lateral configuration, as shown in Figure 5. These results are again ultimately applicable to ultrasonic separation applications. Moreover, this work can be easily extended for spheres of different radii and for ellipsoids and cylinders.

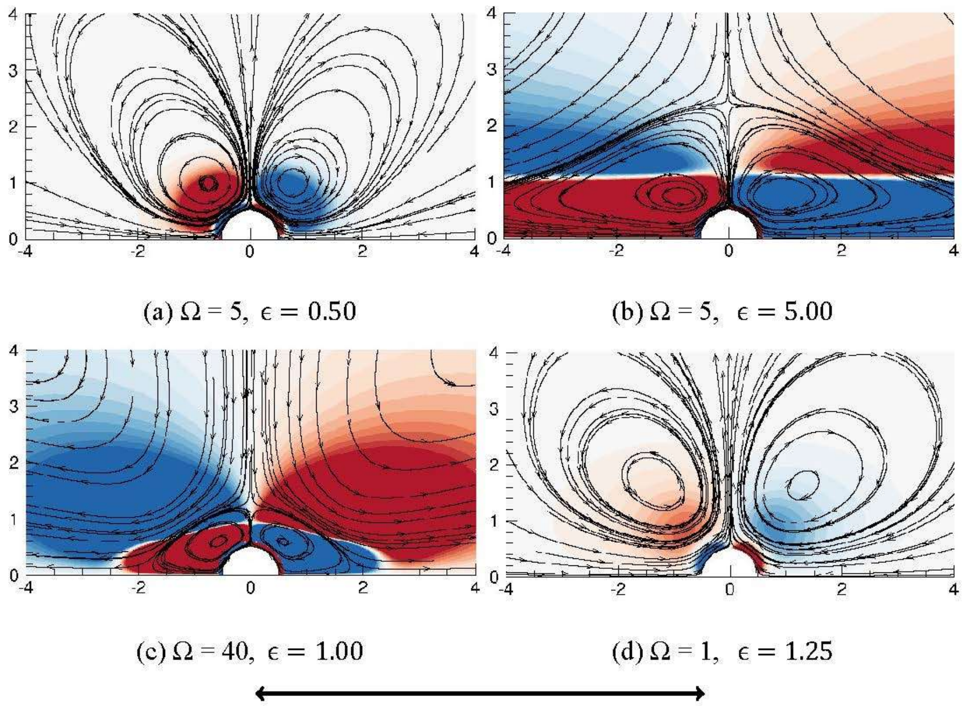


Figure 4. Microstreaming around a single sphere in four different frequencies, Ω, and amplitudes, ϵ, when the imposed flow is oscillating in the direction of the bold black arrow. Colour represents azimuthal component of vorticity, between −0.01 (blue) and 0.01 (red). The mean streamlines start from user-selected points. The colour contour represents the azimuthal component of the vorticity relative to the plane where blue is inwards and red is outwards of the plane.

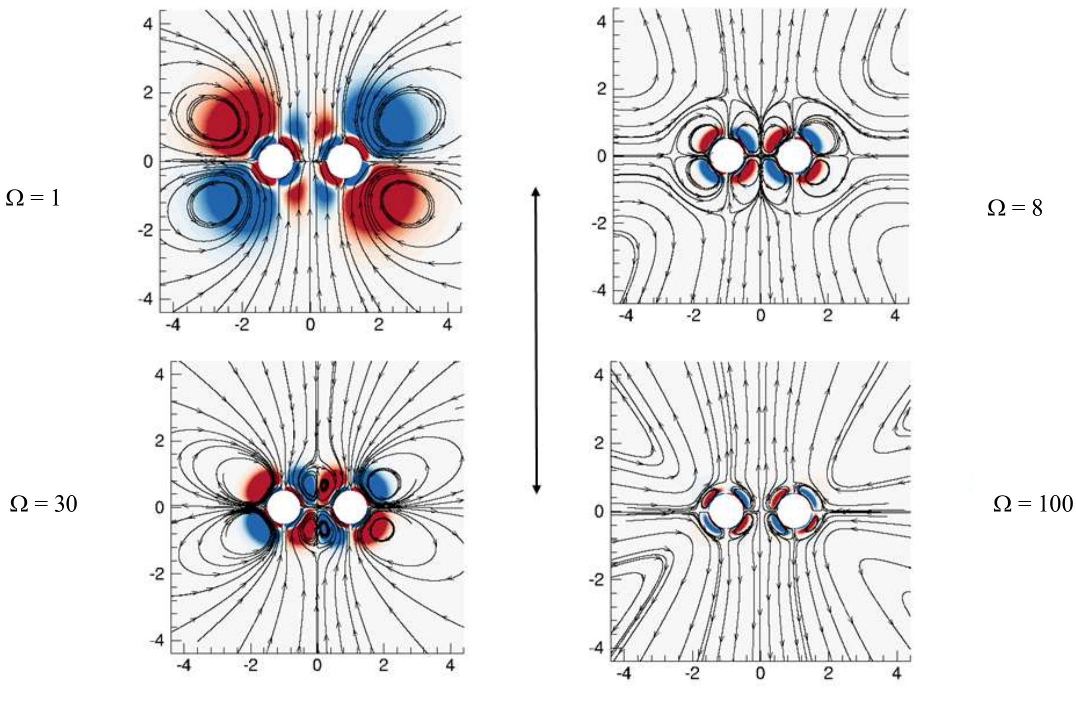


Figure 5. Microstreaming around two spheres placed in a lateral configuration when the distance between the two spheres is 2D, where D is the diameter of each sphere. The imposed flow is oscillating in the direction of the bold black arrow. Colour represents azimuthal component of vorticity −0.01 (blue) to 0.01 (red).

In addition to numerical development, experimental investigations have been used to improve understanding of how streaming flows influence particle motion in the context of particle separation systems. As noted in studies to understand cavitation microstreaming, micro-PIV is a powerful analysis tool and it can be used to experimentally determine both acoustic radiation forces and the microstreaming induced in microfluidic chambers under the influence of an acoustic field driven in the MHz range. While the following studies are not strictly speaking examples of microstreaming by the classical definition, they are recent examples of streaming behaviour in microfluidic systems in which particle separation is the primary objective.

Hagsater et al. [39] performed a series of experiments to understand steady-state motion in terms of the acoustic eigenmodes or standing ultrasound waves. Three different tracer solutions with different physical properties were used to study both in isolation and in combination the effects of acoustic streaming and acoustic radiation forces. Large bead tracer particles were found to be most strongly influenced by acoustic radiation, and these forces dominated when using these tracer solutions, leading to accumulation of the particles at the pressure nodes (Figure 6a). Reduction in the size of the particles (by a factor of 5) led to motion being dominated by acoustic streaming and steady-state vortex streaming being observed (Figure 6b). Compressible particles such as milk globules and red blood cells displayed differing susceptibility to be influenced by either acoustic radiation forces or streaming, again, depending on size. The compressibility in this case influenced their direction towards either the pressure nodes or antinodes.

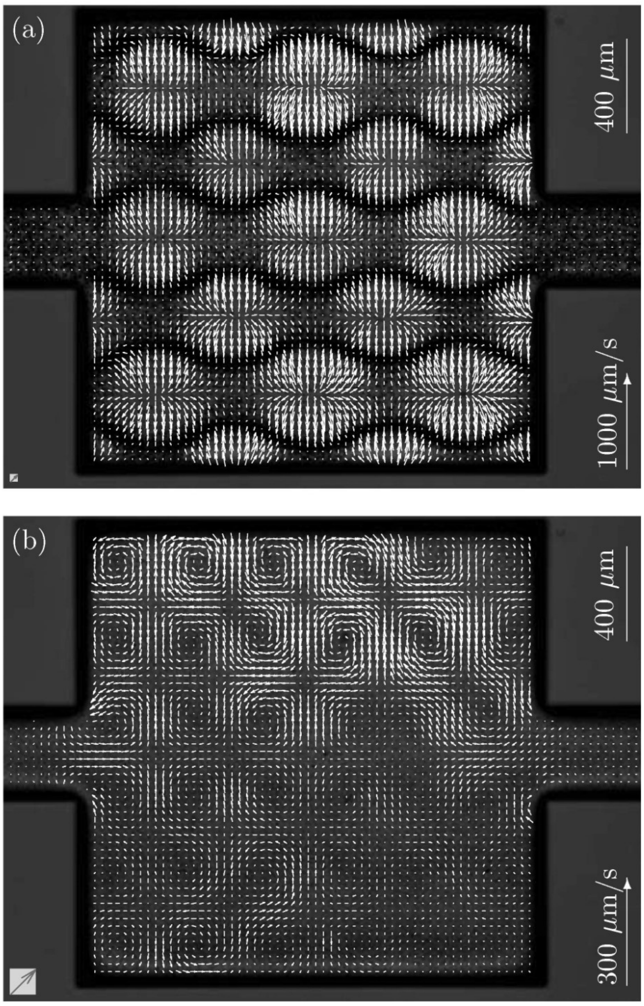
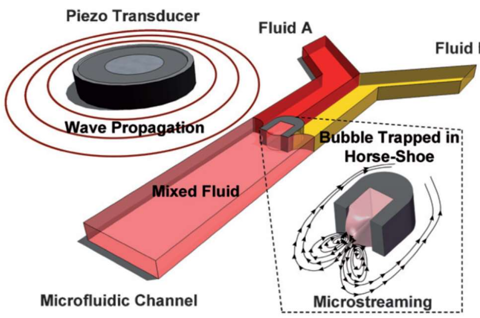


Figure 6. Microstreaming and radiation forces observed at 2.17 MHz acoustic resonance using (**a**) 5-µm beads and (**b**) 1-µm beads. Reproduced with permission from [39].

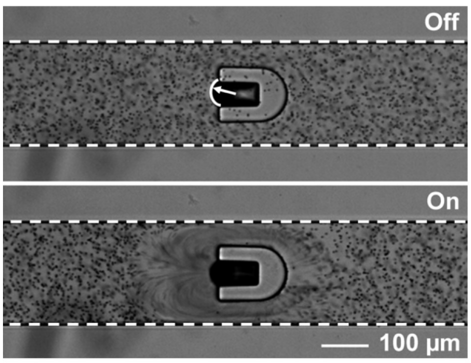
In addition to the particle size, Castro et al. [40] found that by modifying other parameters, such as the resonator geometry in parallel plates, there is a threshold for particle manipulation with ultrasonic standing waves in confined resonators that can occur without the influence of microstreaming. In particular, oval-shaped geometries were found to produce less microstreaming, which improved the ability of particle manipulation below sizes of 2 µm. Understanding the forces present within a standing wave field and the effects based on particle size, therefore, enables more effective separation and even size sorting. Devendran et al. [41] showed that, within a particular field generated in an open microfluidic channel, there are two types of stable collection zones—a lower one within the liquid suspension and an upper one located at the liquid–air interface. Due to the greater effect that microstreaming has on smaller particles, this particular system was able to effectively sort small particles from larger ones, which were more strongly influenced by the radiation forces, and collect at the lower collection zone within the liquid suspension.

2.2.2. Mixing in Microfluidic Systems

In addition to particle separation, one of the issues pertaining to microfluidics is the low degree of mixing that can usually be achieved in microfluidic channels due to the dimensions and flow rates that generally result in low Reynolds numbers. Ahmed et al. [42] reported the use of a single-bubble-based acoustic streaming device to promote the mixing of two initially laminar flows directed into a microfluidic channel. Ultrafast homogenous mixing was achieved on the time scale of milliseconds due to the acoustic streaming generated by a bubble trapped within a horse shoe structure placed within the microfluidic chamber (Figure 7). When the channel is filled with liquid and passes by the horse shoe structure, a single bubble is formed within the horse shoe shape due to surface tension effects. An adjacent piezo transducer oscillates this trapped bubble, inducing the streaming.



(**a**)



(**b**)

Figure 7. (**a**) Schematic representation of horse shoe piezo transducer setup in a microfluidic system to induce mixing and (**b**) experimental visualisation of enhanced mixing when transducer is on vs. off. Reproduced with permission from [42].

This type of device has great potential usefulness in many biochemical studies and applications, since rapid mixing and homogenization is of great importance across a wide variety of applications. At the time at which the study was published, single-bubble-based acoustic mixers were considered the fastest microfluidic mixers that used acoustic-based mechanisms.

Linking the observation of acoustic streaming in the presence of cavitation is important to develop more efficient processes. Louisnard et al. [43] developed a theory to understand acoustic streaming in the presence of cavitation, which to date, had yet to be fully understood. In their theory, the steady liquid flow observed with acoustic cavitation could be successfully predicted using a standard turbulent flow calculation. Comparisons of the calculations with experiments performed at 20 kHz and a perpendicular flow in a duct showed good agreement.

Prior to being well mixed, real fluids may actually be in an inhomogeneous state and produce microstreaming behaviour that differs from those studied using controlled experiments. Recently, Karlsen [44] showed through a theoretical and experimental study that in an inhomogeneous fluid, there is an additional nondissipative force density that acts on the fluid that stabilizes particular inhomogeneity configurations. Experiments performed inside a glass-silicon microchip using inhomogeneous aqueous iodixanol solutions showed that the behaviour differs quite markedly from classical boundary-driven acoustic streaming in homogenous fluids (Figure 8). In inhomogeneous fluids, streaming is initially confined to the boundaries and suppressed in the bulk. As diffusion occurs over time, advection motion begins to "smear" the inhomogeneity and the forces eventually expand into the bulk, similar to homogenous fluids. This suppression behaviour has the potential to enable more effective mixing and understanding of how to improve ultrasonic handling of nanoparticles in standard acoustophoretic separation applications.

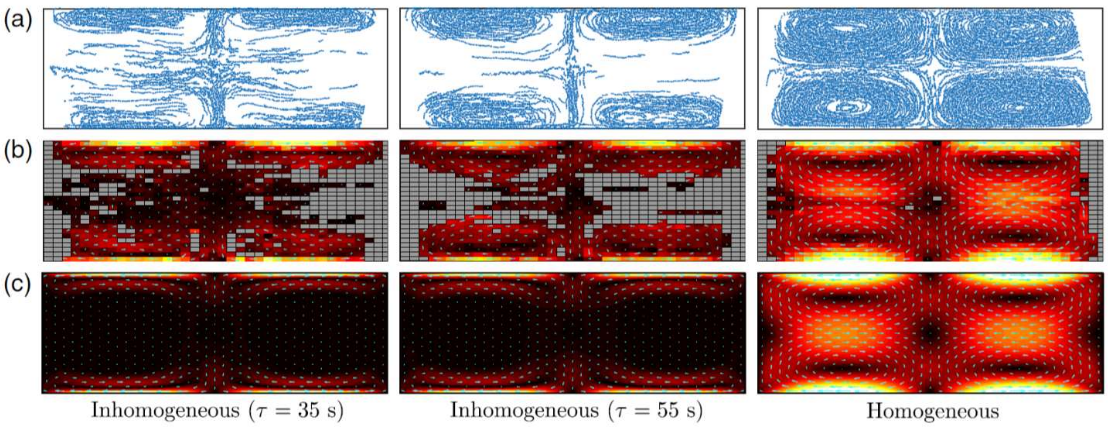


Figure 8. (**a**) Experimental particle positions (**b**), experimental streaming velocity, and (**c**) simulated streaming velocities for inhomogeneous and homogenous fluids. Reproduced with permission from [44].

Whilst many studies have considered cavitation microstreaming on a quasi 2D plane, Marin et al. [45] showed that microparticle trajectories actually produce a much more complex behaviour, with particularly strong out-of-plane dynamics in regions close to the microbubble interface (Figure 9). Using astigmatism particle tracking velocimetry, which is a method by which an astigmatic aberration is introduced in the optical system by means of a cylindrical lens placed in front of the camera sensor to produce an image of a spherical particle showing a characteristic elliptical shape unequivocally related to its depth position, it was revealed that the apparently planar streamlines often observed in a 2D field are actually projections of a stream surface with a pseudo-toroidal shape. Such a result has important implications in applications involving acoustic streaming, such as particle trapping, sorting, and mixing.

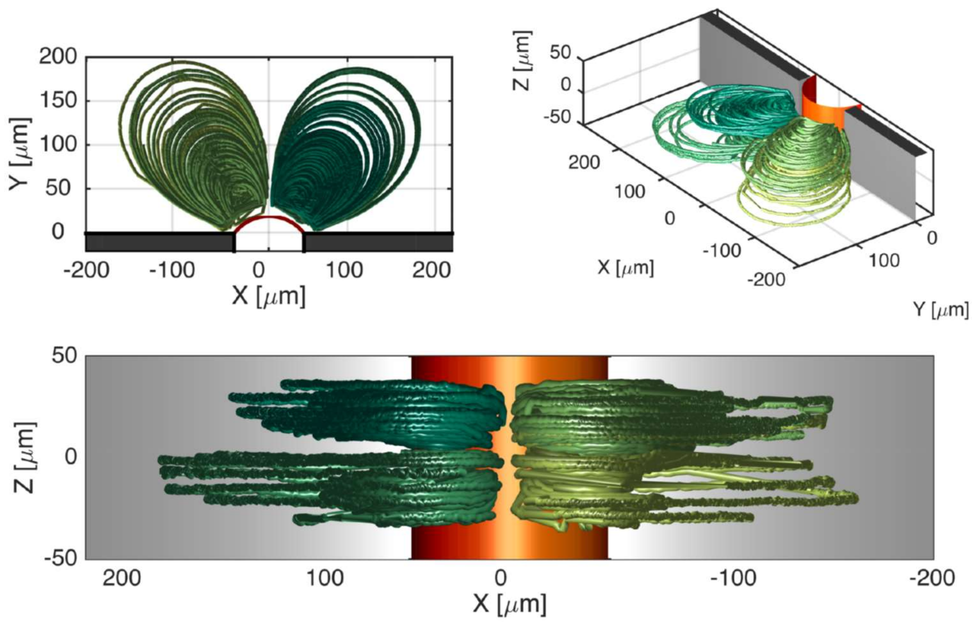


Figure 9. Three-dimensional trajectories of four different particles along different planes. Reproduced with permission from [45].

3. Future Directions and Conclusions

Microstreaming is produced from microscale effects generated within a sound field. These microscale effects produce macroscale phenomena that are of high importance and usefulness in a number of applicable industries ranging from superconductor manufacture to biotechnology. The current state of understanding of microstreaming recognizes its importance in the context of these applications, particularly its influence on mixing in microfluidics and its destructive or constructive effect on particle separation and sorting.

Continued improvement of the understanding both theoretically and experimentally of how microstreaming behaves in microfluidic and large-scale systems is paramount to enable the development of more efficient sonochemical and lab-on-a-chip processes. One of the challenges in developing good understanding in controlled microfluidic scales is its lack of translatability when scales are increased. Increasing the complexity to a larger system, where a large number of cavitation bubbles (i.e., more than two) are present, will ultimately influence the streaming behaviour to differ markedly from the isolated or few bubble cases. Future work will be needed to bridge this difference between an ideal, controlled situation and one that is more representative of real-world conditions with significantly more complex and hence difficult to characterise microstreaming behaviour.

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