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Introduction to the Special Issue on the Theory and Applications of Acoustofluidics

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Acoustofluidics is a burgeoning field that applies ultrasound to micro to nano-scale fluidic systems. The discovery of the ability to effectively manipulate fluids and particles at small scales has yielded results that are superior to other approaches and has been built into a diverse range of research. Recasting the fundamentals of acoustics from the past to include new phenomena observed in recent years has allowed acoustical systems to impact new areas such as drug delivery, diagnostics, and enhanced chemical processes.

The contributions in this special issue address a diverse range of research topics in acoustofluidics. Topics include acoustic streaming, flows induced by bubbles, manipulation of particles using acoustic radiation forces, fluid and structural interactions, and contributions suggesting a natural limit to the particle velocity, the ability to deliver molecules to human immune T cells, and microdroplet generation via nozzle-based acoustic atomization.

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I. INTRODUCTION

This issue introduces the readership to the new field of acoustofluidics and presents recent findings from researchers in the field. Contributions span the discipline from the fundamental[1,2] to applied some of which are close to clinical[3] and commercial[4] utility. Additional goals of this special issue were to bring researchers together from around the world to view each others' work in a more extended context than they would otherwise see at meetings and broaden the discipline's literary contributions to the Journal of the Acoustical Society of America (JASA). We hope the readers of JASA are intrigued by the contributions made in this special issue and that it stimulates further contributions and the growth in the readership of JASA. The articles in this special issue broadly cover key topics in acoustofluidics such as acoustic streaming, bubbles and cavities, particle manipulation, and fluid and structural interaction.

II. ACOUSTIC STREAMING

Acoustic streaming is a nonlinear phenomenon arising from the propagation of sound waves through a viscous fluid. Under study by numerous investigators over the past 150 years, many aspects of this phenomenon remain poorly understood. The acoustofluidics community has undertaken inquiries into this phenomenon while emphasizing its potential applications. Dezfuli, et al.,[5] has provided a comprehensive finite element analysis to quantify the primary acoustic field and consequent flow driven by acoustic streaming in a SAW microdevice with a configuration that can be simple to construct. Acoustic streaming may be used to produce flow sufficient to propel small devices under water, and such a propulsor has been provided by Kong, et al.,[6] where a 2 MHz transducer was used to produce 0.2 mN force and acoustic streaming flow at 6.1 mm/s. Acoustic streaming has also been used to manipulate cells in cell culture systems, and Oyama, et al.,[7] report a method for using acoustic streaming to agitate Chinese hamster ovary (CHO) cell suspensions to reduce the risk of contamination and error when compared to traditional methods of cell transfer and agitation. Winkelmann, et al.,[8] report the analysis of electroosmosis to oppose acoustic streaming that could provide both a means to understand the nature of both phenomena and also provide complementary means to manipulate cells and suspended objects. Finally, in Thompson, et al.,[9] a matched asymptotic analysis has been used to explore the generation of acoustic streaming in the cochlea from the oscillation of the basilar membrane responsible for transmitting sound into the cochlea from the ossicles and tympanic membrane of the ear. This acoustic streaming is locally significant and may be important in the functioning of the ear in response to even weak sounds.

III. BUBBLES AND CAVITIES

The interaction between acoustic waves and bubbles has long been of interest to researchers. Allied physical phenomena include cavitation and intense localized acoustic streaming. Regnault, et al.,[10] explores acoustic streaming around aspherical bubbles that are forced into oscillation by externally imposed acoustic waves. Analytical and experimental results are shown and contrasted to those obtained for bubbles having spherical geometry. Ultrasound may also be used to generate bubbles in the first instance, as explained by Carugo, et al.,[4] where ~180 μm bubbles were produced at a microfluidic T-junction and subsequently divided by ~72 kHz ultrasound to continuously form sub-5 μm bubbles.

The proper generation and propagation of acoustic waves in acoustofluidic devices are vital to their design and adoption. Joergensen, et al.,[11] provides an enhancement of our understanding of how the fields form when thermal effects and appropriate boundaries are included. The acoustic streaming is shown to be in part dependent upon the thermal energy distribution in the system. Centner, et al.,[3] show how acoustics may be used to transport molecules into human immune T cells in an enclosed cavity, illustrating a novel use of controlled acoustic wave propagation in cavities.

IV. PARTICLE MANIPULATION

Acoustofluidics is often applied to particle manipulation, and a majority of papers in this special issue explore this topic. Fan, et al.,[12] provide a fascinating example of an acoustic tractor beam: a method to *pull* particles towards the source of acoustic radiation by exploiting a spatial phase shift. In Kim, et al.,[13] the particles are actually motile *Chlamydomonas reinhardtii* algae that rapidly swim in the fluid; exposing them to standing acoustic waves while in a chamber causes their concentration. The power and other characteristics of the acoustic wave may be determined from the behavior of the algae. Plazonic, et al.,[14] seek to capture biological particles—*Bacillus subtilis var niger* as anthrax spore analogs—using acoustic waves to transport them into contact with an antibody-activated surface to aid in their detection as a biodefense sensor. Microparticles are trapped using standing wave modes in a base plate in Hammarström, et al.,[15] in a glass microfluidic channel with a glycerol-coupled external piezoelectric element in Lickert, et al.,[16] and on an asymmetric structure in Tahmasebipour, et al.[17] Particle separation using acoustic waves is modeled in three dimensions (3D) using finite element analysis in de los Reyes, et al.,[18] indicating the differences between the use of traditional bulk piezoelectric devices, 3D chip bulk piezoelectric devices, and surface acoustic wave devices. Finally, in a recent innovation, acoustic vortex beams are used in Xia, et al.,[19] to manipulate particles along complex helical paths.

The work certainly extends beyond separation and manipulation of particles in complete systems, as the fundamental interaction between acoustic waves and one or two particles remains an active research topic. Leao-Neto, et al.,[20] presents a theoretical study of how force and torque arises upon an elongated spherical particle when exposed to acoustic waves in a simple cylindrical chamber while immersed in a nonviscous fluid. Gong, et al.,[1] compares the angular spectrum and multipole expansion methods to compute the acoustic radiation force and torque present upon a spherical particle in an arbitrary acoustic field and find them equivalent. The effects of the surrounding piezoelectric transducers on the forces present upon a particle is considered in an analytical model in Özer, et al.[21] Lima, et al.,[22] present a semi-analytical method to determine the force and torque on a subwavelength-sized axisymmetric particle benchmarked against exact results for a rigid sphere in water and then used to determine the forces upon a red blood cell in plasma. Finally, Hoque, et al.,[23] consider the dynamic motion of *two* particles near an acoustic pressure node while driven by the acoustic field and forces present between the particles in an analysis and experimental effort.

V. FLUID-STRUCTURE INTERACTION

Atomized droplets are useful for many applications, and in a key contribution from Shan, et al.,[24] they describe the use of ultrasound passed into the bulk of a fluid reservoir to lead to droplet generation from numerous orifices placed at one boundary of the reservoir, with computational and experimental results. Bodé et al.,[25] provides a numerical analysis of the coupling between a transducer and a glass microfluidic channel to demonstrate the importance of considering how the transducer is attached to the microfluidic structure. Another related work by Steckel, et al.,[26] describes the computational modeling of a silicon-glass structure actuated either by lead zirconate titanate (PZT) or a 1 μm $Al_{0.6}Sc_{0.4}N$ transducer; their results suggest similar performance whether using the bulk PZT or the thin-film piezoelectric material. In Singh, et al.[2], a crosscutting inquiry into the physically derived limit of 1 m/s for the particle velocity amplitude in an elastic solid is made. This limit may be applied regardless of vibration mode, material, frequency, and physical shape. This result may be potentially valuable in modeling and designing acoustofluidics devices and in characterizing high-amplitude acoustical phenomena.

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