ACOUSTIC STREAMING IN MICROGRAVITY: FLOW STABILITY AND HEAT TRANSFER ENHANCEMENT

E.H. Trinh , Jet Propulsion Laboratory, California Institute of Technology, MS 183-401, 4800 Oak Grove Drive, Pasadena CA 91109, Eugene.H.Trinh@jpl.nasa.gov

INTRODUCTION

The virtual elimination of natural buoyancy in microgravity significantly impacts the rates of heat and mass transport between solid structures or between phases in disperse fluid systems. Artificially induced flows must therefore be introduced in order to provide the required enhancement and to avoid the shutdown of needed heat and mass exchanges. We are developing an acoustic method based on streaming flows to provide the additional circulation in systems where standard mechanical flow actuators are not easily implemented, or practical. This approach is well suited for small-scale or even miniature structures and for multiphase systems such as multi-bubble or droplet suspensions in a fluid host medium. In addition to providing a precise control on the global streaming flow characteristics, this method also the direct modification of the local single particle environment by inducing oscillatory motion of the fluid particle surface. The application of acoustic streaming to heat and mass transport enhancement is not novel, and it has been investigated in the past **[1-4]**. We believe, however, that the results we present in this paper on the interaction between single fluid particles and streaming flows are new, and they have the potential to impact the technology developed for use in microgravity.

In this paper, we will first briefly discuss the experimental approach, and we will present results for drops and bubbles levitated in a liquid host and the effects of shape oscillations and capillary waves on the local flow fields. We will also report some preliminary results on the use of streaming flows for the control of the evaporation rate and rotation of electrostatically levitated droplets in 1-G. The purpose of this paper is not to discuss technical issues in detail, but to present an overview of the various aspects of this research task.

EXPERIMENTAL APPROACH

The work described in this paper has been carried out using single particle levitation based on ultrasonic and electrostatic methods in liquid as well as gaseous host media. A typical system consists of one or a few single droplets or bubbles levitated or trapped in a resonant cavity. Acoustic streaming flows are generated, and the flow fields are characterized both in the absence as well as in the presence of the particles. Detailed observation of the dynamics of the fluid particle motion and of the local flow environment is carried out through optical observation and visualization through suspended tracer particles. Three-dimensional imaging is implemented through a multi-camera setup, and quantitative flow measurements will be carried out using a pulsed Particle Image Velocimetry system.

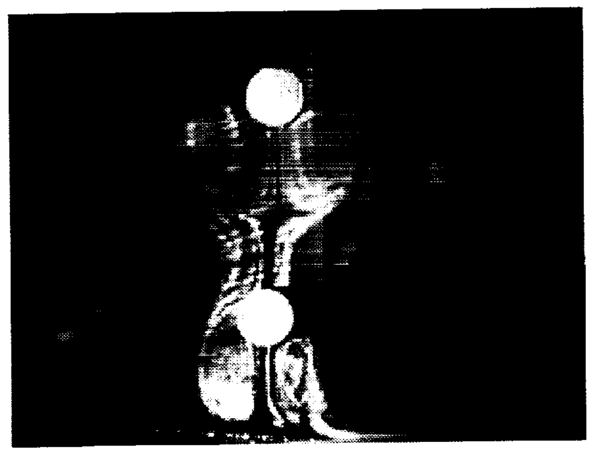


Figure 1 is a photograph showing a chamber enclosing an ultrasonic device and two solid spherical particles levitated in the standing wave. The streaming flow field is visualized using incense smoke, which mostly composed of droplets about 0.5 μm in diameter. Shown are vortices attached to the lower hemisphere of each levitated sample. The ultrasonic standing wave has a frequency of 23 kHz and the host fluid is air.

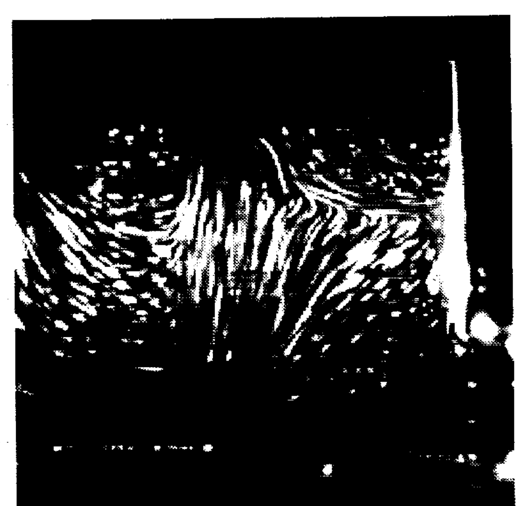


Figure 2 is a time-exposure photograph showing a water-filled ultrasonic resonant cell and the streaming flow generated by a transducer placed at the chamber bottom. The flow has been made visible using suspended polymer particles in the liquid and illuminated by a laser sheet. The water-filled cell resonates at 22 kHz and at 66 kHz.

In some experiments, we have used electrostatic levitated charged droplets in order to investigate the streaming flow fields at low ultrasonic power. This combination of electric and ultrasonic fields allows a quasi simulation of microgravity conditions that might require only low to moderate forced convection.

INDUCED STREAMING FLOW and BUBBLES and DROPLETS in LIQUIDS

The acoustic parameters and the geometry of the cell determine the morphology of the streaming flow fields within closed cavities. The transducer generating the primary sound wave generates a steady outward flow that is redirected by the walls of the container. The presence of a strong primary standing wave also contributes to the detailed distribution of the induced circulation, although the classic results of Andrade [**5**] showing vortices distributed between nodes and antinodes of a standing wave are not often found in our experimental results. In general, for moderate acoustic pressure and in both the cases of gas and liquid host fluids, we have found that the streaming flow pattern in a resonant chamber with a multi-wavelength standing wave is invariably in the form of a single toroidal vortex having its main axis coincident with the chamber symmetry axis. The levitated fluid particles are thus immersed in this primary circulation, and the rate at which they transfer energy and matter to the environment is significantly affected by this outer streaming flow. In the cases where the inner to outer fluid viscosity ratio is low, one would also expect the appearance of internal circulation. This was experimentally confirmed by examining levitated silicone oil drops in distilled water.

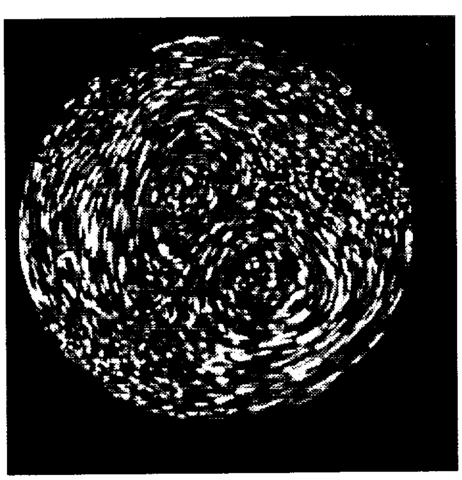


Figure 3 shows a time-exposed photograph of a drop containing undissolved dye particles and trapped at a pressure antinode of a 22 kHz ultrasonic standing wave. The drop is 0.8 cm in diameter and the exposure time is 5 seconds. Although this drop displays a characteristic dipole flow pattern, more typical internal flows do not show such high degree of symmetry.

Figure 4 shows photographs of internal flows observed inside air bubbles trapped at the pressure nodal plane of a 23 kHz ultrasonic standing wave. The bubble diameter is 0.4 cm and contains incense smoke. The photographs are actually prints of a single frame video image taken at a shutter speed of 1/50 s. Although only one lobe is clearly visible on the prints; the flow pattern is that of a symmetrical toroidal vortex. It is thus apparent that streaming will alter both the external and internal flow environments of isolated drops and bubbles immersed in a liquid harboring an ultrasonic standing wave.

In addition to the technical issue of implementing a method for enhancing heat and mass transfer in a low-gravity environment, the quantitative characterization of the induced internal flows in droplets and bubbles must be resolved in the absence of natural buoyancy. A complete isothermal experimental system is extremely difficult to achieve due to the ultrasonic energy input from the sound generator. The resulting slight thermal gradient in the gravitational field invariably drives buoyant convection.

Direct interaction between the ultrasonic field and the fluid particles also contributes to the generation of forced convection in the immediate particle vicinity. Due to parametric coupling, capillary waves with frequency equal to half the acoustic frequency are induced on the upper surface of trapped bubbles. We had previously observed the existence of these waves [**6**(Asaki et al.)], but only recent flow visualization of the flow field external to the bubble has shown that these waves also induce substantial steady fluid flow in the liquid around the bubble surface. A detailed study of the flow inside the bubble also shows a significant enhancement when capillary waves are present. This increase in both internal and external circulation is reflected in a faster rate of air dissolution into the host water: this rate has been measured to be up to a factor of three greater for a bubble with capillary waves than for one with a smooth interface.

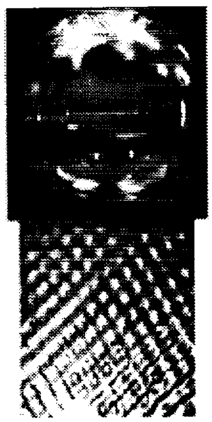
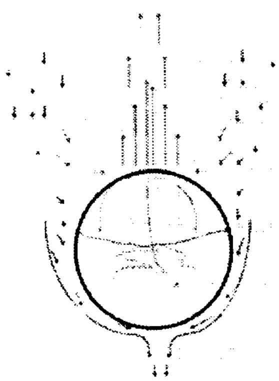


Figure 5 shows a video still frame of the capillary



waves as recorded under stroboscopic illumination. Also shown is a schematic description of the asymmetric forced convection associated with these waves.

Another approach to the generation of local circulation is derived from the effects of driven drop and bubble *shape* oscillations. An examination of the flow field external to the oscillating fluid particles reveals significant symmetrical forced convection spatially extending to a distance equal to several particle diameters.

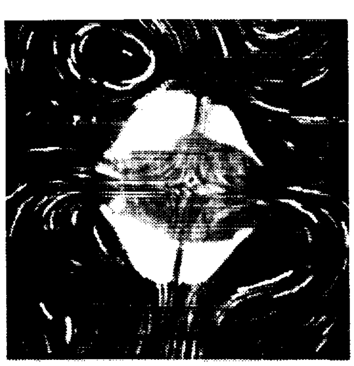
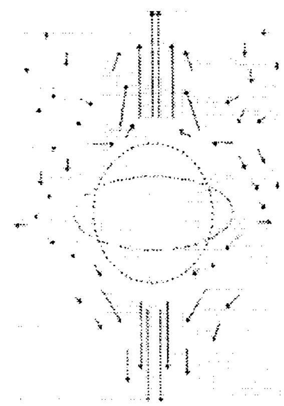


Figure 6 is a time-exposure of a levitated drop driven into the fundamental mode of shape oscillations. The recorded motion of tracer particles illuminated by a laser sheet shows the vortical steady flow generated by the shape oscillations in addition to the time varying oscillatory motion.



Also shown is a schematic description of the induced flow around an oscillating bubble.

STREAMING FLOW in RESONANT CHAMBERS in AIR and AROUND LEVITATED or SUSPENDED SAMPLES

The advantages of the acoustic streaming method in the generation of forced flows arise from the avoidance of major equipment requiring mechanical moving parts, and in the direct interaction between the acoustic field and the objects immersed in it. This is vividly illustrated by the generation of attached vortices on any solid or liquid samples (see figure 1). In a typical application requiring a closed chamber, the only requirement is an acoustic device generating a one dimensional high intensity standing wave to be used as the source of the steady flow. Regular three-dimensional vortical motion will naturally establish itself within the enclosed volume. The length scale of applicable experimental systems can be as large as 10 cm or as small as 0.01 cm. **Figure 7** is a photograph of a steady streaming flow field in a near cubical chamber with a standing wave at 23 kHz. This is a two-dimensional image of a three-dimensional flow field: in addition to the velocity component in the plane of the image, a perpendicular component also exists in the direction normal to the plane of the picture. A thorough mixing of the air within the chamber is therefore carried out by the acoustically-forced convective flow.

A streaming velocity as high as several meters per second has been observed in high amplitude ultrasonic standing waves in closed chambers, thus leading to the generation of turbulent flow fields. Low-gravity applications, however, will probably require a more moderate range of flow parameters as a primary requirement appears to be the need to compensate for the absence of natural buoyancy or free convection.

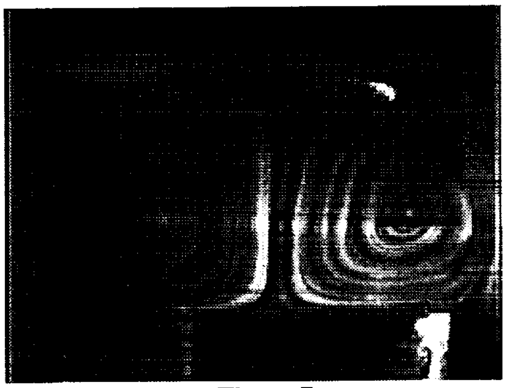


Figure 7

The streaming velocity observed in this study ranges from 0.1 to over 100 cm/s in air and from 0.1 to 5 cm/s in water.

A fundamental scientific issue in fluid dynamics is the stability of vortical flow. We believe that the streaming flows around a heated spherical samples in a high intensity sound wave can be used as a simple experimental system to investigate this problem. In this instance of coupled fluid dynamical and heat transport interaction, a transition to instability of attached vortices is observed as the streaming Reynolds number (based on the streaming flow velocity and the diameter of the spherical sample) is slowly increased. Vortex stretching, instability, and finally shedding can be observed in detail. Experimentation of microgravity would allow the elimination of the natural convection contribution, and would therefore drastically simplify the analysis.

Figure 8 shows the stretching and detaching of toroidal vortex initially attached to the upstream side of a heated sample positioned near the velocity antinode of an ultrasonic standing wave.

Although the results presented in this paper are mostly for isothermal systems, we have also carried out measurements of laser-heated levitated samples and the effects of streaming flow velocity on the hot sample temperature [**7**,**8**]. The results indicate that for the same radiant input power in air at atmospheric pressure, a moderate streaming flow velocity reduces the temperature of a levitated sample by over 30%.

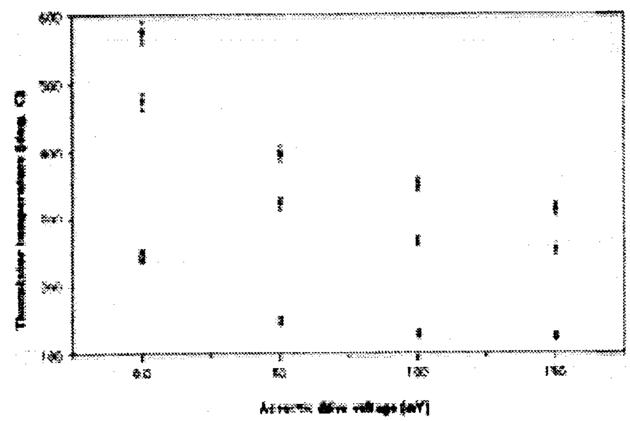


Figure 9 is a plot of the temperature of a spot-heated thermistor positioned at the velocity antinode of an ultrasonic standing wave as a function of the acoustic drive amplitude. The streaming Reynolds number is roughly proportional to the square of the drive voltage. At the highest acoustic level used in this test, the initial temperature of the 2 mm diameter, 5 mm long cylindrical thermistor is lowered from 580 to about 325 °C. The streaming flow and the acoustic motion effectively remove heat from the local heat source into the surrounding gas.

As a final topic, we will address the effects of streaming flows on the rotational stability of freely levitated single particle. Previous flight experiments using acoustic positioning have shown that high intensity sound fields used to position drops in microgravity also induce an uncontrolled sample rotation along a well determined axis whose direction varies with the acoustic parameters settings. Since rotation of a particle also affects its heat and mass transport characteristics, such an issue is relevant to our current studies. We have speculated that the steady streaming flow fields are responsible for this unexpected additional torque. In order to validate this supposition, we have studied the rotational behavior of an electrostatically levitated droplet carrying a surface charge using an ultrasonic-electrostatic hybrid apparatus. This device allows the independent levitation of droplets through either ultrasonic or electrostatic means, but more importantly, it allows the study of the effects of very low acoustic field on a levitated droplet. We have found that sample rotation can be effectively controlled through acoustic parameter adjustments: Both the orientation of the rotation axis and the rotation rate can be varied by changing the frequency and the amplitude of the ultrasonic standing wave. The effects of these parameter changes on the streaming flow field have been observed using flow visualization and PIV methods.

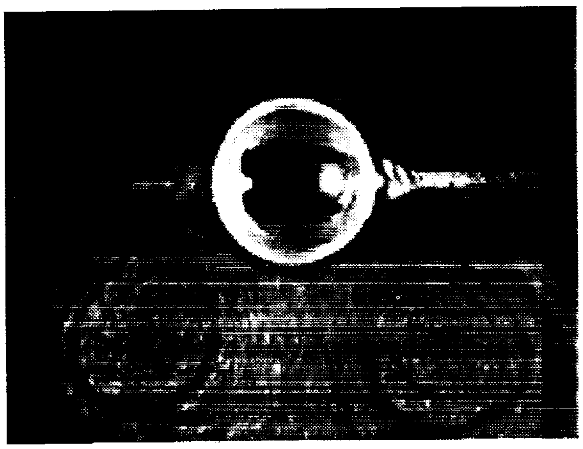


Figure 10a shows a levitated water drop in a stationary, non-rotating state, together with the flow pattern obtained from the scattering from suspended incense smoke illuminated by a laser sheet. A nearly symmetrical toroidal vortex is shown attached to the levitated drop.

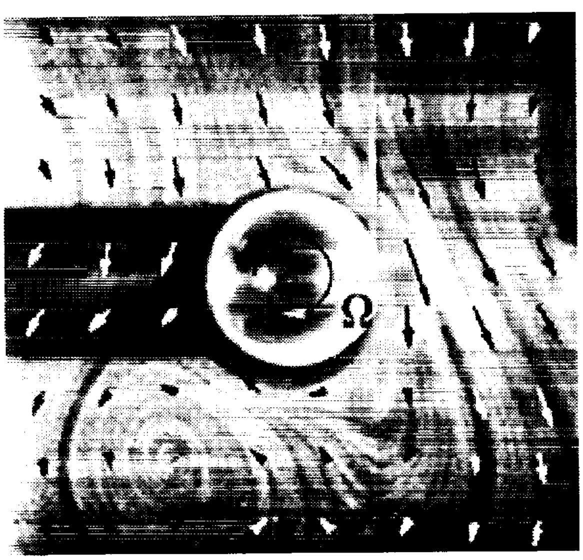


Figure 10b shows the same drop after appropriate changes have been made to the acoustic settings. Upon altering the acoustic parameters, the characteristics of the flow field start to change, breaking the initial symmetrical pattern. Rotation sets in after a threshold is reached, and a steady flow pattern results from the motion of both the air and the levitated drop.

SUMMARY

The objective of above summarized description of this research task is to illustrate the potential for the technological application of acoustic methods to active control of forced convection in microgravity. We believe that the versatility and simplicity of these techniques are a definite improvement over standard mechanical flow generation systems. We have seen that one has the ability to generate substantial forced circulation in both liquids and gases, from a macroscopic to a very small scale, as well as the capability to control the dynamics of individual fluid particles in a multiphase suspension. Significant enhancement of the heat transfer has been demonstrated, and the possibility of fine-tuning experimental parameters to control sample rotation has been validated. In addition to these issues dealing with practical applications, we have discovered a wealth of new physical phenomena of relevance to current interest in fundamental fluid dynamics.

ACKNOWLEDGMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under funding from the Microgravity Research Division of the National Aeronautics and Space Administration.

REFERENCES

B.J. Davidson, "Heat transfer from a vibrating circular cylinder". Int. J. Heat Mass transfer, **16**, 1703 (1973)

Y.Y. Borisov and N.M. Gynkiva, "Acoustic Drying", in *Physical Principles of Ultrasonic Technology*, L.D. Rosenberg Editor, Vol. 2, Plenum, N.Y. (1973)

R.M. Fand and J. Kaye, "the influence of sound on free convection from a horizontal cylinder", J. Heat Transfer **83**, 2 (1961) and **83**, 133 (1961)

P.D. Richardson, "Heat transfer from a circular cylinder by acoustic streaming", J. Fluid Mech. **30**, 337 (1967), J. Acoust. Soc. Am. **36**,2323 (1964), *Proceedings of the Third International Heat Transfer Conference*, **3**, 71 (1966)

E.N. da C. Andrade," On the circulation caused by the vibration of air in a tube", Proc. Roy. Soc. London **A 134**, 445 (1931)

T. J. Asaki, P.L. Marston. and E.H. Trinh "Shape oscillations of bubbles in water driven by modulated ultrasonic radiation pressure: observation and detection with scattered laser light", , J. Acoust. Soc. Am. **93**, 706 (1993)

E.H. Trinh and J.L. Robey, " Experimental study of streaming flows associated with ultrasonic levitators ", Phys. Fluids **6**, 3567 (1994)

E.H. Trinh and S.S. Sadhal "Acoustic streaming and processing of low melting point materials", , Heat Transfer in Microgravity Systems, S.S. Sadhal and A. Gopinath Eds. HTD-vol 290, 46-52, ASME, NY 1994.