# VARIATION OF ACOUSTIC STREAMING FLOW FIELD DUE TO A BOUNDING WALL

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*Summary* The acoustic streaming flow field and its variation due to a bounding wall are experimentally measured using the technique of particle image velocimetry (PIV). The peak streaming velocity and its axial location are found to be significantly reduced as the bounding wall is brought closer to an ultrasound beam. A modified analytical model is introduced to account for the influence of cavitation bubbles, with good overall agreement between model predictions and experimental measurements achieved.

## INTRODUCTION

When a fluid medium experiences intense ultrasound, a stationary fluid motion is induced. Two different types of flow associated with the fluid motion are known to exist: (a) the oscillatory flow associated with a propagating wave and (b) the non-zero time-averaged flow. Such phenomenon is known as "acoustic streaming", which is also referred to as Eckart streaming if its scale is much larger than the acoustic wavelength [1]. The problem associated with acoustic streaming induced by a focused ultrasound beam confined by a normal bounding wall is yet to be fully explored, either theoretically or experimentally. The present study aims to experimentally study how the bounding wall affects the intensity, axial distance and profile of the peak streaming velocity induced by ultrasound radiation with cavitation bubbles.

## EXPERIMENTAL DETAILS

Figure 1(a) illustrates schematically the test rig with a circular focused ultrasound beam submerged in a container filled with distilled water. The distilled water level is fixed at $H_w = 0.14$ m. Continuous pressure waves are radiated by an ultrasound beam (Cole-Parmer™; tip diameter $D = 6.35$ mm) at a pre-specified excitation frequency of 20 kHz. To measure the flow field associated with acoustic streaming, the non-intrusive optical technique – particle image velocimetry (PIV) – is employed. During the experiment, the spacing ($H$) between the radiating surface of the ultrasound beam and the flat bounding wall is systematically varied by linearly traversing the ultrasound beam vertically along the beam axis from 2$D$ to 20$D$.

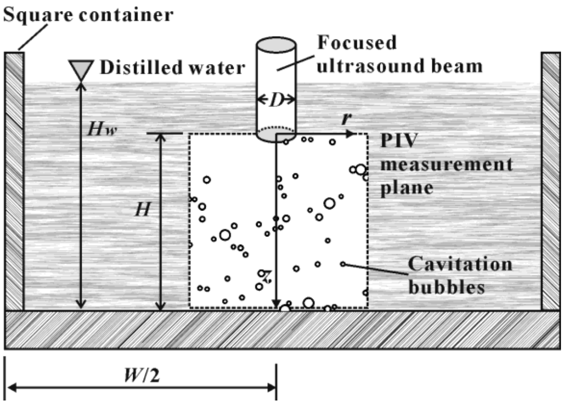


FIG. 1 Schematic of particle image velocimetry flow (PIV) measurement setup for acoustic streaming induced by a focused ultrasound beam.

## DISCUSSION OF RESULTS

### Acoustic streaming flow field

Figure 2 displays the flow field of acoustic streaming obtained with PIV where the $z$-axis coincides with the axis of the ultrasound beam. The axial velocity contour shown in Fig. 2(a) exhibits a high velocity region downstream along the ultrasound beam axis at about $z/D = 3$. When the separation distance between the radiating surface of the ultrasound beam and the bounding wall decreases, it is seen from Figs. 2(b) and (c) that high acoustic streaming velocity regions coincide with the ultrasound beam axis in both cases, consistent with that of the $H/D = 20$ case. The reduced contours of the axial velocity component clearly exhibit a concentrated region of high velocities at $z_p/D \sim 3$ for $H/D = 12$ and $z_p/D = 2$ for $H/D = 4$.

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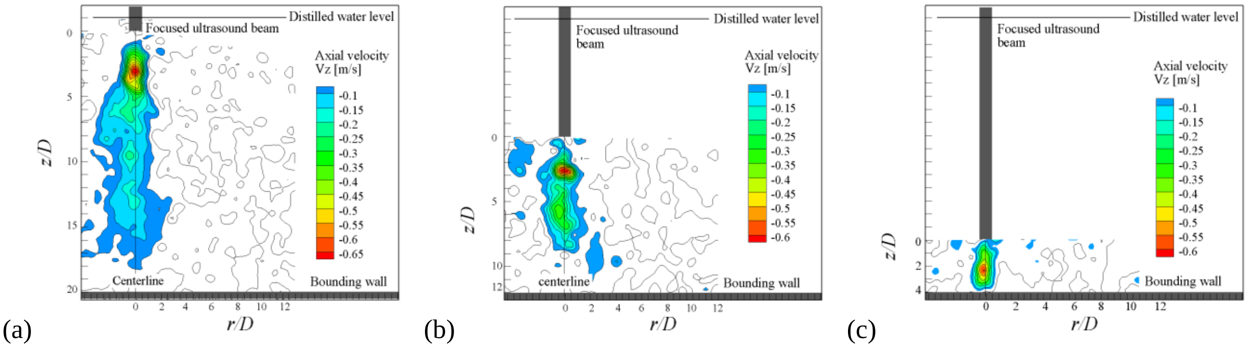


FIG. 2 Axial velocity contours of acoustic streaming in *r-z* plane: (a) *H/D*=20; (b) *H/D*=12; (b) *H/D*=4.

**Experimental data and analysis for on-axis streaming velocity**

The distribution of on-axis streaming velocity profile $V_c$ (extracted from PIV data) is shown in Fig. 3 for selected beam-to-bounding wall separation distances. The results of Fig. 3 suggest that the effect of bounding wall on $V_c$ may be classified as:

(1) $H/D > 16$: A single velocity peak is present, which is coincident with the focus of ultrasound beam ($z_f/D = 3$) and its magnitude is independent of *H/D*.

(2) $z_f/D$ (focus) < $H/D \leq 16$: Both the peak velocity and the focal length are largely constant, same as that in Range 1. A second velocity peak appears away from the focal point.

(3) $H/D \leq z_f/D$ (focus): In this range, the focal length is significantly reduced and the peak steaming velocity is smaller than that of Ranges 1 and 2.

An approximate solution for the on-axis streaming velocity has been obtained as [2]:

$$V_z(0,0,z)=V_c=\left(\frac{\alpha I_0 r\sqrt{\pi}}{2\sqrt{2}\mu cB}\right)\int_0^\infty\left(\sqrt{A(z')}\exp(-2\alpha z')\left\{\begin{array}{l}\exp((2A(z')/r^2)(z-z')^2 erfc\left(\dfrac{\sqrt{2A(z')}(z-z')}{r}\right)\\ -\exp((2A(z')/r^2)(z+z')^2 erfc\left(\dfrac{\sqrt{2A(z')}(z+z')}{r}\right)\end{array}\right\}\right)dz'$$

With the effect of volume fraction ($\varepsilon$) of the cavitation bubbles on the speed of sound ($c$), viscosity ($\mu$) and sound absorption coefficient ($\alpha$) in the gas-liquid mixture accounted for, the solution is modified as [3, 4]:

$$\frac{1}{c_m^2}=\left(\rho_G\varepsilon+\rho_L(1-\varepsilon)\right)\times\left[\frac{\varepsilon}{\rho_G c_G^2}+\frac{(1-\varepsilon)}{\rho_L c_L^2}\right];\ \mu_m=\left\{1+\left(\frac{\mu_L+2.5\mu_G}{\mu_L+\mu_G}\right)\alpha+\left(3\left(1-\frac{\mu_G}{\mu_L}\right)-\frac{\mu_L+2.5\mu_G}{\mu_L+\mu_G}\right)\alpha^2-4\left(1-\frac{\mu_G}{\mu_L}\right)\alpha^3\right\}\mu_L;\ \alpha_m=\varepsilon\alpha_G+(1-\varepsilon)\alpha_L$$

The prediction using the above solution with the assumption of $\varepsilon$ = 4% is presented in Fig. 3, which agrees well with the present experimental measurements.

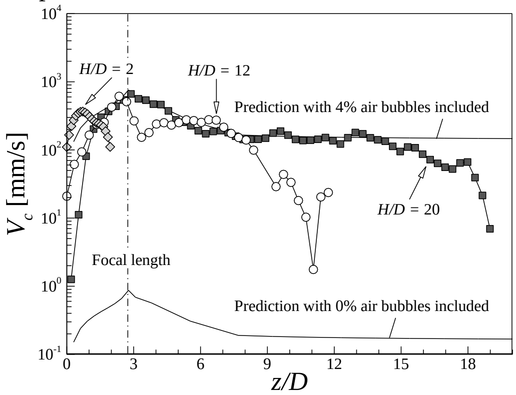


FIG. 3 Velocity profile along the axis of ultrasound beam for selected beam-to-bounding wall separation distances (*H/D* = 2, 12, 20); theoretically predicted on-axis streaming velocity is given for *H/D*=20 with $\varepsilon$ = 4%.

## CONCLUSIONS

Based on the experimental results, the effects of bounding wall upon on-axis streaming velocity have been classified into three distinct ranges, depending on the separation distance. When the separation distance decreases, the high velocity region is concentrated. With the assumption of 4% void fraction, the analytical solution is capable of capturing the detailed features of the on-axis velocity for relatively large separation distances.

## References


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