International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:7, No:12, 2013

Measurement of Steady Streaming from an Oscillating Bubble Using Particle Image Velocimetry

Yongseok Kwon, Woowon Jeong, Eunjin Cho, Sangkug Chung, Kyehan Rhee

***Abstract*—**Steady streaming flow fields induced by a 500 μm bubble oscillating at 12 kHz were measured using microscopic particle image velocimetry (PIV). The accuracy of velocity measurement using a micro PIV system was checked by comparing the measured velocity fields with the theoretical velocity profiles in fully developed laminar flow. The steady streaming flow velocities were measured in the sagittal plane of the bubble attached on the wall. Measured velocity fields showed upward jet flow with two symmetric counter-rotating vortices, and the maximum streaming velocity was about 12 mm/s, which was within the velocity ranges measured by other researchers. The measured streamlines were compared with the analytical solution, and they also showed a reasonable agreement.

***Keywords*—**Oscillating bubble, Particle-Image-Velocimetry microstreaming.

I. Introduction

VIBRATION of a structure immersed inside of a fluid generates fluid field fluctuations, and the temporal average of velocity fluctuations results in mean flow due to the second order non-linear effects, which is called steady streaming. Oscillation of a bubble can be induced by acoustic wave, and steady streaming caused by an oscillation of bubble is called cavitation streaming. Steady streaming of a micron size bubble has important applications in therapeutic use of drug delivery [1]-[3] as well as microfluidic analysis system [4], [5].

Steady streaming caused by a cavitating bubble, which is attached on the wall, showed orderly motion [6], and [7] classified the flow patterns into four streaming regions. Various streaming patterns have been applied to the actuation mechanisms in micro-systems, and the effectiveness of cavitation micro-streaming has been shown in mixing of fluids [8], manipulating biological cells [9], and sorting and focusing of micro-particles [10]. Flow patterns have been shown and some characteristic velocities were measured, but the complete flow field information has not been obtained thoroughly. The microscopic particle image velocimetry (PIV) system has been used to measure the flow fields from cavitating bubbles [11]. These studies showed various patterns of velocity fields in the transverse plane of an attached bubble for the volume oscillation, where the bubble expanded and contracted radially while maintaining its spherical shape. Strong streaming flow could be observed near the resonance frequency for the surface oscillation mode where the surface of a bubble deforms into polygonal shapes with larger radial wall oscillation amplitude. The flow fields for the surface oscillation mode have not been extensively investigated.

The streaming flow fields from a 500 μm oscillating bubble in the sagittal plane were measured in this study. The bubble excited by acoustic wave near the resonance frequency showed wavy surface wall motion, and strong jet flow was measured using a micro PIV system. The accuracy of velocity measurement of a micro PIV system was confirmed, and the measured streaming velocity fields were compared to the analytic solution.

II. Method

In order to validate the accuracy of velocity measurement of the current PIV system, velocity fields of fully developed laminar flow was measured using a PIV system. A 3.8 mm diameter acryl tube was immersed in the hexahedral optical correction box with square cross section, and constant flow was infused by a syringe pump (NE-1000, New Era Pump Systems, Inc., NY, USA). The microscopic PIV system was used to measure the velocity fields. It consisted of a microscope (BX51, OLYMPUS Co., Japan), a high speed camera (Miro-eX4, Vision Research Inc., NJ, USA), and a 1W laser light source (MGL-H-532 nm, Changchun New Industries Optoelectronics Tech Co., China). The light was expanded using a cylindrical lens and illuminated the plane of flow measurement. Fluorescent particles of diameter 7μm (32-2B, Duke Scientific Co., CA, USA) were used as seeding particles, and light re-emitted by particles was filtered by an optical filter (612nm, Thorlabs Inc., NJ, USA) attached to the microscope lens. Red fluorescent image of particles were captured in the symmetry plane of a tube with the frame rate of 1,000 fps, and then processed with commercial PIV software (Insight 3G, TSI Inc., MN, USA). Two consecutive images were obtained, and each was divided into interrogation windows (16 × 16 pixels). Velocities fields were calculated by cross correlating each window with 50% window overlap. The field of view was 7.3mm by 5.4mm.

Streaming induced by a sessile bubble oscillating at 12 kHz with wavy wall motion was measured. An air bubble of 500 μm diameter was generated using a micro-syringe on the vertical wall of a hexahedral polycarbonate chamber filled with water. A 12 kHz sine wave voltage signal was generated by a function generator (33210A, Agilent Co., CA, USA), and it was amplified up to three hundred volts by a voltage amplifier (PZD700, Trek Co., NY, USA). It was transmitted to a cylinder-type piezo-actuator (disk type PRYY-1133, PI Ceramics, Germany) attached to the bottom of the chamber. The bubble was excited by acoustic wave generated by the

K. Rhee is with the Department of Mechanical Engineering, Myongji University, Yongin, Korea (e-mail: khanrhee@mju.ac.kr).

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:7, No:12, 2013

actuator, and the oscillation of bubble wall was observed using a high speed camera attached on a microscope. The microscopic PIV system was used to measure the velocity fields from an oscillating bubble. The laser beam was expanded using a cylindrical lens and illuminated the sagittal plane of an oscillating bubble attached on the vertical wall. The red fluorescent images of particles were captured with the frame rate of 1,000 fps, and velocity fields were computed by cross correlating the interrogation areas of two consecutive images. The field of view and interrogation window were the same as those of the fully developed flow measurement. Steady streaming flow fields were calculated by ensemble averaging 50 velocity fields.

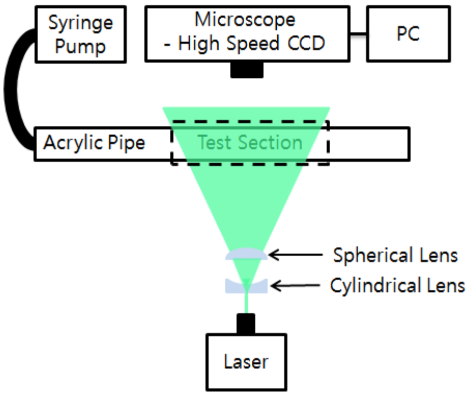


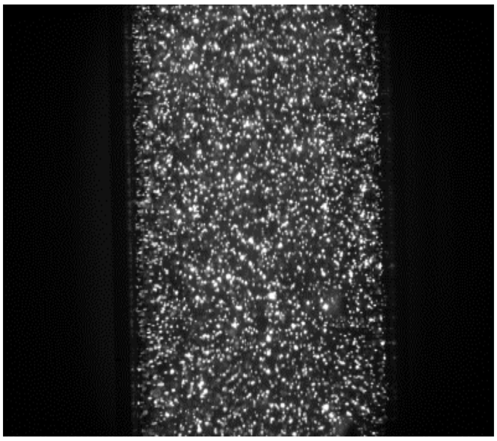
Fig. 1 Schematic diagram of the micro-PIV system for measuring fully developed laminar flow in a tube

III. Results

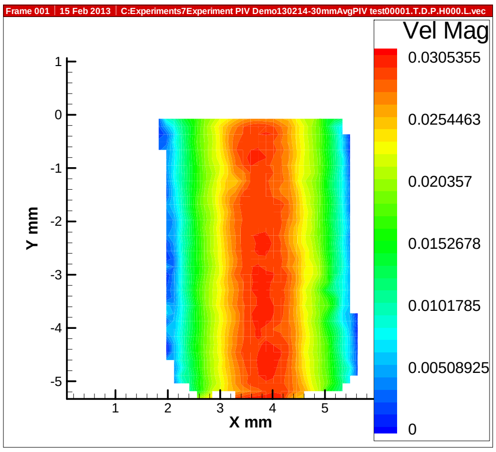
Test section was connected to the flexible tubing (Tygon AAC00012, Saint-Gobain, Paris, France), and the length of the tubing was long enough for flow development. The mean velocity inside of a tube was 15 mm/s, and the Reynolds number was 48. Fig. 2 showed a raw black and white image captured by a camera, measured velocity contour and velocity vectors. The measured velocity field was compared with the theoretical velocity profile of fully developed laminar flow. Measure velocities coincided to the theoretical parabolic velocity profile (1) well as shown in Fig. 3, which assured the accuracy of the velocity measurement system using a micro-PIV.

$$u(r) = u_{\max}(1 - \left(\frac{r}{R}\right)^2) \qquad (1)$$

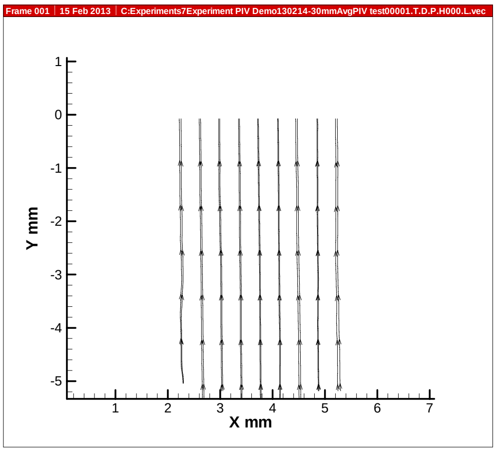
where u is the velocity, r is the radial coordinate, R is the radius of a tube, u_{max} is the centerline velocity.



(a)



(b)



(c)

Fig. 2 Velocity measurement in fully developed laminar flow using the micro-PIV system (a) raw image, (b) velocity contour and (c) velocity vectors

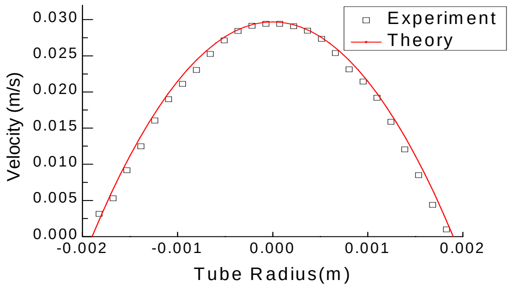


Fig. 3 Comparison of the velocities measured using the micro-PIV and the theoretical velocity profile

The radial oscillation of a wall attached bubble was measured using a high speed camera, and the maximum radial oscillation amplitude (ε_{max}) was calculated using a following equation;

$$\varepsilon_{\max} = \frac{H_{\max} - H_{\min}}{W} \quad (2)$$

where H_{max} and H_{min} are the maximum and minimum height of a bubble, respectively and W is the width of the bubble at neutral state.

The maximum radial oscillation amplitude was about 10%. The flow fields from an oscillating bubble was measured using a micro-PIV, and steady streaming flow fields were calculated by ensemble averaging 50 velocity fields. Strong upward jet flow with two symmetric vortices was shown in the measured flow fields, and the magnitude of maximum velocity was about 12 mm/s. The streaming velocity of 500µm bubble was within the same velocity ranges measured for the 80µm bubble oscillating at 16.8 kHz [10] and the 40 µm bubble oscillating at 40 kHz [9]. The streamline pattern was similar to the analytical solution of Rayleigh-Nyborg-Westervelt streaming [12] using the method of image in Stokes flow [9]. Some discrepancy between the analytical and measured velocity fields, such as the location of the center of circulating vortex and velocity magnitudes, should be related to irregular and inconsistent oscillation of bubble during the experiment.

IV. Conclusion

The streaming flow fields in the sagittal plane of a 500µm oscillating bubble were measured using a micro PIV system. The accuracy of velocity measurement of a micro-PIV system was confirmed by comparing the measure velocities with the theoretical velocity profile of fully developed laminar flow. The bubble was excited by the acoustic wave near the resonance frequency, and it showed wavy surface wall motion with 10% radial wall oscillation. Steady streaming flow fields were measured by ensemble averaging the flow fields, and they showed strong upward jet with two symmetric counter-rotating vortices. Streamline patterns of the measured flow fields were compared with those of the analytical solution, and they also showed a reasonable agreement. The maximum streaming velocity was 12 mm/s, which was within the velocity range measured by other researchers.

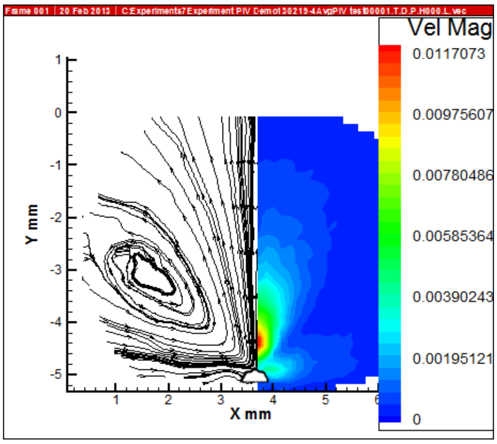


Fig. 4 The velocity fields of steady streaming flow around an oscillating bubble measured by the micro-PIV. The left panel shows streamlines and the right panel shows velocity contours

Acknowledgment

This work is supported by the Fundamental Research Supporting Program (2011-0012100) of the National Research Foundation of Korea.

References

[1] E. C. Unger, T. O. Matsunaga, T. McCreery, P. Schumann, R. Sweitzer and R. Quigley, "Therapeutic applications of microbubbles," *Eur. J. Radiol.*, vol. 42, pp. 160-168, May. 2002.

[2] K. Ferrara, R. Pollard and M. Borden, "Ultrasound microbubble contrast agents: fundamentals and application to gene and drug delivery," *Annu. Rev. Biomed. Eng.*, vol. 9, pp. 415-447, Aug. 2007.

[3] N. McDannold, N. Vykhodtseva and K. Hynynen, "Blood-brain barrier disruption induced by focused ultrasound and circulating preformed microbubbles appears to be characterized by the mechanical index," *Ultrasound Med. Biol.*, vol. 34, pp. 834-840, May. 2008.

[4] H. Andersson and A. Van den Berg, "Microfluidic devices for cellomics: a review," *Sens. Actuators B: Chem.*, vol. 92, pp. 315-325, Jul. 2003.

[5] T. Franke, A. R. Abate, D. A. Weitz and A. Wixforth, "Surface acoustic wave (SAW) directed droplet flow in microfluidics for PDMS devices," *Lab on a Chip*, vol. 9, pp. 2625-2627, Jun. 2009.

[6] W. Nyborg, "Acoustic streaming," *Physical Acoustics*, vol. 2, pp. 265-330, 1965.

[7] S. A. Elder, "Cavitation microstreaming," *J. Acoust. Soc. Am.*, vol. 31, pp. 54-64, 1959.

[8] R. H. Liu, J. Yang, M. Z. Pindera, M. Athavale and P. Grodzinski, "Bubble-induced acoustic micromixing," *Lab on a Chip*, vol. 2, pp. 151-157, Jul. 2002.

[9] P. Marmottant and S. Hilgenfeldt, "Controlled vesicle deformation and lysis by single oscillating bubbles," *Nature*, vol. 423, pp. 153-156, May. 2003.

[10] C. Wang, S. V. Jalikop and S. Hilgenfeldt, "Efficient manipulation of microparticles in bubble streaming flows," *Biomicrofluidics*, vol. 6, pp. 012801, Mar. 2012.

[11] P. Tho, R. Manasseh and A. Ooi, "Cavitation microstreaming patterns in single and multiple bubble systems," *J. Fluid Mech.*, vol. 576, pp. 191-233, Apr. 2007.

[12] S. J. Lighthill, "Acoustic streaming," *J. Sound Vibrat.*, vol. 61, pp. 391-418, Dec. 1978.