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Brief Communication

Computational study of steady streaming from oscillating microbubbles with uniform and wavy wall motions

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ABSTRACT

Steady streaming flow fields of a 5 μm bubble oscillating with uniform radial wall motion and a 500 μm bubble oscillating with wavy wall motion were simulated using a computational fluid dynamics method that incorporated fluid–structure interactions. The steady streaming flow fields for both bubbles were calculated, and they exhibited upward jet flow with two symmetrical counter-rotating vortices. The maximum streaming velocity ranged from a few to tens of millimeters per second. The simulated flow fields were compared with the theory and experimental measurements using particle image velocimetry. The simulation results agreed well with the theoretical and experimental data. Therefore, the proposed computational method would provide a useful tool to predict steady streaming flow fields of oscillating bubbles.

1. Introduction

A periodic oscillation of a bubble excited by acoustic waves generates steady mean flow fields via nonlinear effects (Lighthill, 1978). The steady streaming flow generated by an oscillating micro-sized gas bubble is particularly interesting for drug delivery enhancement that uses ultrasound contrast agents (UCAs), as well as for many microfluidic applications (Kuznetsova and Coakley, 2007). The flow fields generated by the oscillation of UCAs, which are gas bubbles a few micrometers in diameter encapsulated in stabilized shells, are an important physical factor affecting drug transport and tissue permeability (Kooiman et al., 2011; Juffermans et al., 2009). In addition, streaming flow from oscillating microbubbles has been used in mixing (Lee et al., 2012), sorting (Wang et al., 2012), and manipulating objects (Lee et al., 2011). Analytical studies on the flow induced by an oscillating bubble have been conducted (Davidson and Riley, 1971; Wu and Du, 1997), and Longuet-Higgins (1998) solved the viscous streaming flow around a single bubble undergoing small radial and lateral oscillations by using the second-order solutions of Rayleigh–Nyborg–Westervelt (RNW) streaming. Streaming flow fields induced by an oscillating bubble attached to the wall draw attention because flow fields induced by UCAs attached to a cellular membrane or by microbubbles on the substrate of a microfluidic device are particularly interesting (Qin et al., 2009). Marmottant and Hilgenfeldt (2003) solved the streaming induced by a microbubble using the method of images in Stokes flow (Blake and Chwang, 1974; Pozrikidis, 1992), in which a number of image singularities were placed on the opposite side of the wall. They showed that the leading-order far-field term of the solution represents dipole-like streaming. Their analytical solution provides valuable insight into the flow fields of an oscillating bubble attached to a wall, but its applicability is limited because of the assumption of a low Reynolds number and the approximation of a far field. Moreover, analytical solutions for realistic bubble oscillation applications, such as wavy bubble wall oscillation and multiple bubble

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oscillation in complex channel geometry, are not available. The use of a computational fluid dynamics (CFD) method was attempted to solve the steady streaming around a sessile bubble, but the boundary conditions were determined using the analytical solutions (Ko et al., 2009). Experimental studies measuring streaming flow fields have been conducted using particle image velocimetry (PIV) (Tho et al., 2007; Collis et al., 2010; Nazarinia et al., 2012). However, experimental difficulties still remain with regard to the control of bubble oscillations and the limitation of temporal and spatial resolutions in measuring high-frequency oscillation of micro-sized bubbles. Complete streaming flow solutions for acoustically activated bubbles are required for analyzing the transport phenomena in UCA-enhanced drug delivery and microfluidic devices, but they are not yet available.

In the present study, steady streaming flow fields were computed for an oscillating UCA with uniform radial wall motion and for an oscillating sessile bubble with wavy wall motion by employing fluid and structure interaction (FSI) via CFD methods. The CFD method was validated by comparing the computational flow fields with the analytical solutions for a 5 μm bubble which simulate UCA. The steady streaming simulation for a 500 μm-wide sessile bubble oscillating at its resonance frequency was also performed. The bubble streaming Reynolds number (Re_s) is

$$\mathrm{Re}_s = \varepsilon^2 \left(\frac{\omega a^2}{\nu}\right)^{1/2}, \tag{1}$$

where ε is the radial oscillation amplitude divided by the radius of a sphere (a), ω is the angular velocity of radial motion, and ν is the kinematic viscosity. The bubble streaming Reynolds numbers for 5 and 500 μm bubble were 0.02 and 0.7, respectively. Because the theory of RNW streaming is not valid for bubble streaming Reynolds numbers larger than 1, an experiment was performed to obtain the flow fields of a 500 μm bubble and the measured flow fields were compared with computational results.

2. Methods

2.1. Computational simulation

In order to simulate an oscillating UCA, a 5 μm diameter elastic sphere attached to a wall was modeled. The radial oscillatory motion of an attached bubble was accomplished by uniformly pressurizing the elastic wall of a sphere and simultaneously oscillating the center of a sphere vertically using a sinusoidal waveform with a frequency of 1.2 MHz. An axisymmetrical fluid zone (0.1 mm × 0.05 mm) was composed of approximately 27 000 rectangular meshes; further refinement of the mesh did not affect the converged solution. The density and viscosity of the fluid were 999 kg/m^3 and 0.001 N s/m, respectively. The FSI boundary condition was imposed on the bubble surface, and pressure boundary conditions were applied to the other boundaries, with the exception of the bottom wall where a bubble was attached. Unsteady flow field calculations were performed by solving Navier–Stokes equations using commercial software (ADINA ver. 8.8, ADINA R&D Inc., MA). One period of an oscillation cycle was divided into 100 time steps, and the periodic solutions converged within 50 flow cycles. The converged flow field solutions were transported to the post-processing software (Ensight v 9.2, CEI Inc., NC), and steady streaming velocities were calculated by time-averaging the velocities at each node during a period of oscillation for the converged solution.

In order to simulate a 500 μm-wide sessile bubble oscillating with a wavy wall motion, a hemispherical volume was modeled. Instead of solving the bubble dynamics in response to the acoustic wave, the wall motion of a bubble was given as a boundary condition for the flow field calculation. The elastic wall of a hemispherical volume, which was defined as an FSI boundary, was divided into zones, and an appropriate time varying pressure was applied along the boundary zones to simulate the wall motion of the oscillating bubble. The instantaneous wavy wall shape of a bubble was obtained from the images acquired by the high-speed camera. The wavy wall motion of a bubble was simulated by applying a distributed sinusoidal periodic pressure wave with a frequency of 12 kHz to the appropriate zone on the elastic hemispherical bubble wall. An axisymmetrical fluid zone (10 mm × 10 mm) was composed of approximately 24 000 rectangular meshes, and the grid dependence test was also checked.

2.2. Experiment

A 500 μm air bubble was generated using a micro-syringe on the vertical wall of a polycarbonate square cross-section chamber filled with water. For acoustic excitation, a sine wave voltage was generated by a function generator (33210A, Agilent Co., CA), and amplified to a few hundred volts by a voltage amplifier (PZD700, Trek Co., NY). The amplified voltage signal was transmitted to a cylinder-type piezoactuator (disk type PRYY-1133, PI Ceramics, Germany) attached to the bottom of the chamber. The bubble was excited by a 12 kHz voltage signal with an amplitude of 300 V, and the oscillation was observed using a high-speed camera (MIRO EX4, Vision Research Inc., NJ) attached to the zoom lens (VZMTM 450i eo, Edmund Optics Inc., NJ). The microscopic PIV system was used to measure the velocity fields, which consisted of a microscope (BX51, OLYMPUS Co., Japan), a high-speed camera, and a 1 W Nd:YAG 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 measurements. Fluorescent particles with a diameter of 7 μm (32-2B, Duke Scientific Co., CA) were used,