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Numerical simulation of single bubble dynamics under acoustic travelling waves

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ABSTRACT

The objective of this paper is to apply CLSVOF method to investigate the single bubble dynamics in acoustic travelling waves. The Naiver-Stokes equation considering the acoustic radiation force is proposed and validated to capture the bubble behaviors. And the CLSVOF method, which can capture the continuous geometric properties and satisfies mass conservation, is applied in present work. Firstly, the regime map, depending on the dimensionless acoustic pressure amplitude and acoustic wave number, is constructed to present different bubble behaviors. Then, the time evolution of the bubble oscillation is investigated and analyzed. Finally, the effect of the direction and the damping coefficient of acoustic wave propagation on the bubble behavior are also considered. The numerical results show that the bubble presents distinct oscillation types in acoustic travelling waves, namely, volume oscillation, shape oscillation, and splitting oscillation. For the splitting oscillation, the formation of jet, splitting of bubble, and the rebound of sub-bubbles may lead to substantial increase in pressure fluctuations on the boundary. For the shape oscillation, the nodes and antinodes of the acoustic pressure wave contribute to the formation of the "cross shape" of the bubble. It should be noted that the direction of the bubble translation and bubble jet are always towards the direction of wave propagation. In addition, the damping coefficient causes bubble in shape oscillation to be of asymmetry in shape and inequality in size, and delays the splitting process.

1. Introduction

The bubble acted by acoustic radiation forces in the acoustic field will generally exhibits various oscillation types [1,2], which can be applied in different practical technologies, such as medical ultrasound contrast agent [3–5] and the surface cleaning of precise instrument [6–8]. In medical diagnostics, ultrasound contrast agent refers to small gas-filled and encapsulated bubbles, which is required to maintain spherical bubble shape [9]. But the main problem is that surface instability of the bubble induced by the acoustic radiation force may lead to the collapse of bubble and shorten the duration time of the ultrasound contrast agent [10,11]. In surface cleaning system, the high-speed jet is supposed to generate when bubble expands and collapses close to the boundary, which is able to remove particles from the surface [12]. For these purposes, it is necessary to clarify the effect of acoustic waves on the distinct oscillation types of bubbles for different industrial demands.

Early experimental studies on single bubble dynamics in the acoustic field were reported in the works of Leighton [13], Blake and Keen [14], Ma and Xing [15], and Kim et al. [16]. Unlike bubble rising in a quiescent liquid, acoustic bubbles cannot be generated in precise size and location, which significantly affect the experimental observation [17,18]. Furthermore, while the bubble is oscillating and deforming, it is rather difficult to accurately measure the bubble shape, pressure distribution and flow pattern on condition without any interference [19,20]. Kim et al. [16] employed a high speed camera to investigate the single bubble behaviors near the wall. They found the bubble behaviors can be classified into three types, namely, volume, shape and splitting oscillation, depending the bubble size and acoustic pressure. Versluis at al. [21] emphatically investigated the shape oscillation of air bubble under specific ultrasonic frequencies by high speed camera. They found that the moving micro bubble presents the volume response and behaves in an asymmetric shape oscillation. Especially, Lee et al. [22] utilized the high speed camera to investigate

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Nomenclature

Roman letters

Bo	Bond number
c_l	sound velocity in the liquid
D	effective diameter of a bubble
f	frequency of acoustic field
g	gravitational acceleration
F	VOF function
F_a	acoustic radiation force
F_y	vertical component of acoustic radiation force
H	height of the simulation domain
H_ε	smoothed Heaviside function
I	transient acoustic wave intensity
k	wave number of the acoustic wave
L	radical width of domain
m	case dependent
n_l	exponent set to 7.15
p	acoustic pressure
P_a	pressure amplitude
p_0	reference pressure
P_∞	pressure at the bubble
r	angular coordination
R	instantaneous radius of a bubble
R_0	initial radius of a bubble
$\dot{R}$	first time derivative of R
$\ddot{R}$	second time derivative of R
Re	Reynolds number
t	time
T	period of acoustic wave
u	velocity vector
U	maximum horizontal speed at each step
V	maximum vertical speed at each step
V_b	volume of the bubble
v_0	velocity amplitude
y	vertical coordination

Greek letters

α	acoustic attenuation coefficient
κ	surface curvature
η	dynamic viscosity coefficient
μ	viscosity
μ_l	viscosity of the fluid
μ_g	viscosity of the gas
ρ	density
ρ_l	density of liquid
ρ_g	density of gas
γ	polytropic exponent
σ	surface tension coefficient
ω	angular frequency
τ	dimensionless time
ε	thickness of Heaviside function
ϕ	LS function

the visualization of bubble behaviors under ultrasonic excitation. They pointed out that the attached bubble shows a symmetric shape oscillation and the moving bubble presents an asymmetric shape oscillation. In present work, the concerned bubble behaviors are investigated near the wall, so the assumption of axisymmetric model is applied in the calculation.

To further investigate the mechanism of single bubble motion in ultrasonic field, theoretical solution and analysis has been also conducted. The bubble translates due to the primary Bjerknes force, and bubbles interact each other through the secondary Bjerknes force. But the theory of Bjerknes force is based on Rayleigh and Plesset equation (R-P equation), which has been extensively applied to describe the bubble dynamics. Ma et al. [15] used combined experimental and theoretical method to demonstrate the coalescence of gas bubbles in the acoustic field due to the Bjerknes force. They found that primary and secondary Bjerknes forces acting on two bubbles are same in magnitude, but in opposite direction, which indicates that two bubbles attract each other and and coalesce into one. It should be noted that with the above theoretical solutions, the single bubble is treated as a spherical shape, which can just capture spherical oscillation, but not suitable for the non-spherical oscillations. To simulate the bubble dynamics of shape oscillation in acoustic waves, Liu and Sugiyama [23] applied the boundary-fitted finite-volume methods to directly solve the continuity and the Navier-Stokes equation on the orthogonal curvilinear coordinate. They found that shape oscillation is less likely to occur for small single bubble (micrometer size), since the surface tension suppresses the developments of non-spherical shape modes.

In the recent years, significant progress has been made in understanding and modeling complex multiphase flows by the advanced flow simulation method. Wang and Blake [24,25] employed mixed Palerian-Lagrangian method and a modified boundary integral method to investigate the characteristics of non-spherical bubble (especially the bubble deformation with jet) in acoustic travelling and standing waves, respectively. They found that different wave types significantly contribute to single bubble behaviors. In acoustic travelling waves, the bubble jets develop at two poles of the bubble surface when subjected to a weak acoustic wave, while a vigorous jet develops along the direction of the wave propagation when subjected to a strong acoustic wave. In a weak (lower-pressure) acoustic standing wave, a bubble remains spherical shape when initiated at the node or antinode, while in a strong (lower-pressure) standing wave, bubble jet forms and is directed towards the node when initiated between the node and antinode. Nomura and Nishida [26] utilized the cubic-interpolated pseudo-particle (CIP)-combined and unified procedure (C-CUP) method to investigate the effect of the direction of the standing wave on bubble rising in a pipe. They found that bubble periodically accelerates and then decelerates due to passing through the antinode and node of the standing wave alternately when ultrasonic vibration is applied from the pipe bottom wall. Osterman and Dular [27] calculated the effect of initial ultrasonic bubble position near the moving solid boundary on the maximal temperature and pressure by VOF method. They found the maximal temperature increases and the maximal pressure decreases with rising distance from the solid boundary. Calvisi et al. [28] applied boundary integral method to simulate the non-spherical and axisymmetric bubbles driven by acoustic driving. They found that the value of acoustic force conducts a pronounced effect on the peak temperature and pressure caused by non-spherical bubble collapses.

In our previous work [17], the behaviors of bubble rising have been simulated and captured by the CLSVOF method. The comparisons of level set and CLSVOF method demonstrate CLSVOF method can be better in evaluating curvature and satisfy the conservation of volume in the re-initialization step. In addition, the surface tension and viscosity effect of rising bubbles are so different with bubbles in the acoustic field, as well as the significant bubble shape variations. Although the research on bubbles has received much attention in past years, the dynamics and deformation of single bubble in ultrasonic field are still not well understood, and hence additional researches are still needed. The objectives of the present paper are (1) to establish the Naiver-Stokes equation considering the acoustic radiation force to describe the bubble dynamics in acoustic field; (2) to introduce and validate the