Ultrasonics Sonochemistry 26 (2015) 119–127

Contents lists available at ScienceDirect

Ultrasonics Sonochemistry

journal homepage: www.elsevier.com/locate/ultson

Influences of non-uniform pressure field outside bubbles on the propagation of acoustic waves in dilute bubbly liquids

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ARTICLE INFO

Article history:
Received 28 November 2014
Received in revised form 22 January 2015
Accepted 27 February 2015
Available online 6 March 2015

Keywords:
Acoustic waves
Wave attenuation
Wave speed
Sonochemistry
Gas bubbles
Cavitation

ABSTRACT

Predictions of the propagation of the acoustic waves in bubbly liquids is of great importance for bubble dynamics and related applications (e.g. sonochemistry, sonochemical reactor design, biomedical engineering). In the present paper, an approach for modeling the propagation of the acoustic waves in dilute bubbly liquids is proposed through considering the non-uniform pressure field outside the bubbles. This approach is validated through comparing with available experimental data in the literature. Comparing with the previous models, our approach mainly improves the predictions of the attenuation of acoustic waves in the regions with large kR_0 (k is the wave number and R_0 is the equilibrium bubble radius). Stability of the oscillating bubbles under acoustic excitation are also quantitatively discussed based on the analytical solution.

1. Introduction

When acoustic waves are passing through bubbly liquids, bubbles inside the liquids will be forced into oscillations. Meanwhile, the speed of waves will be significantly altered due to the presence of bubbles and the energy of waves will be attenuated during the propagation (e.g. through energy dissipation by the bubble oscillations). This topic has been intensively investigated by numerous researchers over several decades [1–30], covering dilute bubbly liquids [1,2,5,6,15,17–21], shock wave propagations [3,7,26], relaxation effects [4], nonlinearity [9,11,22], wave-bubble interactions [8,10], and dual-frequency mode [13]. For a comprehensive review of this topic, readers are referred to van Wijngaarden [1], Ranjan et al. [8] and references therein. The speed and attenuation of acoustic waves in bubbly liquids depends on many parameters e.g., void fraction of the gases in the liquids, frequency and amplitude of the waves, bubble sizes and their distribution function. Understanding of the influences of above parameters on the propagation of acoustic waves promoted many applications, e.g., sonochemistry [31–33], acoustic measurement [34–36] and ocean engineering [37]. Specifically, in terms of sonochemistry, modelling of the wave propagation (e.g. speed and attenuation) in bubbly media may improve sonochemical reactor interior design by properly arranging the ultrasonic transducer through calculating the pressure fields in the reactors. For example, Dähnke et al. [27–30] proposed a method for calculating the time dependent pressure field in the sonochemical reactor of various shapes with inhomogeneous distributed wave parameters included. For more details of the sonochemical reactor design, readers are referred to systematic work by Pandit and his collaborators [31,32,38,39].

In the present paper, only a brief introduction of papers relating with this topic in the literature will be given. For more references and details, readers are referred to van Wijngaarden [1], Ranjan et al. [8] and Louisnard [12]. van Wijngaarden [2] derived a heuristic model for one-dimensional wave propagation in mixtures containing liquids and gas bubbles. This model was further extended by him and his collaborator [3–6] e.g. through considering the relaxation effects due to relative motion [4]. Caflisch et al. [17] proposed a mathematically rigorous model with suitable averaged equations. If some quantitatively unimportant terms in Caflisch et al. [17] are neglected, the equations of van Wijngaarden [2] are recovered. For linear cases, equations in Caflisch et al. [17] reduce to a classical work by Foldy [18] treating bubbles as multiple scatters of particles. The models developed by van Wijngaarden [2] and Caflisch et al. [17] have been widely extended in the literature. Louisnard [9–11] proposed a simplified model based on Caflisch et al. [17] and found that in the regime of inertial cavitation (above Blake threshold), a huge attenuation, which is three orders of magnitude larger than those predicted by linear theory, is observed. Recently, Jamshidi and Brenner [15] further extended

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http://dx.doi.org/10.1016/j.ultsonch.2015.02.016
1350-4177/

Nomenclature

Roman letters

a_n	a series of unknown coefficients of spherical harmonics
A	attenuation of the acoustic wave in the bubbly liquid
c_l	speed of sound in the liquid
c_m	complex speed of sound in the bubbly liquid
$D_{g,p}$	thermal diffusivity of the gas defined at constant pressure
$D_{g,v}$	thermal diffusivity of the gas defined at constant volume
$f(R_0)$	density function of bubble size distribution in the bubbly liquid
f	frequency of the acoustic wave
f_T	a critical value of the frequency defining valid regions of our new approach
k	wave number
n	total number of bubbles per unit volume; also order of spherical harmonics in bubble instability analysis
M_g	molecular weight of the gas in the bubble
P	average pressure in the liquid
P_∞	ambient pressure
P_A	acoustic pressure amplitude
r_s	vector of non-spherical bubble interface
R	instantaneous bubble radius
$\dot{R}$	first derivative of the instantaneous bubble radius
$\ddot{R}$	second derivative of the instantaneous bubble radius
R_0	equilibrium bubble radius
R_g	universal gas constant
t	time
T_∞	ambient temperature in the liquid
V	phase velocity of the acoustic wave in the bubbly liquid
x	non-dimensional perturbation of the instantaneous bubble radius
$\dot{x}$	first time derivative of x
$\ddot{x}$	second time derivative of x
Y_n	nth order spherical harmonics

Greek letters

α	void fraction of the bubbly liquid
β_{ac}	acoustic damping constant
β_{th}	thermal damping constant
β_{tot}	total damping constant
β_{vis}	viscous damping constant
γ	ratio of specific heats of the gas
κ	polytropic exponent
μ_l	viscosity of the liquid
μ_{th}	effective thermal viscosity
ρ_l	density of the liquid
σ	surface tension coefficient
φ	a function related with the solution of bubble interior problem
Φ	a simplified function related with the solution of bubble interior problem
ω	angular frequency of the acoustic wave
ω_0	natural frequency

the work by Louisnard [11] through considering the effects of compressibility up to the first order and an increase in thermal damping was observed. Kobelev and Ostrovsky [22] studied the nonlinear acoustic effects induced by spatial variation of bubble concentration due to bubble drift on the wave propagation in the bubbly liquids. Servant et al. [13] modified equations in Calflisch et al. [17] to account for the dual-frequency acoustic excitation and then numerically modelled the interactions between wave propagation and bubble clouds. Shock wave-bubble interactions have been also investigated by many researchers e.g. [26].

In the linear regime, based on van Wijngaarden's model [2], Commander and Prosperetti [19] proposed a series of equations for linear wave propagation in dilute bubbly liquids (i.e., low concentrations of gas bubbles). Comparing with experimental data (e.g., [20]), predictions given by Commander and Prosperetti [19] show considerable agreement except for regions with resonance effects and high frequencies. For the latter case, in terms of non-dimensional parameter, large discrepancies between experimental data and theoretical predictions in Ref. [19] are observed in the region with large kR_0. Here, k is the wave number and R_0 is the equilibrium bubble radius. Hence, kR_0 reflects the ratio between the bubble radius and wavelength in the liquid and also the bubble wall Mach number. Recently, Ando et al. [21] improved Commander and Prosperetti's approach by considering some terms up to the second order of the sound speed in the liquid, which was neglected in the work by Commander and Prosperetti [19]. The improvement is obvious but is still not satisfactory. Hence, in the present paper, for the completeness of the theory, we re-visited this classical problem by considering the non-uniform pressure distribution outside bubbles. Our formulas were validated using the experimental data in Ref. [20] and also compared with previous works (e.g. [19] and [21], respectively). Our findings will be prominent for the regions with large kR_0, which is usually experienced in sonochemical reactor design due to the enlarged parameter zone in current applications. In this region, oscillations induced by the non-uniform exterior pressure field could possibly modify the spherical shapes of bubbles into non-spherical ones. Hence, in the present paper, a quantitative analysis of non-spherical bubbles is also given for determining bubble instability in order to check the validity of the assumption of spherical bubbles employed in our model. Other applications of our approach include the development of high-frequency acoustic camera for high resolution imaging in turbid water [40,41] and green solvent using high-pressure liquid carbon dioxide [42–44] (noticing that large kR_0 in this case due to the limited value of sound speed).

The whole paper is organized as follows: in Section 2, theoretical analysis of the acoustic wave propagation with the assumption of the non-uniform pressure field outside bubbles is performed; in Section 3, the previous theoretical equations in the literature (e.g. [19,21]) are obtained with proper simplifications of the present approach; in Section 4, the validity of our approach is shown through comparisons with experimental data and influences of our approach are also demonstrated with several examples; in Section 5, a quantitative analysis of the bubble instability is given and the assumption of spherical bubbles employed by us in Section 2 and also in previous models is quantitatively discussed; in Section 6, the major findings in the present paper are summarized with a brief suggestion of future work.

2. Theoretical analysis

In this section, a new approach for predictions of the propagation of acoustic waves in dilute bubbly liquids is introduced. Here, we assume that the amplitude of acoustic pressure is small hence a linearization process can be employed. For propagation of linear acoustic waves in bubbly liquids, the equation is [19]