Applied Thermal Engineering 133 (2018) 483–492

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Wave propagation in liquids with oscillating vapor-gas bubbles

Yuning Zhang*, Zhongyu Guo, Xiaoze Du

Key Laboratory of Condition Monitoring and Control for Power Plant Equipment (Ministry of Education), School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing 102206, China

HIGHLIGHTS

- Effects of oscillating vapor-gas bubbles on wave speed are theoretically investigated.
- Three regions are defined in wave speed curve by employing two critical frequencies.
- Vapor mass fraction shows remarkable influences in regions 1 and 2.

ARTICLE INFO

Keywords:
Wave propagation
Cavitation
Vapor-gas bubbles
Wave speed
Cavitation modelling

ABSTRACT

In the present paper, wave propagation in liquids with oscillating vapor-gas bubbles is numerically investigated with a focus on the variations of the wave speed. A wide range of influencing parameters (including frequency, vapor mass fraction, bubble radius and void fraction) on the phenomenon are shown and discussed. According to the influences of frequency, the wave speed in the vapor-gas bubbly liquids could be categorized into three regions by two critical frequencies. In regions 1 and 3, the wave speed is frequency-independent while in region 2, the wave speed varies strongly with the frequency. Vapor mass fraction shows remarkable influences on the wave speed in regions 1 and 2 together with the critical frequencies separating the two regions. Finally, the influences of variations of the ambient temperature on the wave speed are discussed with demonstrating examples.

1. Introduction

In applied thermal engineering, bubbly flow are usually involved in boiling flows, channels and heat exchangers. The behavior of (vapor) bubbles are essentially important for the determination of the system performances (e.g. heat transfer efficiency [1,2], flow instability [3,4], and energy savings). In hydraulic systems, the bubbly (cavitation) flow could lead to serious unstable phenomenon [5,6], component damage [7], and unwanted vortices [8]. It should be noticed that the stable operations of traditional thermal power plant is also critical for adopting the renewable energies (e.g. wind energy [9]). In reality, there is always non-condensable gases (e.g. air) dissolved in the liquids. During the oscillations of vapor bubbles, those gases could diffuse across the bubble interface, forming a complex vapor-gas bubbles [10]. One of the physical effects of oscillating vapor-gas bubbles is their prominent influences on the wave propagation in the system. Specifically, the wave speed, attenuation and pressure distribution will be remarkably affected by the oscillations of vapor-gas bubbles. As wave propagation significantly alters the nucleation sites, growth rate and sliding velocity of bubbles, it is quite necessary to investigate this phenomenon thoroughly.

In the present paper, a brief review of the literature relating with the wave propagation in liquids with gas, vapor or vapor-gas bubbles are demonstrated. For the wave propagation in bubbly liquids, the two paramount parameters are wave speed and wave attenuation [11], which are generally required in the many engineering practice (e.g. transient flow simulation and water hammer defense). During the wave propagation, the oscillations of the bubble could transfer the wave energy into various kinds of motions (e.g. acoustic emissions), leading to the wave energy dissipation (or wave attenuation). In total, there are three kinds of damping mechanisms (viscous, thermal and acoustic damping mechanisms respectively) [12,13]. For a detailed review and survey of the damping mechanisms, readers are referred to our previous work [12] and related references therein. Generally, the wave speed and attenuation strongly depend on many bubble related parameters (e.g. bubble radius and void fraction) and also acoustic wave parameters (e.g. frequency), leading to a complex scenario for the analysis.

As the first step, the cases of gas bubbles will be introduced. For gas bubbles, Commander and Prosperetti [11] proposed a well-known framework for the propagation of linear acoustic waves in gassy liquids.

---

* Corresponding author.
E-mail address: y.zhang@ncepu.edu.cn (Y. Zhang).

https://doi.org/10.1016/j.applthermaleng.2018.01.056
Received 28 July 2017; Received in revised form 1 December 2017; Accepted 16 January 2018

Nomenclature

Roman letters (alphabetical order)

c_H	constant speed in the high-frequency limit
c_l	wave speed in the pure liquid
c_L	constant speed in the low-frequency limit
c_m	complex wave speed
c_{ph}	wave (phase) speed
c_{pl}	liquid specific heat at constant pressure
D_b^T	thermal diffusivity of the vapor-gas bubbles
D_l^T	thermal diffusivity of the liquid
f_L	low critical frequency separating region 1 and region 2 defined in the present paper
f_H	high critical frequency separating region 2 and region 3 defined in the present paper
h_{lv}	latent heat of vaporization
ΔH_{vap}^*	non-dimensional parameter of the enthalpy of vaporization
J_c^*	non-dimensional mass transfer flux across the interface of vapor-gas bubbles
J_{max}^*	a parameter relating with the mass transfer rate of the vapor
k_L	a constant for the calculation of the low critical frequency
k_H	a constant for the calculation of the high critical frequency
n	total number of vapor-gas bubbles within a unit volume of the mixture
p_0	ambient pressure of the surrounding liquids
$p_{in,eq}$	equilibrium pressure at the bubble side of the bubble-liquid interface
Pe_b	bubble Péclet number
	liquid Péclet number
R_0	bubble equilibrium radius
Re	real part of the complex function
Sh_D	Sherwood number
T_0	ambient temperature
ΔT_c^I	a non-dimensional parameter reflecting the temperature variations across the bubble-liquid interface during bubble oscillations
Y_0	vapor mass fraction in the vapor-gas bubbles

Greek letters (alphabetical order)

β	void fraction of bubbles in the liquid
β_{tot}	total damping constant
γ	specific heat ratio of the vapor-gas mixture inside the bubble
ρ_l	density of the liquid
ρ_v	density of the vapor
σ	surface tension coefficient of the liquid
Φ	a transfer function between the variations of the internal pressure and the response of the bubble radius changes
ψ	correction term of surface tension
ω	angular frequency of the external acoustic field
ω_0	natural frequency of the oscillating vapor-gas bubble

This framework has been adopted by many researchers [14–18] with further modifications e.g. the high order scattering of bubbles [14], bubble-bubble interactions [16] and non-uniform pressure distribution [17]. For the nonlinearity, Caflish et al. [19] derived the equations of nonlinear acoustic wave propagation in bubbly liquids based on the microscopic description with a focus on the heat conduction. Louisnard [20,21] combined the bubble dynamics equations with the nonlinear equations of Ref. [19] and found that the attenuation of nonlinear wave is three times more than that of linear wave. Other paramount contributions include the effects of liquid compressibility by Jamshidi and Brenner [22], multiple scattering theory by Doc et al. [23], interphase heat transfer by Kudryashov and Sinelshchikov [24], nonlinear standing ultrasonic waves by Sastre and Vanhille [25] and nonlinear design theory by Dogan and Popov [26]. For the cases with intensive pressure wave or shock wave, readers are referred to Refs. [27–29]. There are also many studies relating with unconventional mediums (e.g. liquid aluminum [30] and marine sediments [31]) and confined area (e.g. pipeline [32,33], duct [34], and mini-channels [35]).

Now, previous studies on the acoustic wave propagation in liquids with vapor bubbles [36–46] or vapor-gas bubbles [47–53] will be introduced and discussed. For the cases of vapor or vapor-gas bubbles, the aforementioned theoretical framework set up for the gas bubbles are still very valuable and generally adopted with some necessary revisions (e.g. strong evaporation/condensation rate of vapor inside the bubbles [49]). As shown in our recent work [37], the mass transfer caused by vapor evaporation/condensation plays an important role on the damping mechanisms of bubble oscillations. For a detailed review of vapor bubbles, readers are referred to Prosperetti [36]. Zhang et al. [38] investigated the stability mechanisms of an oscillating vapor bubble through incorporating both the spherical and stiffness stabilities. Ardron and Duffey [39] studied the sound speed and attenuation in a transient non-equilibrium vapor-liquid flow. Xu and Chen [40] considered the mechanical and thermal non-equilibrium status during the wave propagation. Coste and Laroche [41] studied this phenomena in a standing-wave tube. For heat transfer engineering (e.g. heat transfer mechanism [42] and flow boiling [43]), vapor bubbles are also of great interest. For the vapor-gas bubbles, due to its physical complexity, there are only very limited studies. Based on the framework of Commander and Prosperetti [11], Fuster and Montel [49] proposed a set of formulas to investigate the oscillating vapor-gas bubbles. In Ref. [49], liquid compressibility was ignored during the modelling. Nigmatulin et al. [47] numerically studied the vapor-gas bubbles under acoustic waves and a sudden pressure change through incorporating the capillary effects and phase transitions. Prosperetti [10] studied the effect of the amount of gas in vapor-gas bubbles on the wave propagation and found that the presence of a very small amount of gas can also have a significant impact on the behavior. Other paramount contributions include Yasui [50,51], Gubaidullin et al. [52] and Khabeev [53].

Based on the literature survey, the predictions of the wave speed and attenuation within a wide range of parameter zone are still not clear. Briefly speaking, the contributions of the present paper are threefold. Firstly, the wave (phase) speed and attenuation in liquids containing oscillating vapor-gas bubbles are accurately predicted based on a revised model within a wide range of parameter zones (e.g. from 10^{-4} Hz to 5×10^7 Hz in terms of frequency). Secondly, three regions are proposed to categorize the types of the wave propagation based on the frequency response of the wave speed (referring to Figs. 1 and 2) together with discussions on the low-frequency and high-frequency limits. Such wide range of parameter zones are emphasized here because the behaviors of the vapor-gas bubbles are quite different from those of gas bubbles. For example, as shown in Fig. 2, the wave speed of gas bubble will be a constant for frequencies lower than 3×10^3 Hz while the wave speed of vapor-gas bubbles will still strongly depend on the frequency. Thirdly, the key assumptions employed in the model (e.g. ignoring the variations of ambient temperature) are quantitatively evaluated together with the influencing parameters on the cases of the low-frequency and high-frequency limits.

The following sessions of the present paper is organized as follows. In Section 2, the full model of three-phase (vapor, gas and liquid respectively) bubbly flow is introduced together with the reduced