



Modeling quiescent phase transport of air bubbles induced by breaking waves

Fengyan Shi^{*}, James T. Kirby, Gangfeng Ma

Center for Applied Coastal Research, University of Delaware, USA

ARTICLE INFO

Article history:

Received 17 February 2010

Received in revised form 7 June 2010

Accepted 5 July 2010

Available online 11 July 2010

Keywords:

Air bubble

Breaking wave

RANS model

ABSTRACT

Simultaneous modeling of both the acoustic phase and quiescent phase of breaking wave-induced air bubbles involves a large range of length scales from microns to meters and time scales from milliseconds to seconds, and thus is computationally unaffordable in a surfzone-scale computational domain. In this study, we use an air bubble entrainment formula in a two-fluid model to predict air bubble evolution in the quiescent phase in a breaking wave event. The breaking wave-induced air bubble entrainment is formulated by connecting the shear production at the air–water interface and the bubble number intensity with a certain bubble size spectra observed in laboratory experiments. A two-fluid model is developed based on the partial differential equations of the gas–liquid mixture phase and the continuum bubble phase, which has multiple size bubble groups representing a polydisperse bubble population. An enhanced 2-DV VOF (Volume of Fluid) model with a $k - \epsilon$ turbulence closure is used to model the mixture phase. The bubble phase is governed by the advection–diffusion equations of the gas molar concentration and bubble intensity for groups of bubbles with different sizes. The model is used to simulate air bubble plumes measured in laboratory experiments. Numerical results indicate that, with an appropriate parameter in the air entrainment formula, the model is able to predict the main features of bubbly flows as evidenced by reasonable agreement with measured void fraction. Bubbles larger than an intermediate radius of $O(1 \text{ mm})$ make a major contribution to void fraction in the near-crest region. Smaller bubbles tend to penetrate deeper and stay longer in the water column, resulting in significant contribution to the cross-sectional area of the bubble cloud. An underprediction of void fraction is found at the beginning of wave breaking when large air pockets take place. The core region of high void fraction predicted by the model is dislocated due to use of the shear production in the algorithm for initial bubble entrainment. The study demonstrates a potential use of an entrainment formula in simulations of air bubble population in a surfzone-scale domain. It also reveals some difficulties in use of the two-fluid model for predicting large air pockets induced by wave breaking, and suggests that it may be necessary to use a gas–liquid two-phase model as the basic model framework for the mixture phase and to develop an algorithm to allow for transfer of discrete air pockets to the continuum bubble phase. A more theoretically justifiable air entrainment formulation should be developed.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

The simulation of breaking wave-induced bubbly flows is a great challenge due to the complexity of air entrainment and bubble evolution processes, and to the range of spatial and temporal scales involved. According to previous studies based on field or laboratory experiments (e.g., Thorpe, 1982; Garrett et al., 2000; Terrill et al., 2001; Deane and Stokes, 2002), the lifetime of wave-generated bubbles can be categorized into two phases. The first phase is called the acoustic phase, during which bubbles are entrained and fragmented inside the breaking wave crest. The second phase happens after bubble creation processes cease and the newly formed bubbles evolve under the influence of turbulent diffusion, advection, buoyant

degassing, and dissolution. Because this phase is acoustically quiescent, it is called the quiescent phase. The duration of the acoustic phase is very short and the time scale of bubble fragmentation is typically tens of milliseconds (Leighton et al., 1994). Therefore, Direct Numerical Simulations (DNS) of the acoustic phase require higher resolution in both time and space in order to capture the details of the air entrainment process, making computations so expensive that the main use of this kind of model will be limited to applications to studies of bubble creation mechanisms.

Instead of a direct simulation of the air entrainment process, the use of an initial air entrainment formulation in modeling of bubbly flows was reported recently (Moraga et al., 2008; Shi et al., 2008). The idea was to prescribe air bubbles entrained during the acoustic phase in a two-phase model using a bubble entrainment formulation. The model fed with the initially entrained bubbles simulates bubble plumes and requires much less spatial and temporal reso-

^{*} Corresponding author. Tel.: +1 302 831 2449.

E-mail address: fyshi@udel.edu (F. Shi).

lution than needed to capture the air entrainment process. The initial bubble number density and bubble size distribution were formulated based on theoretical and observational studies.

In a simulation of air bubbles entrained by naval surface ships, Moraga et al. (2008) presented a sub-grid model that detects the location of the air bubble entrainment region. The localized region of high void fraction is bounded by the surface at which the downward liquid velocity reaches a certain value (0.22 m/s was used in Moraga et al.'s application). The initial bubble size distribution in the localized region follows the bubble size spectrum measured by Deane and Stokes (2002) who suggested that, at the beginning of the quiescent phase, the size spectrum follows a certain power-law scaling with bubble radius. Deane and Stokes (2002) found two distinct mechanisms controlling the size distribution, depending on bubble size. For bubbles larger than the Hinze scale (about 1 mm in Deane and Stokes (2002)), turbulent fragmentation determines bubble size distribution, resulting in a bubble density proportional to $r_b^{-10/3}$, where r_b is bubble radius. Bubbles smaller than the Hinze scale are generated by jet and drop impact on wave face, with a bubble density proportional to $r_b^{-3/2}$. The Hinze scale, which separates the two processes, is the scale where turbulent fragmentation ceases, and is related to the turbulent dissipation rate and the surface tension. A parallel study was carried out by Shi et al. (2008), who used the same strategy to avoid modeling of the bubble entrainment process, but applied a different air entrainment formulation for breaking wave-induced air bubbles. The initial air bubble entrainment is formulated by connecting the flow shear stress at air–water interface and the bubble number intensity with the bubble size spectra as observed by Deane and Stokes (2002). The model was used to simulate wave transformation, breaking, and bubble generation and evolution processes over a barred beach in the Large Wave Flume at Oregon State University. Although there were no data for bubble quantities for comparison, the model results showed that the evolution pattern of void fraction at the water surface is consistent with bubble foam signatures sensed by video systems during the laboratory experiments. The study showed the potential to use an air entrainment formulation in modeling of air bubbles inside the surfzone.

Models based on the volume or ensemble averaged two-fluid approach seem best suited for practical use in modeling air bubbles in large-scale systems such as breaking wave-induced bubbles in coastal water because of their efficiency (Sokolichin et al., 2004). Carrica et al. (1998) reported a multiphase model for simulating bubbly two-phase flow around a surface ship. The bubble phase is modeled using the integrated Boltzmann transport equation for the bubble size distribution function (Guido-Lavalle et al., 1994) and the momentum equations for the gaseous phase. The liquid phase is modeled using mass and momentum equations for liquid along with a turbulence closure. The gas–liquid interactions are represented by drag, pressure, lift and buoyancy forces. The model accounts for intergroup bubble transfer through bubble coalescence, dissolution and breakup. The recent work of Moraga et al. (2008) followed the approach of Carrica et al. (1998). A similar approach is used by Buscaglia et al. (2002) who developed a double-averaged multiphase model without taking into account the momentum balance in the bubble phase. The exclusion of momentum equations for the bubble phase makes the model more efficient, especially in a simulation involving a number of bubble groups with different sizes. Shi et al. (2008) used the method of Buscaglia et al. (2002) in the preliminary investigation of air bubbles generated by breaking waves inside the surfzone. Although Carrica et al.'s approach is more rigorous in theory in terms of the Favre-averaging, Buscaglia et al.'s method still remains a valuable alternative as a computational efficient model for practical purposes.

The focus of the present study is to estimate bubble population evolution and spatial distribution in a breaking wave event. Due to

the complexity of wave breaking processes and the lack of sufficient knowledge of bubble entrainment and water–bubble interaction, we intend to develop a simple and physically based model. We will show developments of the model based on Buscaglia et al. (2002) and components representing bubble coalescence, breakup and bubble-induced turbulence effects. The model is tested against laboratory data reported by Lamarre and Melville (1991), referred to hereafter as LM91.

2. Two fluid model

Buscaglia et al. (2002) derived a two-fluid model using a double-averaging approach. The first average was performed at spatial scales of the order of the bubble-to-bubble spacing L_{bb} and resulted in mass and momentum conservation equations for a gas–liquid mixture. The second average was carried out using Reynolds averaging over the gas–liquid mixture equations at larger turbulence scales. The governing equation for the bubble phase was the Reynolds-averaged mass balance equation, taking into account bubble diffusion due to turbulence. The two-fluid model of Buscaglia et al. (2002) involves a liquid chemistry process which incorporates oxygen and nitrogen dissolution in applications to bubble plumes. Two bubble groups, i.e., oxygen group and nitrogen group, with a uniform bubble size were considered. No bubble breakup or coalescence is taken into account in their model.

In this section, we review the basic equations of the two-fluid model derived by Buscaglia et al. (2002). Some modifications and additions are made in order to represent polydisperse bubble population, bubble-induced turbulence, bubble breakup and coalescence.

2.1. Mixed fluid phase

The double-averaged equations include mass conservation and momentum equations for the mixture fluid phase:

$$\nabla \cdot \mathbf{u}_m = 0, \quad (1)$$

$$\frac{\partial \mathbf{u}_m}{\partial t} + \mathbf{u}_m \cdot \nabla \mathbf{u}_m + \frac{1}{\rho_0} \nabla P_m = \frac{1}{\rho_0} \nabla \cdot (2\mu_t \mathbf{S}) - \frac{\rho_m}{\rho_0} g \mathbf{k}, \quad (2)$$

where $\mathbf{u}_m$, P_m and ρ_m represent the mixture quantities of fluid velocity, pressure and density, respectively. $\mathbf{k}$ is a vertical unit vector. ρ_0 is a reference density which has replaced ρ_m in all terms but the gravity term using the Boussinesq approximation. It is noted that the Boussinesq approximation is invalid for the mixture fluid with a high and inhomogeneous distribution of void fraction. It is assumed in the present study that high void fraction is localized within a limited region so that the pressure gradient caused the spatial variation in density would not affect much the overall wave form evolution. The assumption is confirmed to be appropriate in the numerical results shown in Section 3.2.

$\mathbf{S}$ represents the rate of strain tensor of the mean flow defined by

$$\mathbf{S} = \frac{1}{2} (\nabla \mathbf{u}_m + \nabla^T \mathbf{u}_m), \quad (3)$$

μ_t is the eddy viscosity coefficient which is related to turbulent kinetic energy, k , and turbulent dissipation, ϵ , in the $k - \epsilon$ turbulence equations shown in Section 2.3. The relation between k and ϵ can be expressed by

$$\mu_t = \rho_0 C_\mu \frac{k^2}{\epsilon}, \quad (4)$$

where C_μ is an empirical coefficient and $C_\mu = 0.09$ was used as suggested by Rodi (1980).

The last term in (2) represents the buoyancy force which can be evaluated by

Download English Version:

<https://daneshyari.com/en/article/4552453>

Download Persian Version:

<https://daneshyari.com/article/4552453>

[Daneshyari.com](https://daneshyari.com)