International Journal of Multiphase Flow 98 (2018) 36–44

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

A more fundamental wall lubrication force from turbulent dispersion regularization for multiphase CFD applications

Nazar Lubchenko, Ben Magolan, Rosie Sugrue, Emilio Baglietto*

Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

ARTICLE INFO

Article history:
Received 3 June 2017
Revised 25 August 2017
Accepted 7 September 2017
Available online 8 September 2017

ABSTRACT

Accurate prediction of the gas volume fraction distribution in the near-wall region is critical for the simulation of bubbly flows. Resolving the near-wall gas profile remains a considerable challenge for multiphase computational fluid dynamics (M-CFD) simulations based on the Eulerian–Eulerian framework, where the coupling of interfacial momentum exchange through closure relations for lift and turbulent dispersion leads to a non-physical gas accumulation in the wall-layer cells. Wall lubrication models have been developed in an attempt to remedy this behavior by providing an artificial force to move the void fraction profile away from the wall. Currently, such models suffer from a severe lack of generality, being characterized by overspecified formulations that are highly dependent on tunable coefficients; moreover, their application often leads to dramatic overcorrections of the void fraction profile, resulting in the first few wall-layer cells being unphysically devoid of the gas phase. Here, we propose a new wall lubrication model that is derived through regularization of turbulent dispersion in the near-wall region to account for the decreasing cross-sectional area of the bubbles. This novel approach is assessed via simulation of experiments from the Liu and Bankoff database using a custom modified version of the twoPhaseEulerFoam solver in OpenFOAM v3.0.1. Comparison with the original model of Antal et al. (1991) and a mesh sensitivity study demonstrate the model's strong performance in volume fraction prediction in addition to its ability to scale well with varying thicknesses of the first wall-layer. This methodology is entirely general and can be used to derive a wall lubrication model from any turbulence dispersion model and assumed void fraction profile. The approach could further be extended for application to multi-group bubble size models.

1. Introduction

Understanding and predicting two-phase flow behavior is essential for a wide range of industrial applications including nuclear reactors and various chemical processes. Of particular interest is the distribution of the gas volume fraction profile in the near-wall region, as it directly affects other flow parameters such as turbulent quantities and, when involved, heat transfer. As the application of multiphase computational fluid dynamics (M-CFD) based on the Eulerian–Eulerian two-fluid model (Bestion et al., 2009; Lo et al., 2011; In and Chun, 2009) is gaining increasing popularity in the attempt to deliver predictions of design flow quantities, great care must be taken to ensure that these methods are equipped with physically based closure relations for turbulence and interfacial momentum exchange.

Interfacial momentum exchange is partitioned into a series of component forces that describe the interaction between the gas and liquid phases, which together impact the resulting volume fraction distribution, while also affecting other flow parameters such as velocities and turbulent quantities. In the axial (primary) flow direction, the drag force is the dominant mechanism that opposes the buoyancy force and determines the terminal rising velocity of the bubbles. Likewise, in the lateral flow direction it is common practice to model the effects of only lift and turbulent dispersion; such treatment however disregards the effects of the walls on the gas distribution and most often leads to non-physical overshoots of the gas fraction in the near wall computational cells in case of upward flow.

Several wall lubrication models have been proposed, which attempt to correct the non-physical gas accumulation through prescription of an artificial force in the near-wall region to drive

* Corresponding author.
E-mail addresses: nazarij@mit.edu (N. Lubchenko), emiliob@mit.edu (E. Baglietto).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2017.09.003

the gas phase away from the wall. Antal et al. (1991) derived the first such closure relation for cylindrically-shaped bubbles in laminar flow, by assuming asymmetrical drainage of the liquid around the bubble in the near-wall region; the model coefficients were then adjusted to account for the spherical bubble shape. While modifications were later advanced by Tomiyama (1998) and Frank et al. (2008), all models deriving from the Antal et al. (1991) lineage inevitably suffer from a lack of generality in their formulation, being highly dependent on the calibration coefficients that require re-tuning for each flow condition. Most importantly, all such models typically overcorrect for the issue, prescribing a disproportioned lubrication force that propagates a few bubble diameters away from the wall, thereby pushing all gas away from the wall and further influencing the bulk distribution. Consequently, it is common practice to neglect modeling wall lubrication in engineering applications that are highly sensitive to void fraction at the wall, such as boiling (Mimouni et al., 2008).

Recently, two modeling approaches have been proposed that both involve deactivation of the lift force in the near-wall region. Shaver and Podowski (2015) achieve this by forcing the lift coefficient to zero near the wall and neglecting wall lubrication; they model solely the effects of turbulent dispersion, which leads to a flat volume fraction profile in the near-wall region. Vaidheeswaran et al. (2017) do not solve for momentum transfer near the wall, effectively truncating the lift force to zero thereby obtaining a flat volume fraction profile; from this flattened profile they reconstruct a parabolic volume fraction profile based on geometrical arguments by considering the bubble chord length.

In the present work, a wall lubrication model is advanced that is fundamentally different from previous works. While sharing some similarity with the work of Vaidheeswaran et al. (2017) in that it relates the volume fraction profile to the bubble geometry, it considerably deviates from their approach by associating this dependence with the cross-sectional area of the bubble. More importantly, in this work the void fraction profile is *resolved* in the near-wall layer through modification of the wall lubrication force, as opposed to *reconstructed* solely based on geometric arguments. This is accomplished through regularization of turbulent dispersion in the near-wall region in order to restore the desired behavior of the gas volume fraction. It is important to note that the present work was conducted without any awareness of the work of Vaidheeswaran et al. (2017), and the commonalities are a confirmation of the physical soundness of the underlying idea.

This newly proposed approach for modeling wall lubrication is assessed on the simulation of two representative cases from the Liu and Bankoff experimental database (Liu, 1989; Liu and Bankoff, 1993a; Liu and Bankoff, 1993b) using a custom version of the twoPhaseEulerFoam solver of OpenFOAM v.3.0.1. The model is directly compared with the existing model of Antal et al. (1991) to evaluate its merits. A sensitivity study of the first wall layer element is also performed to examine the effect of mesh size on volume fraction distribution.

Section 2 of this paper motivates the need for this work by delving into the formulation of momentum closures, highlighting the limitations of current wall lubrication models, and examining the collective behavior of lateral redistribution forces on the void fraction profile. Section 3 presents the new wall lubrication model through an analysis of the physical behavior of the void fraction profile, introduced its derivation from the turbulent dispersion force, and lastly, discusses the stability and limitations of the current implementation in CFD. Section 4 discusses the model assessment on the Liu and Bankoff test cases (Liu, 1989) as well as providing a sensitivity study for the first wall layer element. Lastly, Section 5 concludes with a discussion of the present model's extension to other turbulent dispersion models along with its applicability to multi-group methods.

2. Governing equations

The Eulerian–Eulerian framework, or two-fluid model (Bestion et al., 2009; Lo et al., 2011; In and Chun, 2009), is employed in this analysis. Turbulence is modeled solely for the liquid phase using the standard k-ε model (Launder and Spalding, 1974). Interfacial forces are modeled in accordance with the Bubbly And Moderate void Fraction (BAMF) model (Sugrue et al., 2017), which consists of the drag coefficient model by Tomiyama (Tomiyama et al., 1998), a constant lift coefficient of 0.025 with adjustment in the near wall region (Shaver and Podowski, 2015), and the turbulent dispersion model by Burns (Burns et al., 2004). Each of the three forces are discussed first in the following sections, and a review of wall lubrication models is presented later to highlight and motivate the present work. Lastly, the collective behavior of the lateral redistribution forces is examined to explore how the combination of these forces serve to impact the resulting void fraction profile.

2.1. Drag force

The drag force quantifies the momentum exchange due to the relative motion between the gas and liquid phases. It opposes the relative motion of the gas phase and is expressed as:

$$\mathbf{F}_D = -\frac{3}{4}\frac{C_D}{D_b}\alpha\rho_L|\mathbf{V}_G - \mathbf{V}_L|(\mathbf{V}_G - \mathbf{V}_L) \tag{1}$$

Here, D_b is the average bubble diameter and C_D is the drag coefficient which is determined from the drag model. Since most drag models for bubbly flow work well in low void fraction regimes (as demonstrated by Rzehak and Krepper (2013)), the choice of the model has minimal impact on the results. In the present paper, the Tomiyama drag coefficient model assuming moderate contamination by surfactants is utilized (Tomiyama et al., 1998):

$$C_D = \max\left(\min\left(\frac{24}{\mathrm{Re}_b}\left(1 + 0.15\mathrm{Re}_b^{\,0.687}\right), \frac{72}{\mathrm{Re}_b}\right), \frac{8}{3}\frac{\mathrm{Eo}}{\mathrm{Eo}+4}\right) \tag{2}$$

where bubble Reynolds number Re_b and Eötvös number Eo are:

$$\mathrm{Re}_b = \frac{\rho_L|\mathbf{V}_G - \mathbf{V}_L|D_b}{\mu_L} \tag{3}$$

$$\mathrm{Eo} = \frac{g(\rho_L - \rho_G){D_b}^2}{\sigma} \tag{4}$$

2.2. Lift force

The lift force accounts for the lateral motion of bubbles due to velocity gradients in the continuous phase (Drew and Lahey, 1987):

$$\mathbf{F}_L = -C_L\alpha\rho_L|\mathbf{V}_G - \mathbf{V}_L| \times (\nabla \times \mathbf{V}_L) \tag{5}$$

The lift coefficient, C_L, is currently assumed to depend mostly on the size of the bubbles while the influence of turbulence properties is not fully understood (Tomiyama, 1998). A positive lift coefficient is used for small spherical bubbles of low Eötvös number, which results in wall-peaked distribution of void fraction; conversely, a negative coefficient is used for large deformable bubbles that results in a center-peaked distribution. In the present paper, we focus only on wall-peaked distributions in the low Eötvös number regime. There remains no consensus for the value of the lift coefficient should be, with models delivering predictions that vary by more than an order of magnitude. It was recently demonstrated that for small bubbles a value of the order of 0.025 is most appropriate (Baglietto and Christon, 2013).

The lift force reaches its maximum at the wall, where the gradient of liquid velocity is the highest. This results in the already mentioned unphysical asymptotic spike for the gas fraction at the walls. As the introduction of an 'artificial' wall lubrication force