Numerical Simulation of the Buoyancy-Driven Bouncing of a 2-D Bubble at a Horizontal Wall

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Abstract. The rise of a buoyant bubble and its interaction with a target horizontal wall is simulated with a 2-D numerical code based on the Boundary Element Method (BEM). Developed from a viscous potential flow approximation, the BEM takes into account only the part of the energy dissipation related to the normal viscous stresses. Hence, a simple analytical model based on lubrication approximation is coupled to the BEM in order to compute the drainage of the interstitial liquid film filling the gap between the bubble and the near wall. In this way the bubble–wall interaction is fully computed: the approach stage, the bubble deformation stage and, depending on the values of the Reynolds number and the Weber number, the rebound and the bubble oscillations. From computation of both the bubble interface motion and the liquid velocity field, a physical analysis in terms of energy budget is proposed. Though, in the present study, the bubble under consideration is basically supposed to be a 2-D gaseous cylinder, a comparison between our numerical results and the experiments of Tsao and Koch (1997) enlightens interestingly the physics of bouncing.

1. Introduction

Bubbly flows play a key role in many chemical engineering processes (gas–liquid extraction, fluidised beds, flotation, sedimentation, electrochemical reactors, etc.) as well as in nature (air entrainment due to breaking waves, chutes and spillways, volcanic activity, etc.).
Investigation of the motion of a deformable bubble at the vicinity of a rigid wall is of particular relevance as it is an essential prerequisite for the development of many Eulerian/Lagrangian codes devoted to the simulation of bubbly flows. Very often, there is actual difficulty in choosing the convenient boundary condition for the dispersed phase at walls; many behaviours are observed: bubble sliding along the wall, bouncing or “sticking” on the wall.

In the literature, most of the theoretical, numerical or experimental studies devoted to the interaction of an inclusion with a wall focus on the case of solid spheres (see, e.g. Brenner, 1961; Dagan et al., 1982; Ambari et al., 1984; Søndergaard et al., 1990; Gondret et al., 1999). The impact and bouncing of droplets on hydrophobic substrates has been recently studied by Richard and Quere (2000). However, here again, like for many other experimental studies involving solid spheres, the interaction with surrounding fluid is disregarded and the rebound is analysed through the reductionist concept of elastic restitution. The other papers, which investigate the behaviour of a deformable bubble or droplet at the vicinity of a wall, are highly motivated by modelling the coalescence of a bubble/droplet with a plane wall or with another bubble/droplet.

To our knowledge, the hydrodynamical interaction of a bubble with a wall has never been computed in its whole, that is, the calculation of both the deformation of a liquid/gas interface and its possible bouncing. Tsao and Koch (1997) are the only authors who analysed experimentally the motion of a bubble within a liquid towards a wall. They observed, before viscosity dissipates completely its initial mechanical energy, that the bubble bounces on the wall in a dynamic process that can be understood in terms of an energy balance including the kinetic energy associated with the liquid motion, the potential energy of the interface and the gravitational potential energy gained or lost by the bubble. They distinguished three convenient times for their physical analysis:

(i) the time when the bubble is rising at its terminal velocity at a sufficient distance from the wall so that the effect of the wall on the bubble shape and fluid velocity can be neglected,
(ii) the time at which the bubble’s motion is arrested upon impact with the wall and
(iii) the time when the lowest point of the bounce at which the bubble velocity again goes to zero.

Shopov et al. (1990) present numerical solutions for the unsteady viscous flow induced by a deformable gas bubble approaching or receding from a rigid boundary at moderate values of the bubble Reynolds number and the Bond number. However, the dynamics of the bubble bouncing process was not fully obtained because of the difficulty of simultaneously solving the thin liquid film entrapped between the bubble and the wall and the larger scale outer flow with their finite element solution of the Navier–Stokes equations.

The large number of theoretical or numerical studies dealing with bubble flows usually take the general potential approach: the fluid is supposed to be incompressible and irrotational which implies that the flow is potential. The dynamics of the liquid phase is therefore described by a Laplace equation. Later, using momentum conservation, non-linear equations are derived for the velocity potential at the deformable interface for the motion of the latter. This approximation is valid if the bubble Reynolds number is large and the Weber number is small. In this way Miksis et al. (1982) studied the steady rise of a bubble in an unbounded liquid and accounted for surface tension. A system of integro-differential equations was derived, including the normal component of the free-surface force balance, and treated numerically. The assumption of inviscid external flow used by these authors reduces the practical importance of their results.

In the present study the numerical procedure developed to study the interaction of a bubble with a rigid horizontal wall is based on a potential theory devoted to unsteady viscous flows. A computational model for a 2-D plane flow configuration is implemented; a Boundary Element Method (BEM) is coupled with a fourth-order Runge–Kutta explicit time-stepping technique for the temporal evolution. We thus consider the rise of a deformable gas bubble towards or away from a plane horizontal rigid wall in an unbounded liquid at moderate Reynolds number. The liquid is supposed to be initially motionless and the bubble motion is set up by buoyancy alone. This paper aims at simulating the bouncing dynamics in its whole. This objective is reached by introducing a simple drainage model between the bubble and the rigid wall. This model, coupled with the BEM code, is suitable since it is easily solved numerically (Appendix A). Further physical mechanisms like the Marangoni effect due to interfacial gradients of a surfactant concentration or like the London–Van der Waals forces (Chen and Slattery, 1982) are disregarded here despite their practical importance.