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Abstract

A systematic study of the hydrodynamic mechanisms governing the collision of a rising bubble with a solid wall in the creeping flow regime (Re < 1) is presented, using direct numerical simulation. The presented results reveal self-similar aspects of the bubble-wall collision with respect to the capillary number, in particular of the film between the bubble and the wall as well as of the deformation and shape of the bubble. This similarity holds despite the extreme deformation of the bubble in some of the considered cases and is shown to be independent of the approach velocity and the fluid properties, indicating that the collision of a bubble with a solid wall in the creeping flow regime is governed by the balance of viscous stresses and surface tension, while the inertia of the bubble has a negligible influence. The timescale associated with the drainage of the film separating the bubble surface and the wall is also related to the viscocapillary balance, and is found to be independent of the size of the bubble. An empirical correlation is proposed based on the presented results to a priori estimate the drainage time of this film. Because the behaviour of a bubble during film drainage is quasi-stationary, the findings associated with film drainage also apply to bubble-wall collisions outside the remit of the creeping flow regime (Re $\gg 1$).

Keywords: Bubble-wall collision, Bubble deformation, Film drainage, Creeping flow, Viscocapillary balance

1. Introduction

The collision of bubbles with solid walls or particles plays an important role in various natural phenomena and engineering application, such as the formation of foams [1–3] (or similarly emulsions), froth flotation [4] or the enhancement of convective heat transfer [5, 6]. In the past two decades a number of experimental and numerical studies have unraveled some of the dominating mechanisms and characterising parameters governing the hydrodynamics of the collisions of bubbles with solid walls [6–16]. As a bubble approaches and collides with a wall, the kinetic energy of the bubble has to be dissipated, a process which is dominated by two hydrodynamic mechanisms [3, 9]: a) an increase in surface energy due to deformation of the bubble, and b) drainage of the film separating the bubble surface and the wall.

If the kinetic energy of the bubble is sufficiently high, the bubble bounces off the wall a number of times, indicating that the energy transfer between surface energy and kinetic energy is faster than the dissipation in the film between the bubble and the wall [3, 9, 10]. The dissipation in this film becomes the dominant hydrodynamic mechanism once the kinetic energy is sufficiently low [1]. In experiments reported by Tsao and Koch [7], the collision of a bubble with Re $= 420$ (the Reynolds number Re is formally defined in Section 2) with a solid wall was found to be almost fully elastic, with approximately 95% of the surface energy being transferred back into kinetic energy during the first bounce. Tsao and Koch [7] further suggested that the dissipation of energy is strongly influenced by a separation of the boundary layer from the wall of impact when the bubble bounces off that wall as well as by acoustic radiation due to high frequency oscillations of the bubble. In fact, Krzan et al. [17] and Malysa et al. [8] reported experimental measurements with bubbles oscillating at a frequency of $f > 1000\,\mathrm{s}^{-1}$ as the bubble moved away from the wall after the first bounce. Numerical simulations by Albadawi et al. [13] indicate that these oscillations are predominantly driven by pressure fluctuations as a result of the rapid filling of the film separating the bubble and the wall as the bubble moves away from the wall. Legendre et al. [18] and Zenit and Legendre [10] devised a coefficient of restitution for bubbles bouncing off a wall using a modified Stokes number, based on the mass and added mass of the bubble during collision.

In cases where the kinetic energy of the bubble is too low, the bubble is not bouncing off the wall [19] and the film drains until rupture and the formation of triple phase contact. In special cases, such as the collision

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