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Historical perspective

Measurement and modeling on hydrodynamic forces and deformation of an air bubble approaching a solid sphere in liquids

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ABSTRACT

The interaction between bubbles and solid surfaces is central to a broad range of industrial and biological processes. Various experimental techniques have been developed to measure the interactions of bubbles approaching solids in a liquid. A main challenge is to accurately and reliably control the relative motion over a wide range of hydrodynamic conditions and at the same time to determine the interaction forces, bubble–solid separation and bubble deformation. Existing experimental methods are able to focus only on one of the aspects of this problem, mostly for bubbles and particles with characteristic dimensions either below 100 μm or above 1 cm. As a result, either the interfacial deformations are measured directly with the forces being inferred from a model, or the forces are measured directly with the deformations to be deduced from the theory. The recently developed integrated thin film drainage apparatus (ITFDA) filled the gap of intermediate bubble/particle size ranges that are commonly encountered in mineral and oil recovery applications. Equipped with side-view digital cameras along with a bimorph cantilever as force sensor and speaker diaphragm as the driver for bubble to approach a solid sphere, the ITFDA has the capacity to measure simultaneously and independently the forces and interfacial deformations as a bubble approaches a solid sphere in a liquid. Coupled with the thin liquid film drainage modeling, the ITFDA measurement allows the critical role of surface tension, fluid viscosity and bubble approach speed in determining bubble deformation (profile) and hydrodynamic forces to be elucidated. Here we compare the available methods of studying bubble–solid interactions and demonstrate unique features and advantages of the ITFDA for measuring both forces and bubble deformations in systems of Reynolds numbers as high as 10. The consistency and accuracy of such measurement are tested against the well established Stokes–Reynolds–Young–Laplace model. The potential to use the design principles of the ITFDA for fundamental and developmental research is demonstrated.

Contents

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1. Introduction

1.1. Background and motivations

Interaction between bubbles and solid surfaces in aqueous solutions plays a crucial role in various industrial processes, most notably in froth flotation that is widely used in the separation of mineral particles, treatment of wastewater, recycling of fibers from waste paper, removal of toxic components from industrial effluent and separation of biological cells [1,2]. Since the selective attachment of air bubbles to target particles determines the separation between hydrophobic and hydrophilic particles in a flotation cell, understanding bubble–particle interactions in froth flotation is absolutely crucial [3,4]. An important feature of bubble–particle interaction is drainage of aqueous liquid films between air bubbles and solid surfaces under the influence of hydrodynamic and surface forces, compounded by bubble deformation. Accounting for such deformations under the hydrodynamic forces makes analysis of liquid film drainage dynamics much more challenging. Derjaguin and Kussakov [5] are among the first who analyzed non-equilibrium interactions between an air bubble and a flat mica plate. They showed for the first time dimple formation on the bubble surface.

A number of different experimental techniques have been used to study liquid film drainage dynamics and time dependent interactions between an air bubble and a solid surface immersed in a liquid [6]. One of the earliest methods to study the drainage dynamics of the liquid film involving deformable interfaces was based on the Scheludko cell although only the time evolution of the central liquid film thickness, $h(t)$, was obtained.

The atomic force microscope (AFM), on the other hand, has been widely and effectively used to measure both static and dynamic interaction forces of deformable bubbles [7–10] or oil drops [11–20] approaching solid probe particles in aqueous solutions [21–23]. The AFM colloidal or bubble probe technique allowed direct measurement of interaction forces, but provided no direct information on bubble deformation. Different techniques such as free bubble rise method, bubble expansion method and surface force apparatus were used to study the thin film drainage between an air bubble and a solid surface.

However, none of these techniques is capable of determining simultaneously the deformation of air bubbles and colloidal forces. Moreover, the experiments conducted by the thin liquid film apparatus, surface force apparatus, bubble expansion method and AFM probe technique are mostly in the low Reynolds number regime. For example, the reported maximum bubble approach speed towards a particle in AFM measurement was ~100 μm/s [24], corresponding to a bubble Reynolds number of ~0.02 which is much lower than the Reynolds number of particle–bubble encounters in a flotation cell.

To better understand interactions between air bubbles and solid particles in aqueous media as encountered in flotation practice, it is important to develop a device that measures both forces and bubble deformation in systems of higher Reynolds numbers. For this purpose, an integrated thin film drainage apparatus (ITFDA) was developed recently to measure the bubble–particle interactions over a wide range of dynamic conditions [25,26]. The ITFDA is capable of measuring simultaneously the dynamic forces and the geometric properties of the bubble interacting with solid particles. Using the diaphragm of a high frequency speaker as the drive of the bubble, the approach speed of the bubble to a solid particle can be as high as 5000 μm/s, which gives a bubble Reynolds number of 10, making the ITFDA an ideal device to study the bubble–particle interactions under dynamic conditions. It should be noted that even though the Reynolds number that characterizes bubble motion can be as large as 10 with the ITFDA, the Reynolds number that characterizes drainage of intervening liquid film is small, typically $Re_{film} < 1$. Therefore the Stokes–Reynolds–Young–Laplace model based on the lubrication theory can still provide a quantitative description of film drainage dynamics and bubble deformation [27].

1.2. Coverage and scope

Historically, the systematic investigation of bubble–particle interactions in the context of colloid and interface science began in the late 1930s, with Derjaguin and Kussakov [5] as the pioneers who studied the behavior of a bubble in water rising under buoyancy towards a mica plate. The experiment was intended to measure surface forces that were the foundation of the Derjaguin–Landau–Verwey–Overbeek theory of colloidal stability [28,29]. The short-ranged nature of such forces required measurement using molecularly smooth surfaces such as a bubble–mica system. In a typical force measurement experiment, one either varies the separation between surfaces and measures the force, or imposes a known force and observes how the intervening liquid film thins. In the Derjaguin and Kussakov experiments, the buoyancy force was known. However, being a time-dependent dynamic experiment, it was necessary to track the position of the bubble and the separation between the bubble surface and the mica plate as a function of time. Furthermore for deformable bubbles, it is also necessary to measure variations of the interfacial deformation of the bubble as a function of position and time during the experiment. These technical and theoretical challenges were perhaps too overwhelming at the time for quantitative measurements. Nonetheless, Derjaguin and Kussakov were able to infer that the hydrodynamic repulsion that arose as the bubble approached the mica plate caused the bubble surface to form a dimple whose shape changed over the time. The work by Derjaguin and Kussakov demonstrated that any attempt to measure dynamic forces involving deformable bubbles has to be able to: i) control and/or measure the force as a function of time; ii) measure the spatial and temporal profile of the bubble or the film thickness between the bubble and the solid surface; and iii) control and/or measure