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Model and experimental visualizations of the interaction of a bubble with an inclined wall

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Abstract

In this paper we derive a model based on lubrication theory to describe the interaction of a bubble with an inclined wall. The model is an extension of the model derived by Klaseboer, Chevailier, Mate, Masbernat, Gourdon [2001. Model and experiments of a drop impinging on an immersed wall. Physics of Fluids 13(1), 45–57.] and Moraga, Drew, Larreteguy, Lahey [2005. Modeling wall-induced forces on bubbles for inclined walls. Multiphase Science and Technology 17(4), 483–505.] in the case of a horizontal wall. We consider bubbles of diameter 1–2 mm, which corresponds to high Reynolds numbers $Re \sim O(100)$, and moderate deformation effects (with a Weber number of $O(1)$). Predictions of the model are compared with experimental visualizations of air bubbles rising in water toward an inclined wall. The dynamical behavior of bubbles is observed to depend on the wall inclination. We find that the model reproduces the bubble trajectories for wall inclinations smaller than 55°–60°. This critical value for the wall inclination corresponds to an experimentally observed transition in the bubble bouncing behavior, which agrees with the observations of Tsao and Koch [1997. Observations of high Reynolds number bubbles interacting with a rigid wall. Physics of Fluids 468, 271.]. We show that the main features of our lubrication-based model for rebound with an inclined wall can be expressed with a simple force model proposed by Moraga et al., suitable for use in direct numerical simulations of multiphase flow.

Keywords: Bubbles; Lubrication theory; Wall interaction

1. Introduction

The numerical simulation of multiphase flows in complex, realistic geometries involves a wide variety of scales and therefore requires adequate modelling to describe some aspects of the fluid–particle, particle–particle, particle–wall interaction. In industrial processes such as cooling of nuclear reactors or pharmaceutical processes (Mudde, 2005), the phase ratio of bubbles to the liquid phase tends to be high, so that collisions of bubbles with each other or the wall happen frequently. Bubble–bubble and bubble–wall interactions have been found to be of crucial interest for medical applications such as echography (Becher and Burns, 2000). Drag reduction using injected microbubbles has also been the focus of intensive study (Xu et al., 2002), with promises to reduce the costs and increase the performance of sea transport by as much as 30%. Despite ever-increasing computer power, direct numerical simulation of large numbers of bubbles is not yet possible. Moreover, even the dynamics of a single bubble are not completely understood (Prosperetti, 2004). Generally speaking, research studies involving bubbles tend to focus only on a few selective aspects of the physics, while using crude modelling for those aspects considered less important for the application at hand (Theofanous, 2004). The interaction of a bubble with a wall constitutes only a relatively small piece of the puzzle in many applications of multiphase flows, and as such has often been neglected in the past. The

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simplest and most commonly used model consists in defining a restitution coefficient for the bubble velocity (Canot et al., 2003). We also observe that in most theoretical and numerical developments (Shopov et al., 1990) the wall is chosen to be horizontal or vertical, whereas in real-life applications, the wall may well be slanted. Yet wall inclination strongly conditions the behavior of the bubbles such as their velocity or their shape, as shown by the observations of Tsao and Koch (1997) or Perron et al. (2006). A ship hull for instance has walls of various inclinations, each corresponding to a different force balance, which has consequences for the effectiveness of a drag reduction strategy.

The goal of this paper is to evaluate the relevance of an extension of Moraga et al.'s (2005) force model to describe the rebound of a bubble on an inclined wall. An additional objective of the paper is to verify and validate the 2D lubrication equation as a first step before coupling it with a 3D solver. Coupling the lubrication solver to a simple bubble trajectory equation as Klaseboer et al. (2001) and Moraga et al. (2006) did, instead of to a 3D solver, has the advantages of producing a much simpler algorithm that can still solve the bubble rebound problem if the bubble and the wall inclination angle are kept small enough. However the coupling to the trajectory equation forces the introduction of simplifying assumptions for the boundary conditions of the 2D lubrication equation solver. These assumptions include a simplification of the bubble shape and the extent of the 2D lubrication solver: it is assumed that (a) the deformation of the portion of the bubble interphase further away from the wall is negligible and (b) that the 1D flow assumptions needed to derive the lubrication equations hold in a volume of fluid of small extent separating the bubble from the wall, i.e. with a characteristic radius of $r < r_{\max}$. These assumptions can be removed by coupling the lubrication equation solver to a 3D solver. The feasibility of this coupled multiscale solvers has been already proven by Shopov et al. (1990), which show the development of a film between the bubble and the wall. Canot et al. (2003) have coupled an analytical model based on lubrication theory with a boundary element method to simulate a 2D (cylindrical) bubble approaching a horizontal wall. They compare the bubble trajectory to the experimental observations of Tsao and Koch (1997), which were made for horizontal as well as inclined walls. Klaseboer et al. (2001) have developed a model for the rebound of a drop impacting a horizontal plane wall. The model is based on a force balance for the drop and the use of lubrication approximation to compute the force exerted by the wall. The model prediction was satisfactorily compared with experimental results. Moraga et al. (2005) solved the model for a horizontal wall to derive a simple law which could be implemented in a two-fluid simulation of bubbly flows. To better understand the physics of the interaction, we use experimental vizualizations of air bubbles rising in water through buoyancy and bouncing against an inclined wall. We describe the experimental configuration in Section 2. The model equations are provided in Section 3. Comparison of experimental observations with the model is given in Section 4. Conclusions are given in Section 5.

2. Experimental configuration

In this study an apparatus is built to generate air bubbles in a liquid and observe their rebound on a wall with controllable inclination. The apparatus is a rectangular water tank with 0.5 in thick Plexiglas walls. It is 30 cm long, 30 cm high and 3 cm wide. A rotating solid wall is placed 15 cm above the bubble injection point. Air bubbles were first generated using a syringe and a Hamilton needle with 50 μm diameter. The bubble diameter ranged from 0.4 to 2 mm. In order to control the bubble size and therefore ensure the reproducibility of the experiments, we used an solenoid valve through which pressurized air entered a nozzle. The inner diameter of the nozzle was 127 μm, which allowed us to produce bubbles of diameter between 1 and 2 mm. Typical opening times of the valve ranged from 0.5 to 5 ms.

The main difference between the apparatus and that of Tsao and Koch (1997) is that we use a plate instead of a channel as a solid impact boundary. This modification reduces the amount of interfaces between the illumination and the camera objective from 8 to 4, which allows us to improve the quality of our pictures. The setup allowed varying the angle between the wall and the bubble vertical trajectory from 90° to 5°. The liquid phase consisted of distilled water (Type 2). The system was backlit from one side with a halogen lamp. A schematic of the apparatus is shown in Fig. 1. The total height of the tank was chosen so that the bubbles could reach their corresponding terminal velocity before they interact with the solid surface.

Let ρ and μ be the respective density and viscosity of the fluid. Let σ be the surface tension at the air–water interface σ=0.07. The air bubble is characterized by its equivalent diameter $d=2R$ and terminal velocity V_T. Three adimensional parameters govern the wall–bubble interaction. One is the Reynolds number defined as

$$Re = \frac{\rho V_T d}{\mu}$$

which relates the importance of inertial effects to that of viscous effects. The other one is the Weber, which characterizes the bubble capacity for deformation:

$$We = \frac{\rho V_T^2 d}{2\sigma}.$$

The third one is the wall inclination

$$0 < \theta < 90°.$$

The Reynolds numbers in the experiment range from 40 to 560 and the Weber number varies between 0.02 and 1.80. As the bubbles rose at their terminal velocities, their trajectory was recorded using a high-speed camera (Pixelink PLA-741), which was able to capture up to 1000 frames per second (FPS). A compromise had to be found in order to have both a sufficiently high-time resolution and a sufficiently large field. In practice the frame rate varied around 300 fps, while the total extent of the field of view was 40 mm × 30 mm. The centroid of the bubble was found by processing individual frames in ScionImage, and coupling it with a MATLAB routine, which determined