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Dynamics of dewetting and bubble attachment to rough hydrophobic surfaces – Measurements and modelling

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ABSTRACT

The influence of solid surface roughness (hydrophobic Teflon®) on the timescale of the ascending air bubble (R_b = 0.74 mm) attachment and the kinetics of the spreading of the three-phase contact (TPC – gas/liquid/solid) line was studied. The moment of the rising bubble collision with a horizontal Teflon® plate immersed in ultrapure water was monitored using fast video recordings (4000 fps). It was shown that, depending on the solid surface roughness, the time of the TPC formation was significantly different. Similarly to our previous studies, it was shorter for higher roughnesses. Using high-frequency video acquisition, an additional factor, kinetics of the spreading of the TPC line associated with various bubble shape changes during TPC formation, could be determined. The registered attachment kinetics and bubble shape variations were very reproducible for smooth and very rough Teflon® surfaces, whereas for Teflon® of intermediate roughness, up to five different attachment scenarios were observed, with a relatively large standard deviation of time of TPC formation. Numerical calculations used for simulation of the bubble collisions with a horizontal solid wall with precisely controlled hydrodynamic boundary conditions revealed that the experimentally observed timescales of the bubble attachment and spectacular bubble shape variations can be accurately (qualitatively) reproduced for each roughness of the Teflon® plate studied. Good agreement between experimental and numerical data is, in our opinion, rather strong evidence for air-induced rupture of the liquid film formed between the colliding bubble and the hydrophobic solid plate. This supports the hypothesis that depending on the solid surface roughness, different amounts of air entrapped in solid surface irregularities could drastically change the solid surface hydrodynamic boundary conditions and, consequently, the kinetics of spreading and formation of the TPC.

1. Introduction

Collisions of gas bubbles with various interfaces play an important role in many applications. For example, in flotation, a widespread physicochemical separation technique based on differences in surface properties of the minerals being separated, the effectiveness of the separation process depends on the outcome of interactions between bubbles and solid particles (Ralston, 2000). The flotation separation of ore's useful components is based on a selective attachment of the colliding bubble with hydrophobic solid surfaces only. Interactions between a bubble and particle can be divided into three sub-processes: (i) collision, (ii) attachment (three-phase contact – TPC – formation) and (iii) detachment. In industrial flotation processes, attachment of mineral grains and formation of a stable bubble-grain aggregate must occur during the very short collision time. Detachment of the bubble and its bouncing results in prolongation of the attachment time and can affect the effectiveness of the flotation separation by decreasing the attachment probability.

Generally, the probability of the bubble attachment to a solid particle depends mainly on the stability and kinetics of drainage of the intervening (wetting) film separating the bubble and solid surface. The liquid film drainage kinetics are governed by hydrodynamic boundary conditions at the film interfaces. To ensure a desired and controlled outcome of the flotation separation process (as well as a variety of processes involving multiphase flow), the properties of the interacting interfaces should be tuned. Among many other factors, hydrodynamic boundary conditions at both gas/liquid and solid/liquid interfaces are among the most significant. For gas/liquid interfaces in flotation, the boundary conditions are changed by adding various surface-active substances (SAS),

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whose strong adsorption capability changes the fluidity (mobility) of the interface (Levich, 1962; Dukhin et al., 1998; Ybert and di Meglio, 2000; Zhang et al., 2001; Krzan et al., 2007; Laskowski, 2010; Zawala et al., 2010). The degree of immobilization of the rising bubble surface depends on the nature (ionic, non-ionic) of the SAS and, obviously, its concentration. It was shown that depending on the surface activity of the SAS molecules, the threshold concentration needed for complete immobilization of the gas/liquid interface could vary even by several orders of magnitude (Malysa et al., 2005; Krzan et al., 2007). In the case of the solid/liquid interface changing boundary conditions are much more difficult to obtain and control. However, this effect is extremely interesting and important because the slip boundary conditions tend to reduce the relatively large surface drag coefficient (Voronov et al., 2006; Vinogradova and Belyaev, 2010) and can influence the kinetics of liquid film drainage.

It is rather well established that near rough hydrophobic solid surfaces, the boundary slip could be significantly increased (Pit et al., 1999; Zhu and Granick, 2001; Baudry et al., 2001; Cottin-Bizzone et al., 2003; Lauga and Stone, 2003; Voronov et al., 2006; Joseph et al., 2006; Vinogradova and Yakubov, 2006; Wang and Bhushan, 2010; Xu and Li, 2007). One of the most probable reasons for this effect is the presence of air either trapped in surface irregularities (Cottin-Bizzone et al., 2003; Voronov et al., 2006; Vinogradova and Belyaev, 2010) or formed spontaneously in the form of interfacial submicroscopic (nano-) bubbles at rough solid surfaces (Attard, 2003; Lauga and Stone, 2003; Krasowska et al., 2009; Craig, 2011). Attard (2003) wrote that: "... *Such nanobubble coverings also have surprising consequences for the motion of particles in liquids or the flow of liquids next to surfaces or in capillaries. One can well anticipate a reduction in drag by such a nanobubble film, since slip obviously occurs at a fluid interface whereas stick boundary conditions are traditionally invoked in the hydrodynamic flow at solid surfaces* ...". Despite the ongoing debate on nanobubble stability (Craig, 2011; Peng et al., 2013; Weijs and Lohse, 2013), the fact that they do exist at hydrophobic surfaces immersed in aqueous phase is rather well established (Hampton and Nguyen, 2010). Air-induced modification of hydrodynamic boundary conditions of the hydrophobic solid surfaces is very probable, especially in the case of rough surfaces. This can have extremely important implications for flotation, during which well-controlled solid surface patterning is not possible owing to the routine, industrial and large-scale character of the process (Fan et al., 2010; Calgaroto et al., 2014). In flotation, under reduced drag, the separating liquid film between a colliding bubble and a solid surface can be squeezed out faster. This can result in significant time reduction of the TPC formation (Zhou et al., 1996; Krasowska et al., 2007, 2009; Kosior et al., 2013; Ahmed, 2013; Kosior et al., 2014), which in flotation is known as induction time. This time span is the total time required for the attachment of an air bubble with a solid particle and involves the thinning and rupture of wetting film and expansion of the TPC contact line (Gu et al., 2003; Albijanic et al., 2010).

This paper presents experimental and theoretical (via numerical simulation) studies on the timescale of bubble attachment to a hydrophobic solid surface and the spreading of the TPC line. Experimentally, the kinetics of bubble collision and attachment were studied in detail at model hydrophobic Teflon® surfaces of different roughness. In the numerical case, to reproduce the experimental observations, the boundary conditions of the hydrophobic solid surface were changed in a well-controlled (patterned) manner. The qualitative comparison between kinetics of the bubble attachment to the hydrophobic solid surface obtained experimentally and numerically was then shown. This comparison provides additional evidence supporting the hypothesis about important the role of air presence at hydrophobic rough surfaces on kinetics of the TPC line spreading and bubble attachment.

2. Methods

2.1. Experimental approach

The experimental setup used for monitoring the bubble collision with a hydrophobic solid surface was described in detail elsewhere (Zawala et al., 2007; Kosior et al., 2013). Briefly, a single bubble was formed at the capillary orifice with inner diameter 0.075 mm at the bottom of a square glass column (45 × 45 mm) in Milli-Q® water. For the controlled bubble formation, a precise syringe pump (NE-1000, NewEra Pump Systems) was used. By careful adjustment of the airflow rate, it was possible to precisely control the time interval between subsequent bubble detachments. The bubble formation time was always 1.6 s, whereas the time interval between subsequent bubbles was 10–12 s. The radius of the bubble was very reproducible and was $R_b = 0.74 \pm 0.01$ mm. The motion of the bubble was monitored and recorded using a high-speed video camera (Weinberger, SpeedCam MacroVis) with frequency 4000 fps. Sequences of the recorded frames were analysed frame by frame using image analysis software ImageJ (Abramoff et al., 2004) to determine bubble size, deformation ratio, spatial displacements and local velocities. The bubble local velocity was determined as:

$$u = \frac{s}{\Delta t} \tag{1}$$

where $s = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2}$, (x_i, y_i) and (x_{i+1}, y_{i+1}) are the coordinates of the subsequent positions of the bubble with respect to its bottom pole, and Δt is the time interval between subsequent bubble positions. The bubble size and deformation ratio were determined through an average of 20–40 (n) independent measurements. The bubble size was determined by means of its equivalent radius (R_b) as:

$$R_b = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{(d_v)_i}{2}\cdot\left(\frac{(d_h)_i}{2}\right)^2\right]^{1/3} \tag{2}$$

where d_h and d_v are the horizontal and vertical axes, respectively, of the rising bubbles determined. The bubble deformation ratio (χ) was calculated as:

$$\chi = \frac{1}{n}\sum_{i=1}^{n}\left[\left(\frac{d_h}{d_v}\right)_i\right] \tag{3}$$

The Teflon® solid plate, used in our studies as a model hydrophobic surface, was positioned horizontally just beneath the water/air interface at a distance far larger than that necessary for establishment of the bubble's terminal velocity. The terminal velocity of the bubble at the moment of collision, i.e., its impact velocity, was $u_t = 34.7 \pm 0.2$ cm/s. The value of u_t determined experimentally remains in perfect agreement with corresponding values reported by other researchers for an air bubble of similar R_b rising in pure water (Duineveld, 1995; Wu and Gharib, 2002; Legendre et al., 2012). The roughness of the solid plate was modified manually by polishing the surface with sandpaper of different grid numbers—namely, 100 (Klingspor KL 375 J), 600 (S.G. Abrasives 600) and 2500 (S.G. Abrasives 2500 wet paper). For convenience, these three plates will be further referenced in the text as T100, T600 and T2500, respectively. The lateral roughness of the plates was determined on the basis of light microscopy observations as a range of lengths of surface scratches. For the T100 and T600, the roughness was equal to 80–100 μm and 40–60 μm, respectively, whereas for T2500, it was equal to 1–5 μm. The corresponding contact angles of the Teflon® plates, measured for Milli-Q® water using the sessile drop technique, were 120 ± 5°, 110 ± 4° and 100 ± 3°, for T100, T600 and T2500, respectively