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The shape of non-axisymmetric bubbles on inclined planar surfaces

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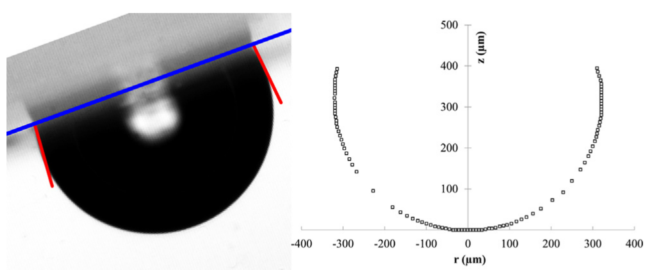
HIGHLIGHTS

- ADSA-P modification for bubbles adhering to an inclined solid surface.
- Contact angles on lower and upper bubble parts are described separately.
- Very good agreement of calculated and experimental data was obtained.
- The method could improve description of TPC line expansion.

GRAPHICAL ABSTRACT



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ABSTRACT

Bubble-particle interaction is a common phenomenon that is used in numerous industrial applications, and the knowledge of contact angles is important for the description of the expansion of the three-phase contact line. In contrast to drops, the capture of bubbles adhering to a solid surface is an extremely rapid process, and the image quality that can be achieved is worse. For bubble adhesion on a slightly inclined plane, different curvature radii should be considered on the upper and lower bubble sections of the three-phase contact line. The method proposed here is based on the assumption that the ADSA-P approach could be used separately for both bubble parts.

Bubble motion during the adhesion process was recorded using a high-speed digital camera, and points located on the bubble boundary were detected using image analysis. The bubble was divided into two independent parts, and the ADSA-P technique for contact angles of greater and less than 90° was applied to describe the bubble shape.

The calculated coordinates of the bubble profile were compared to the experimental data, and an excellent agreement was obtained. The proposed methodology could improve and simplify the description of bubble-particle interactions on non-horizontal surfaces.

1. Introduction

Contact angles have been a subject of interest in both pure and applied sciences. Contact angles are also used to characterize the wettability of materials in many industrial applications. The broad relevance of this topic has led to a great deal of development in measurement techniques. The overwhelming majority of these techniques is focused on the description of the shape of a sessile liquid drop and on the measurement of the contact angle of a drop placed on a horizontal, flat, and homogeneous surface. The simplest "direct" method involves aligning a tangent with the sessile drop profile at the point of contact with the solid surface. A summary of other conventional techniques may be found in more detailed reviews [1]. During the last few decades, the incorporation of computer tools has led to the development of new methodologies. In the present day, methods such as ADSA (axisymmetric drop shape analysis) and APF (automated polynomial fitting) enable the measurement of contact angles with a reproducibility of $\pm 0.2°$ [1].

The first axisymmetric drop shape analysis was conducted by Bashforth and Adams [2]. They tabulated drop profiles for liquids with various surface tensions and radii of curvature at the drop apex. Since that time, the methodology has undergone constant

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improvement, and computer calculation of the drop profile has been adopted. In general, ADSA methods provide a contact angle by finding a numerical axisymmetric solution of the Young–Laplace equation with given experimental parameters (drop volume, density, diameter, height, capillary length, etc.) and then calculating the slope of the tangent to the drop surface at the liquid–solid–vapor interface line. Huh and Reed [3] developed the methodology for describing the profile of a drop with a contact angle of greater than 90°. Rotenberg et al. [4] developed a powerful technique called ADSA-P (axisymmetric drop shape analysis-profile), which fits points of the experimental profile to a theoretical Laplacian curve using a nonlinear procedure. The objective function is the sum of the squares of the normal distances between the measured points and the calculated points; one of the independent variables of the objective function is the coordinates of the origin (the drop apex). Skinner [5] modified the basic ADSA method into the ADSA-CD (contact diameter), which is based on the measurement of the contact diameter of the drop from the top view. This method is suitable for drops with contact angles of less than 20° for which other methods fail. Cheng [6] improved the ADSA-P method by introducing the automatic digitalization of images. He incorporated image pre-processing into the ADSA procedure. Finally, del Rio [7] summarized the ADSA-P method for the calculation of contact angles of greater and less than 90°, thereby developing the second generation of ADSA methods, which utilize more efficient algorithms, e.g., using the curvature at the apex instead of the radius of curvature and using the angle of vertical alignment as an optimization parameter. Prokop et al. [8] used the ADSA-P method to study a captive bubble after the equilibrium state was reached. This method is often recommended for liquids or solutions with a low surface tension, in which case the classical pendant drop method fails. At present, a great deal of effort is also being dedicated to the improvement of image quality and analysis [9].

APF (automated polynomial fitting) methodology utilizes new tools of high-resolution image analysis. The contact point is captured in detail, and the drop shape is described using a suitable polynomial fitting module. This technique can also be used for non-axisymmetric drops. The drawback of this technique is the necessity of recording high-quality images with detailed resolution close to the contact point. For example, the method of Chini and Amirfazli [10] is based on the sub-pixel polynomial fitting principle, in which points along the bubble edge are replaced with a polynome. According to the authors' conclusions, an excessive increase in the number of pixel points beyond the plateau region could result in an error in contact angle estimation because of the polynomial's inability to trace the drop boundary shape.

At present, the development of more precise experimental techniques for determining the liquid drop profile and the growing demand for probing smaller scales or achieving quicker processes require the development of novel numerical methods that can go beyond the axisymmetric approximation for the shape of a drop. An important application is the description of the drop or bubble shape on an inclined plane. In 1979, Brown et al. [11] described the shape of a static drop on a tilted surface using the finite element method. The finite element method was also used by Iliev [12,13] for the general description of a sessile drop shape. The goal of this method is to determine the shape and the local contact angles along the contact line for an a priori contact line, volume, and capillary length. The equilibrium drop shape forms as a result of the influence of the surface tension and gravitational forces. The surface is described as Laplacian and minimal. Rotenberg et al. [14] have used the finite element method to predict the shape of a drop slowly sliding down a sloping plane. They described the boundary conditions along the contact line in the form of a functional relationship between the contact angle and the velocity of the three-phase line. Other authors have dealt with the shapes of critical drops, e.g., the determination of the maximum drop volume. Nguyen [15] has suggested predicting the critical drop volume based on the knowledge of receding and advancing contact angles. El Sherbini [16,17] has developed a method for drop-shape approximation on a tilted plane using two circles fitted to the drop contour line. This method is used primarily for the estimation of the contact angle of critical drops. Finally, Dupont and Legendre [18] have introduced a novel numerical macroscopic-scale method based on the implementation of a sub-grid description of the contact line that relies on imposing an apparent angle for static and moving contact lines.

All the methods mentioned above were proposed primarily for the description of sessile axisymmetric or non-axisymmetric drops. Although, the descriptions of both drop and bubble shapes are based on the same theoretical background; the literature concerned with the description of bubble shape in various industrial applications is scarce. Flotation, which is an example of an important separation method, is based on the ability of certain solids to remain attached to the bubble interface. Flotation was originally used for the separation of coal or mineral ore particles from mined ore deposits. Currently, it is also used for waste-water treatment and for the separation of oil sands, print inks in paper recycling and various plastic materials; in the latter case, the bubbles are smaller than the solid particles. Bubble attachment to a solid surface is the fundamental process of bubble-particle interaction. The attachment process begins with the drainage and rupture of the liquid film between the bubble and the particle, and it continues with the establishment and enlargement of the three-phase contact (TPC) line until its equilibrium state is reached. The contact-line expansion can be described using mathematical models such as the hydrodynamic and molecular-kinetic models [19,20]. Both models relate the dynamic contact angle to the TPC line velocity, and knowledge of the time dependence of the contact angles is essential for the TPC-velocity and TPC-diameter calculations. For a small bubble adhering to a horizontal plane, Phan [19] considered the bubble shape to be spherical. In such a case, the contact angle can be calculated using a simple mathematical relation that describes the intersection of a plane and a sphere. However, this assumption is inapplicable for larger deformable bubbles adhering to a horizontal or even an inclined plane.

When images of a sessile drop and a sessile bubble are compared, the quality of the bubble image is usually lower. This is because the experimental apparatus is more complex. Bubble adhesion is captured using a high-speed camera, which requires a powerful light source. The light rays penetrate through the vessel material and the liquid bulk, so light reflection at both the solid-liquid and gas-liquid interfaces must be considered. Therefore, the analysis of the image data of the area near the three-phase contact point is accompanied by an increase in experimental error, and the application of the APF method is not recommended.

The aim of this project is to design a new methodology for the relatively simple and rapid calculation of bubble contact angles. The method proposed here is based on the assumption that the ADSA-P method can be used separately for two (upper and lower) bubble sections of differing curvature radii.

2. Theoretical description of the bubble shape on horizontal and inclined planes

The process of bubble adhesion on an inclined plane is illustrated in Fig. 1, together with the time information. The moment of three-phase-line establishment was defined as the zero time. Because of prior bubble motion along the plane and bubble inertia, the bubble's center of gravity moves forward, and then the bubble center oscillates around its equilibrium position. Initially, bubble adhesion is characterized by a rapid increase in the contact angle. Not