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Influence of surface tension on bubble nucleation, formation and onset of sliding

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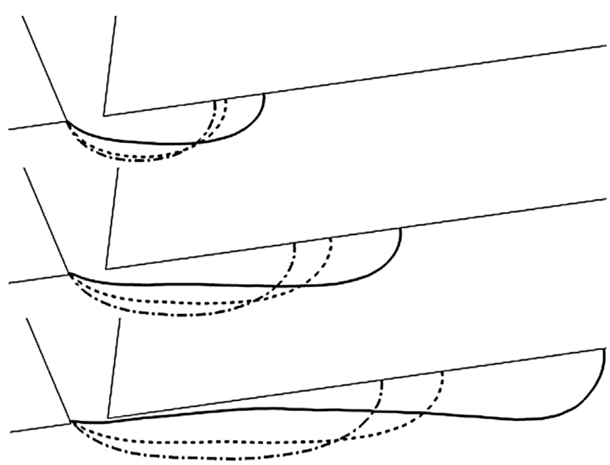
HIGHLIGHTS

- Study of bubble-induced flow using Volume of Fluid (VOF) technique.
- The influence of the surface tension on the bubble formation, detachment and sliding.
- The surface tension force tends to minimise the bubble stretching ratio.
- The bubble holdup time increases significantly due to the surface tension.

GRAPHICAL ABSTRACT



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ABSTRACT

The influence of the surface tension on the bubble formation, detachment and onset of sliding underneath an inclined surface has been investigated using VOF technique in ANSYS-Fluent environment. Air is injected at a constant flow rate through a 2 mm diameter nozzle underneath an inclined plane, with varying surface inclinations ranging from 4° to 12°, submerged in viscous media. Bubbles evolve with spherical shape, underneath the inclined plane, gradually flattens and soon becomes an asymmetric shape forming two counter-rotating vortices in the surrounding fluid. The detachment of bubble from the nozzle-tip (nucleating site) is significantly influenced by the surface tension of surrounding fluid. It is predicted that the bubble holdup time at the nozzle-tip increases with increase in surface tension thereby making the bubble larger during detachment, which in turn changes the hydrodynamics of the surrounding fluid when detached. An experimental study has been performed to validate the VOF model with reference to the stretching characteristics of the bubble during initial growth. In general, the higher mass flux increases the buoyant force in the direction of sliding and at the same time the drag force that arises due to the shape opposes the sliding. The balancing act of these forces is the main cause that influences the detachment and subsequently the sliding behaviour of the bubble underneath an inclined plane.

1. Introduction

The nucleation, detachment and sliding characteristic of a bubble underneath an inclined plane constitute a fundamental fluid

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dynamics problem and plays a key role in many industrial applications such as chain bubbling, foaming in chemical reactors and jetting/bubbling in gas-liquid-solid fluidized beds. Bubble generation is usually accomplished by injecting gas through an orifice into a quiescent liquid medium. A large number of studies [1–3] have been conducted on vertically rising bubbles when detach from the nozzle due to the buoyancy force (gravity). However, bubble nucleation underneath an inclined/horizontal plane submerged in viscous media is complex due to the strong interplay between gravity, drag, viscous and surface tension forces. Several studies have reported the bubble generation and detachment from submerged nozzle under full gravity and in still or moving fluid [4]. Weber et al. [2], Maneri and Zuber [5], Couët and Strumolo [6] and Maxworthy [1] have studied rise velocity of gas bubbles in an inclined channels. Chen et al. [3] have presented bubble rise results for inclination up to 12° to the horizontal. Perron et al. [7] discussed about the Fortin bubble morphology, where the front region of the bubble is large and thicker, in contrast, to the rear of the bubble. Li et al. [8] studied kinematics of vapour bubbles (FC-87) rising underneath a constant temperature surface at four inclinations of 2°, 5°, 10° & 15° by photographic technique. All above studies relate the effect of inclination on bubbles with fixed volumes, but in most application the volume of the nucleating-bubble keeps changing and the size of the detached/sliding bubble vastly depends on the surrounding forces like gravity, the drag and surface tension. More recently, Das et al. [9] have reported the influence of surfactants on bubble nucleation underneath an horizontal plate, however, they don't characterise the hydrodynamics in sufficient detail. The numerical study [10] of bubble evolution and necking reveals that the bubble-volume for downward facing orifice could be 4–5 times higher than the bubble released at upward facing orifice. Studies thus far on the influence of surface tension on the nucleating-bubble at constant rate of flow injection through nozzles have been very few.

2. Theoretical description of the nucleating bubble

Nucleating/sliding bubbles feature a very important phenomenon which is crucial to their dynamics, i.e. the balance between gravity, drag and surface tension forces usually referred as contact angle hysteresis. The factors that influence the bubble formation may be seen in Fig. 1, which depicts the component of forces acting on the bubble on the downward facing horizontal plate. In

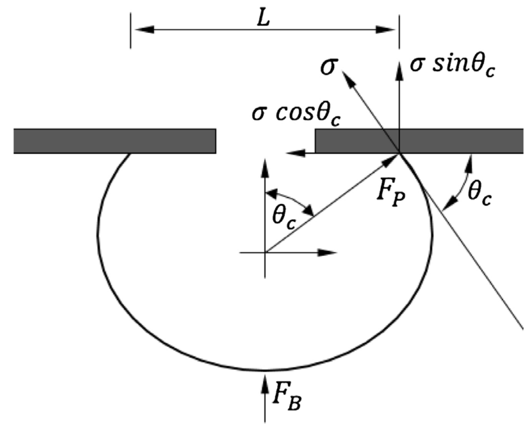

Fig. 1. Schematic representation of bubble nucleation underneath a surface.

Fig. 1, F_P is the force at the three-phase contact point (line) due to the pressure inside the bubble. The forces that cause the bubble to attach to the surface are:

$$F_1 = 2\pi r_b \left(\sigma \sin\theta_c + F_P \cos\theta_c\right) \quad (1)$$

$$F_2 = F_B = V_b \left(\rho_l - \rho_g\right) \quad (2)$$

F_1 and F_2 both act vertically upward making the bubble adhering to the surface while the horizontal component of the surface-tension prevents the bubble from expanding/spreading as illustrated in Fig. 1. This horizontal component resists the bubble from expanding laterally along the surface, whereas the force due to the internal pressure helps spreading the bubble with increase in the bubble base diameter [9]. However, bubble formation on an inclined plane involves more complexity as the advancing and receding contact angles begin to change due to the presence of a uniform gravity field causing a net drifting force, which gives rise to an unsymmetrical shape [11,12]. The presence of three phase contact lines in such situations adds another level of complexity to evaluate the influence of surface tension on bubble dynamics. The effect of such forces, expressed as an additional "disjoining" pressure in the thin layer of liquid between the bubble and wall, would be to deform the bubble, thereby changing the hydrodynamic forces acting on it [13]. The horizontal force components keep changing with both advancing and receding contact angles

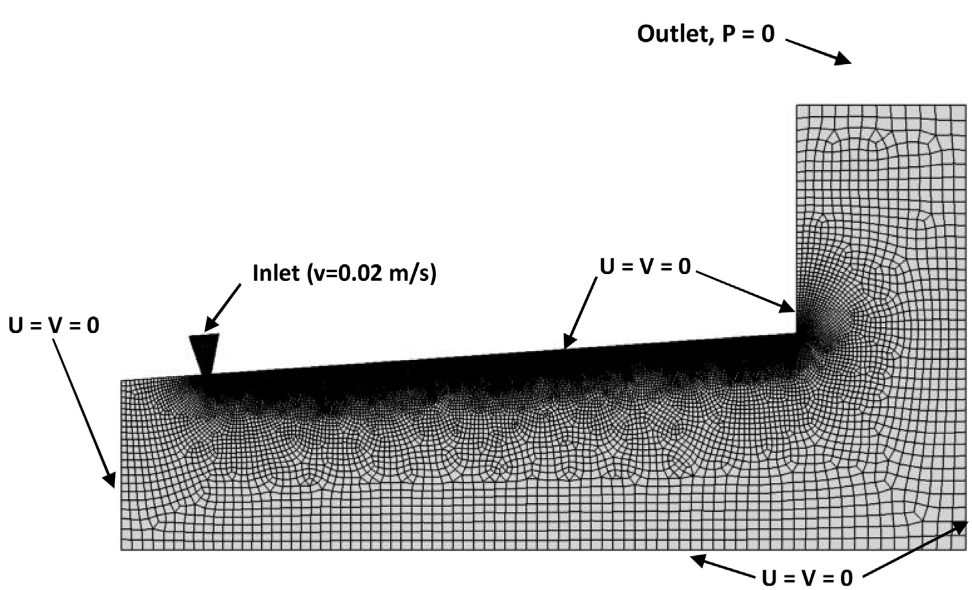

Fig. 2. Schematic representation of the computational domain.