Experimental study on path instability of rising bubbles

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Abstract:

The main objective of this work is to study the path instability of a freely ascending air bubble in water and silicon oil at varied Bond numbers (ratio of body forces to surface tension) and Galileo numbers (ratio of gravitational force to viscous force). Below a certain threshold of the Galileo number, the path of the bubble remains straight. But above a critical Galileo number (related to the size of the bubble) a new regime sets in and the bubble changes its shape and follows a zigzagging path. Experimental investigation of the path instability of bubbles is needed because earlier existing numerical work suffers from simplifications likely to bias predictions, such as the assumption of fixed shape [1,2], and recent simulations accounting fully for shape deformation are either still too sparse to provide a reliably established marginal stability curve [3,4] or bring controversial results [5]. Our work aims to contribute reliable observations on the onset of instability. In our experimental set up, bubbles of variable size are released in a rectangular tank filled with silicon oil known to present no problem of surface impurities. Bubble path is recorded by a fast camera and is post-processed to determine the size and shapes of the bubbles and their trajectory in the fluid. Bond and Galileo numbers are calculated based on the volume of bubble and on the physical properties of the working fluid used.

Keywords : Path instability, Bubble, Marginal stability curve.

1. Introduction

The path instability of rising bubble inside a liquid is a fascinating topic of research since 1500th century when it was first noticed by Leonardo DaVinci, as mentioned by Prosperetti in 2004 [7]. Since then, many scientists have studied this challenging three dimensional phenomena of rising bubbles to investigate and define the path and shape followed by the bubble in various liquids. Bubble dynamics is present in many natural phenomena like aerosol transfer from sea, oxygen dissolution in lakes and in industrial applications like bubble column reactors, petroleum industry and many other.

It is now known, that bubbles of small volume (equivalent diameter d<1.5mm) rising in a liquid, follow straight paths and their shape remains axisymmetric. Depending on the surface tension effect, their shape only more or less flattens when they reach their asymptotic velocity. Beyond a critical size, the paths become unstable. While rising, the bubbles change shape and the path becomes zigzagging, sometimes helical paths were observed. Various attempts have been made to describe the threshold of instability by many researchers. To characterize the dynamics, Galileo, Bond, Eötvös and Morton numbers are usually considered. The Reynolds number is not an appropriate parameter since the terminal velocity is the result of the bubble dynamics and is not known *a priory* and, moreover, is not constant as soon as the instability sets in. Many numerical studies are carried out by considering frozen bubble shape [1,2]. Recent simulations account for the realistic shape deformation of bubbles [3,4] but the computing costs make it difficult the delimit the onset of instabilities accurately. Earlier theoretical considerations related the instability of the path of bubbles to the wake instability behind the bubble. More recently, it appeared [2] that path instability occurs even in the absence of wake instability even for bubbles with frozen shape. The shape deformation facilitates moreover the instability onset as documented in the numerical study [5] attempting to obtain an accurate marginal stability curve. Numerical simulations based on fixed grid methods [3,4] might not give accurate results considering the thin boundary layer of bubble which changes drastically during the path. The parametric studies they provide are also too sparse to describe precise instability thresholds and establish the marginal stability curve reliably. The results [5] predict unexpected shape deformation in the linear regime of instability amplification. Hence experimental investigation of instability in bubble path is needed to set the precise threshold of instability and to obtain as many points as possible on marginal stability curve.

2. Mathematical Formulation

We assume that the bubble is of constant volume V and of equivalent diameter d $(V=\pi d^3/6)$ with a free surface of constant surface tension σ. It is rising in a liquid of density ρ and kinematic viscosity v. The motion of air inside bubble is neglected due to the low density of air compared to the density of surrounding liquid. The non-dimensional equations of flow inside liquid using d as length scale and $U_g = \sqrt{gd}$ as velocity scale and ρU_g^2 as pressure scale are expressed as

$$\frac{\partial v}{\partial t} + [(v-u).\nabla] + \nabla p - \nabla.\left(\frac{2}{Ga}\tau\right) = 0$$

and

$$\nabla.v = 0$$

Where $\tau = 1/2\ (\nabla v + \nabla v^T)$ and u accounts for a moving frame and, possibly, moving mesh.

The boundary condition at free the bubble surface is: $-pn + \frac{2}{Ga}\tau.n - \frac{1}{Bo}kn = -(p_b - z)n$
where k stands for the curvature.
The Galileo number is defined as $Ga = \sqrt{g\,d^3/v}$ and the Bond number $Bo = \rho g\,d^2/\sigma.$
As such, the problem depends on two external parameters Ga and Bo.

3. Experiment Setup

The experimental setup consists of a tank of rectangular cross section. At the bottom, a small opening covered with septum film allows us to inject bubbles by a syringe. The tank is filled with silicon oil (for now of viscosity 5cst) avoid the effects of surfactants.

Figure 1 :Experimental Setup.

A light source is placed behind the tank to provide sufficient illumination for the recorded images. Bubbles are injected with the help of needles of different diameters. A high speed camera is placed in front of the tank to record the motion of the bubble. Images are taken at 1000image/second frame rate.

4. Marginal instability Curve

Figure 2 plot indicates the marginal stability curve calculated by W.Zhou and J.Dusek [5]. Figure 2 also represents previous numerical simulation and previous experimental work of Tripathi et al, Cano-lozano et al [2,3] and Zenith et al. [6].

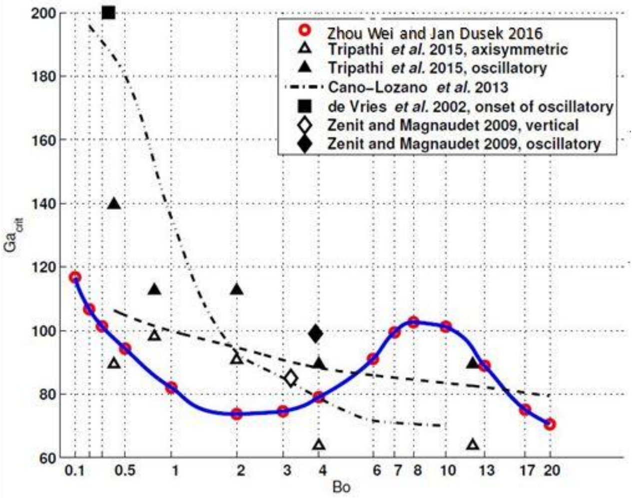
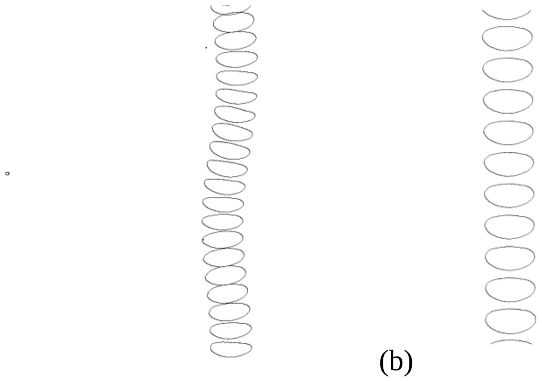


Figure 2 : Marginal stability curve

The previous instability curve was obtained by extensive numerical simulations of W.Zhou and J.Dusek [5]. In the present work we are validating these results with precise and detailed experiments conducted with our laboratory set up. From the marginal stability curve it can be seen that most of the threshold values are expected to be between 80-100 in terms of Galileo numbers.

5. Results

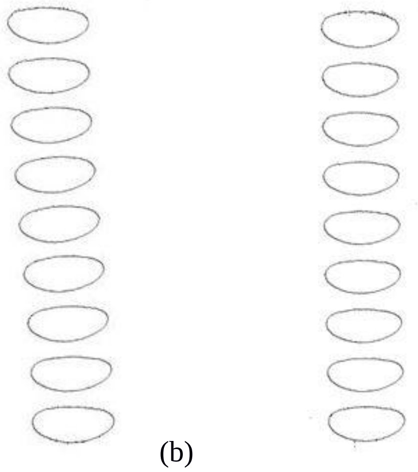
Bubbles are injected into silicon oil by using needles. Unlike water, the working fluid is free of contamination by traces of surfactant or polymers which could change the surface tension and rigidity of the interface. Using matlab image processing techniques the following images could be obtained.



(a) (b)

Figure 5.1 (a): Bubble trajectory of Bo=5.2 and Ga=114; (b): Bubble trajectory of Bo=0.8 and Ga=27.

The time between two successive images of bubbles in image (a) is 10milliseconds and in image (b) 6 milliseconds. The bubble trajectory in image (b) is clearly straight and the bubble shape does not vary since the Galileo number is very low due to a small diameter of the bubble. In contrast, the bubble trajectory in image (a) is in a planar zigzag regime. Initially, the bubble is vertical with its minor axis parallel to the vertical axis. The bubble experiences a lateral drift perpendicular to the path direction. It can also be observed that the bubble tilts with respect to the vertical direction. The largest inclination occurs at mean horizontal position when the drift velocity is the largest. The motion is periodic zigzagging. The amplitude of the zigzag is approximately 0.3d, d being the equivalent diameter of the bubble. So far, we only measure the bubble path in one plane, and the represented figure captures the motion of the trajectory in one plane. Attempts are made to generate bubbles of sizes corresponding to the onset of instability.



(a) (b)

Figure 3: (a): Bubble oscillatory trajectory at Bo=2.9,Ga=74.4; (b): Bubble vertical trajectory at Bo=2.7,Ga=69.9.

In the image (b), the bubble follows a straight path for a bubble volume yielding Ga=69.9 and Bo=2.7. For a slightly larger bubble volume, the bubble starts to oscillate (Figure a). This indicated that the threshold of instability is between Galileo values of 74.47 and 69.98 for a Bond number slightly below 3. These values are in agreement with the marginal stability curve of Wei Zho and Jan Dusek [5] (see figure 2) where the instability threshold is seen to be at Ga=74.6 for Bo=3. The difficulty of the present set up consists on controlling the volume of the injected bubble. Efforts are being to better control the injection of the bubbles. The idea is to use a solenoid valve, a pressure vessel and nozzle of different sizes to be able to produce bubbles of well controlled different sizes. With our experimental setup it is clear that the shape and path of the bubble can be obtained easily at various Galileo numbers and the validation of the previous numerical results can be done efficiently. A next improvement consists in recording the bubble path in two different planes to reconstitute the trajectory and the bubble shape fully in 3D.

6. References

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