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Numerical modelling of the rise of Taylor bubbles through a change in pipe diameter

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ABSTRACT

The rise of Taylor bubbles through expansions in vertical pipes is modelled using Computational Fluid Dynamics. The predictions from the models are compared against existing experimental work and show good agreement, both quantitatively and qualitatively. Many workers, including the present work, find that, as the bubble passes through the expansion, it will either remain intact or split into one or more daughter bubbles. We find that the critical length of bubble, defined as the maximum length that will pass through intact, is proportional to the cosecant of the angle of the expansion. Further, we show that for an abrupt expansion, the critical bubble length became unaffected by the walls of the upper pipe as the diameter was increased.

1. Introduction

The rise of Taylor bubbles is a well–documented and well–studied phenomenon in many fields, from chemical reactions in micro-scale systems to the eruption of volcanoes. Taylor bubbles are elongated, bullet-shaped gas bubbles that move through stagnant or co-flowing liquid in horizontal, inclined or, in the present context, vertical pipes (Fig. 1). Research in this field has focussed in a variety of topics, in particular the characterisation of the rise rate of the bubbles [9,27], the determination of the flow fields ahead of Nogueira et al. [20], in the liquid film around [4] and in the wake region behind the bubble [21]. Despite these and numerous other studies, there is a paucity of published experimental or numerical work on Taylor bubbles that encounter a change in pipe diameter as they rise.

James et al. [12] reported the results of an experimental investigation into the rise single Taylor bubbles through a variety of pipe expansions and contractions (using 0.038, 0.05 and 0.08 m diameter pipe sections). Sugar syrup solutions of different concentrations, with viscosities of 0.001, 0.1 and 30 Pa s, were used to compare the rise behaviour across a range of Froude numbers. These experiments were monitored quantitatively by means of pressure sensors and force meters and also qualitatively by video recording. They observed that when a Taylor bubble encountered an expansion in pipe diameter, it rapidly expanded both vertically and laterally from the nose. It was hypothesised that this resulted in an increase in the flow in the liquid film surrounding the bubble which caused the observed necking or pinching of the bubble. For bubbles above a certain length, this necking process splits the bubble into two or more daughter bubbles as shown in Fig. 2, which is a schematic of the process taken from James et al. [12]. The splitting will also generate oscillations in the pressure, which they measured both above and below the expansion. The objective of their work was to compare the experimental pressure signals measured against the acoustic seismic data recorded at active volcanic sites; their hypothesis being that the source of pressure oscillations observed in seismic data are caused by a large bubble of gas rising through a sudden expansion in the cross-sectional area of the conduit. They were able to show that the pressure changes measured during in their experiments exhibited similar behaviour to those recorded in the field, hence adding weight to their hypothesis.

Kondo et al. [16], whose primary focus was on co-current bubbly liquid gas flow, conducted a number of experiments using single Taylor bubbles in a quiescent liquid. In these, a Taylor bubble rises through a pipe of diameter 0.02 m which undergoes a sudden expansion to one with a diameter of 0.05 m. Fig. 3 shows a still video image taken from Kondo et al. [16] showing the bubble during the necking process–the poor quality is due to the standard of photocopy available. After the neck of the bubble closes, the rear of the leading bubble bursts through the nose of that part of the bubble. This process can be observed in the still video images shown in Fig. 4. These images have been taken after the sudden expansion but are cropped to the central 0.02 m of the pipe.

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Fig. 1. Examples of an air Taylor bubble rising through (a) water and (b) silicone oil [7].

Danabalan [8] investigated the rise of Taylor bubbles as they move from a straight, vertical pipe into either a rounded glass bowl or else a cubic box–the rationale being that this is an analogue of a conduit in a volcano expanding into a lava lake. One novel aspect of the work was that she looked for the maximum volume of bubble that could pass through the expansion without breaking into two or more daughter bubbles. It was found that the critical volume at which this splitting occurred was dependent on the viscosity of the liquid and the geometry of the expansion, with the rounded glass bowl being able to support a larger bubble passing through intact. Notice that in Fig. 5 there is no evidence of the bursting of the bubble from behind as was reported by Kondo et al. [16]. This is due to the much higher viscosity of the liquid in Danabalan's work.

Another experimental study recently conducted by Soldati [24] employed a Hele-Shaw cell to investigate the effect of the angle of expansion, fluid viscosity and volume of bubble may have on the rise characteristics. A Hele-Shaw cell is made up of two parallel plates some distance apart which are sealed at the sides. By varying the volume of air injected into the base of the apparatus, different lengths of Taylor bubbles were generated in the cell and it was possible to find the critical volume of bubble which can pass through the expansion without splitting by the necking of the bubble. Similar to approach of Danabalan [8], an exact value for the critical length could not be found, but only upper and lower bounds for it. Thus the critical bubble volume was deemed to lie between a lower volume, which could pass through the expansion unbroken, and an upper volume, when the bubble did break up.

Fig. 3. A still video image extracted and cleaned-up from Kondo et al. [16] which shows a Taylor bubble during the necking process while passing through a sudden expansion from a pipe of diameter 0.02 m to 0.05 m in water.

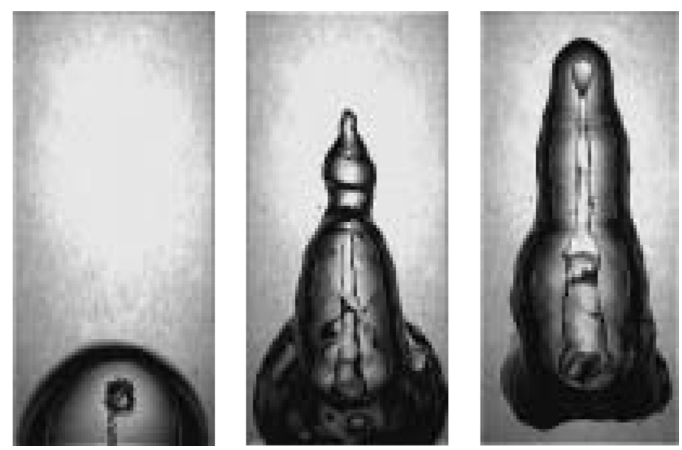

Fig. 4. A series of still video images extracted from Kondo et al. [16] which show a Taylor bubble which has passed through a sudden expansion from a pipe of diameter 0.02 m to 0.05 m in water.

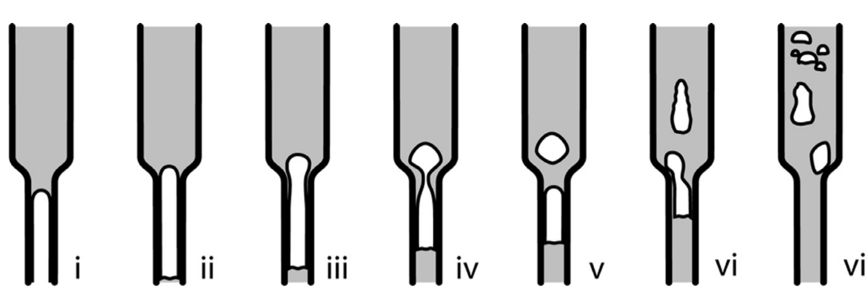

Fig. 2. Sketches of the breakup of a long parent bubble into several daughter bubbles [12].