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Flow around individual Taylor bubbles rising in a vertical column with water: Effect of gas expansion

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ABSTRACT

This paper presents an experimental study to evaluate the effect of bubble expansion on the dynamics of an isolated Taylor bubble rising in a vertical column of water by inspection of the liquid flow around the bubble front. An increase in bubble volume results from gas decompression due to hydrostatic pressure drop as the bubble ascends through the liquid. Two reduced pressures (33.3 and 20.0 kN/m^2) and atmospheric pressure were maintained at the free liquid surface to provide a wide range of expansion rates.

PIV coupled with a Shadowgraphy Technique was used to simultaneously obtain the flow field ahead the bubble and a well-defined gas–liquid interface.

A very good correlation was found between predicted bubble volume expansion rates considering ideal gas behavior and the upward net volumetric liquid flow rate obtained by integration of the velocity profiles. Above the bubble nose, the liquid velocity at the centerline decreases rapidly from the value of the Taylor bubble velocity at the tip of the bubble. For distances greater than $0.5D$, the liquid flow is undisturbed, with a significant axial velocity component for high bubble volume expansion rates due to the displacement of the liquid promoted by gas expansion. The Reynolds number calculated for the liquid flow was less than 2100 for all conditions used. While this suggests a laminar flow regime in the liquid, coefficient C from Nicklin's equation obtained from data was equal to 1.4. The shapes of the velocity profiles obtained at the undisturbed liquid flow show that for high expansion rates they resemble the power-law velocity profile for turbulent flow. The bubble volume expansion rate modifies continuously during the Taylor bubble rise and a well-defined liquid velocity profile is never attained.

1. Introduction

Slug flow and Taylor bubbles rising through liquids have been widely studied in recent years. Experimental studies using techniques such as Particle Image Velocimetry (PIV), Particle Tracking Velocimetry (PTV) and Shadowgraphy Technique (ST) allow the characterization of liquid flow around a Taylor bubble nose and in the descending liquid film surrounding the cylindrical body of the bubbles, as well as in the wake.

Individual Taylor bubbles ascending through stagnant Newtonian and non-Newtonian liquids in vertical columns were characterized by van Hout et al. (2002), Nogueira et al. (2006a, 2006b), Sousa et al. (2005, 2006a) and Saad and Bugg (2010), using PIV. Nogueira et al. (2006a, 2006b) and Sousa et al. (2005, 2006b) implemented PIV coupled with ST in their experimental studies. This technique not only allows the determination of liquid flow field and simultaneously the bubble shape but it also contributes for solving some optical problems identified in two-phase flow applications (Dias and Riethmuller, 2000; Nogueira et al., 2003). Conditions for coalescence of pairs of Taylor bubbles rising through carboxymethylcellulose (CMC) solutions of different concentrations covering the flow patterns identified in the wake were described by Sousa et al. (2007). In their experimental work Nogueira et al. (2006b) also studied individual Taylor bubbles ascending in co-current flowing Newtonian liquids with different viscosities. By characterizing the wake and near-wake region the authors identified the minimum length of liquid to have an undisturbed flow, an essential parameter to understanding the interaction between bubbles and coalescence. PIV technique was also used by Shemer et al. (2007) to investigate the structure of

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the Taylor bubble wake for air–water system and more recently was applied in cryogenic two-phase flow by Liu et al. (2012, 2013).

Numerical investigations have been carried out in parallel with the experimental work. Numerical models applied to Taylor bubbles rising in stagnant liquids in vertical columns over wide ranges of conditions have attracted the attention of several teams of scientists (Bugg et al., 1998; Bugg and Saad, 2002; Taha and Cui, 2006; Lu and Prosperetti, 2009; Kang et al., 2010; Araújo et al., 2012; Li et al., 2013; Zudin, 2013, for example). The effect of upward and downward liquid flow on the dynamics of Taylor bubbles rising in vertical columns was the focus of numerical studies recently published by Lu and Prosperetti (2009), Xia et al. (2009), Yan and Che (2010, 2011) and Quan (2011). Numerical approaches are also used to explore the interaction between consecutive Taylor bubbles rising through vertical liquids as described by Araújo et al. (2013).

Hydrodynamics investigations in two-phase slug flow regime encountered in micro and mini-channels was object of experimental and theoretical studies in the last two decades. The work of Gupta et al. (2010), Abiev and Lavretsov (2011), Zaloha et al. (2012), Howard and Walsh (2013), Abiev (2013), Zeguai et al. (2013) and Chaoqun et al. (2013) could be mentioned as examples of recent studies in the field.

The proliferation of studies concerning Taylor bubbles is not only a consequence of advances in experimental techniques and improvement of physical models. The multiple applications of slug flow in industry and natural phenomena such as volcanic eruptions also justify the diversity of studies undertaken.

In practical situations of interest, slug flow occurs in long vertical pipes. During ascent the Taylor bubbles expand continuously due to hydrostatic pressure drop. This gas expansion contributes to the liquid displacement above the bubble nose with important consequences in bubble interaction. Some efforts have been made to study the influence of gas expansion due to a hydrostatic gradient on the bubble velocity. Polonsky et al. (1999a) presented experiments with the aim of measuring changes in bubble parameters (such as velocity and length) during the rise in stagnant and upward flowing water. The authors used an arrangement of two cameras, one placed at the lower section of the column and the other at the upper region. As described by the authors, the effects of gas expansion were small because the maximum absolute pressure drop was less than 30%. Sousa et al. (2006a) later characterized the liquid flow ahead the bubble nose using PIV. In order to have different bubble expansion rates with PIV measurements obtained at the same location several bubbles with different lengths were released at the column bottom in aqueous solutions of CMC (0.1–1% of polymer were used). The experimental liquid flow rates calculated for the conditions used were always less than 3.5×10^{-6} m^3/s. Once more, low gas expansion rates and resulting liquid flow rates were observed and two different techniques were used to measure bubble parameters and velocity distribution in the liquid.

James et al. (2008) refer to a lack of studies in the engineering literature concerning the effect of gas decompression during the ascent of long bubbles for high expansion rates. In volcanology, very rapid gas expansion of large Taylor bubbles near the surface of low viscosity magma is observed with periodic eruptions, classified as Strombolian style eruptions. In their study, James et al. (2008) described as interesting for volcanological scenarios effective gas volume doubling timescales of nearly 2 s. Laboratory experiments are usually conducted at atmospheric pressure. For a Taylor bubble ascending through water at a velocity of nearly 0.2 m/s, the decompression rate is about 2 kN/m^2 s due to hydrostatic pressure drop. In this situation the bubble doubles its volume while rising in the last 10 m of water column on a time scale of nearly 50 s. In order to reduce the time scale to duplicate the bubble volume in a laboratory environment the pressure maintained above the free liquid surface must be well below atmospheric pressure.

In our own previous study (Santos et al., 2008) experiments conducted at reduced pressures of 33.3 kN/m^2 and 20.0 kN/m^2 were presented. Although the effective gas expansions were not as high as in the volcanic phenomena, the effective gas volume doubling timescale was reduced to nearly 10 s for the lowest pressure used. Monitoring a single Taylor bubble rising through water contained in vertical columns with three different internal diameters the authors made some important conclusions about the effect of gas expansion on bubble velocity. The mean velocity in the liquid induced by gas expansion rate was predicted, using the ideal gas law to calculate the bubble volume increase rate while ascending through the liquid. For all conditions used, a Reynolds number (based on the mean liquid velocity) lower than 2100 was obtained, suggesting laminar regime for the liquid flow induced by bubble expansion. According to Nicklin et al. (1962), the Taylor bubble velocity (U) is affected by the liquid motion, and for laminar regime

$$U = U_0 + 2.0U_L \tag{1}$$

where U_0 is the Taylor bubble velocity ascending through stagnant liquid and U_L is the mean velocity in the liquid. However, from the experimental values of U measured using laser diodes, Santos et al. (2008) obtained a constant with a value less than 2.0 from Nicklin's equation. The constant that multiplies U_L in Eq. (1) is usually referred to as the velocity coefficient C ($=U_C/U_L$; U_C is the liquid velocity at the centerline in front of the bubble). The Nicklin equation is commonly expressed in terms of C as

$$U = U_0 + CU_L \tag{2}$$

being $C = 2.0$ for laminar regime in the liquid (see Eq. (1)) and $C = 1.2$ when the regime is turbulent. Since Santos et al. (2008) obtained values of C ranging between 1.13 and 1.40, depending on the column dimensions they concluded that a fully-developed laminar regime in the liquid ahead of the bubble is never reached because the bubble expands continuously with an increasing expansion rate.

The present work complements the previous study where only bubble parameters (such as velocity and length) were measured at different levels of their ascending path. The contribution proposed for gas expansion on the velocity of a Taylor bubble is now corroborated, analyzing the induced liquid flow in detail using PIV and ST simultaneously. The conditions used in image acquisition also allowed bubble velocity measurement because the nose of the Taylor bubble was registered in consecutive images. The simultaneous measurement of bubble parameters and characterization of liquid flow around the bubble give rise to the best conditions to establish the relation between bubble expansion rate and the induced upward liquid flow. The high gas expansion rates obtained mainly near the free liquid surface change continuously and so quickly that bubble parameters and liquid flow field measurements must be done at the same instant and at the same location.

2. Experiments

2.1. Experimental set-up and conditions

The experimental facility used to perform the experiments is described at Santos et al. (2008). A vertical acrylic column 4 m in height with an internal diameter of 0.032 m was used to obtain the liquid velocity profile in front of a single Taylor bubble rising in a vertical column of stagnant water under different pressure conditions.

The system used for bubble injection and to maintain reduced pressure above the free water surface and measure the pressure is the same as presented at Santos et al. (2008). The experiments