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Unsteady dynamics of Taylor bubble rising in vertical oscillating tubes

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ABSTRACT

The present work deals with the motion of a Taylor bubble rising through vertical oscillating pipes. The aim is to perform a more detailed and quantitative study of this unsteady flow, still seldom addressed in the literature. The investigation is restricted to high Reynolds numbers to understand inertia effects. Experimental results are provided for two different configurations: (1) pipes with two different inner diameters (9.8 mm and 20 mm) filled with water, (2) the thinner pipe ($D = 9.8$ mm) filled with four low viscous fluids. So the Bond number Bo based on the steady rise velocity varies from 13 to 57, where the effects of surface tension can be considered. The bubble trajectory is tracked by using a high-speed video camera. The average terminal and fluctuating velocity, as well as the phase shift with the oscillating plate are obtained by using image processing. The main results show that for weak acceleration, the mean velocity decreases with the relative acceleration as the fluctuating velocity increases in proportion to this acceleration. Beyond a critical relative acceleration, the average velocity increases and the fluctuating velocity increase seems to slow down. Additionally, comparisons are made with experimental results of Brannock and Kubie [Brannock, D., Kubie, J., 1996. Velocity of long bubbles in oscillating vertical pipes. Int. J. Multiphase Flow 22, 1031–1034] and numerical results of Clanet et al. [Clanet, C., Heraud, P., Searby, G., 2004. On the motion of bubbles in vertical tubes of arbitrary cross-sections: some complements to the Dumitrescu Taylor problem. J. Fluid Mech. 19, 359–376].

1. Introduction

Among two-phase flow regimes in a vertical pipe, slug flow appears in a very wide range of flowing conditions. This kind of flow is characterized by large elongated bubbles, also called Taylor bubbles or gas slugs, which nearly occupy the entire cross section of the pipe. A thin film of liquid flows between the gas interface and the pipe wall.

Slug flows occur in several industrial applications. It is useful in desalination industry, in heat exchangers, boilers and heat pipes in order to improve the efficiency by increasing the mass and heat transfer. Slug flow is also widely encountered in the oil extraction industry where it is very undesirable. It causes serious mechanical process and corrosion problems in oil field facilities. Thus it is essential to predict slugging characteristics so as to be able to reach a safe, economic and efficient design in applications such as these. Thus many researchers have been interested in Taylor bubble flow and various investigations have been carried out on this subject. In order to understand the hydrodynamics of such a complex flow, the first step has been to study a single gas slug evolving in a vertical pipe.

The rise velocity of Taylor bubbles depends on the pipe diameter and its inclination angle, the physical properties of gas and liquid phases (density, viscosity and surface tension), and the flow rates of the two phases. White and Beardmore (1962) established by using dimensional analysis, the main dimensionless numbers which govern the motion of Taylor bubbles in pipes: Bond ($Bo = g(\rho_L - \rho_G)D^2/\sigma$), Froude ($Fr = U_b/\sqrt{gD}$) and Morton ($Mo = g\mu_L^4/\rho_L\sigma^3$) numbers, where D is the pipe diameter, U_b is the Taylor bubble mean velocity, ρ_L and ρ_G are the liquid and gas densities, μ_L is the viscosity of the liquid, σ stands for the surface tension and g is the gravity. Other dimensionless numbers could be used, e.g., Collins et al. (1978) used Froude number as a unique function of Morton number and a dimensionless inverse viscosity number, N_f, given by $N_f = \rho_L g^{\frac{1}{2}} D^{\frac{3}{2}}/\mu_L$ ($\sim Re$). It is known that in cylindrical tubes of diameter D, for a Taylor bubble motion in a liquid of kinematic viscosity ν, high Reynolds number bubbles ($Re \equiv U_bD/\nu \gg 1$) are characterized by:

$$U_b = Fr\sqrt{gD} \quad (1)$$

The first studies on the bubble rise velocity in circular cross section pipes and in stagnant fluids, were carried out by Dumitrescu (1943), Davies and Taylor (1950). These studies were limited to the case of bubbles moving in low viscous liquids and where the surface tension effects were considered to be negligible. According to the literature, these conditions are satisfied when $N_f > 300$ (negligible viscosity regime) and $Bo > 100$ (negligible surface tension). In this case, the theoretical solution for a bubble rising in a stagnant column, is given by Eq. (1) where the Froude number is constant. The estimated Froude number by Dumitrescu (1943), Davies and

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Taylor (1950) is 0.351 and 0.328, respectively. Comparison with experimental results of White and Beardmore (1962), Nicklin et al. (1962), Zukoski (1966) indicates that Dumitrescu's estimate of the Froude number $Fr = U_b/\sqrt{gD}$ is the most accurate one and agrees well with experiment. Dumitrescu also studied the effect of surface tension by investigating the influence of the interface curvature. He observed the bubble propagation in tubes whose diameter is comparable with the capillary length $l_c = \sqrt{2\sigma/\rho g}$. His experimental results for air bubbles in water showed that Eq. (1) is valid only within the limit $D/l_c > 4\sqrt{2}$ or $Bo > 64$. Below this limit, Fr is no longer constant but decreases as the Bond number, $(Bo = 2(D/l_c)^2)$ does. The effects of surface tension were also studied by other authors. Tung and Parlange (1976), Bendiksen (1985) investigated theoretically the influence of surface tension on bubble motion. Both found that surface tension monotonically reduces the rise velocity and this was in agreement with their experiments as well as with the experiments of Zukoski (1966). The simplified result of Bendiksen given by Fabre and Line (1992) can be written as:

$$Fr = 0.344 \frac{1 - 0.96\exp(-0.0165Bo)}{(1 - 0.52\exp(-0.0165Bo))^{3/2}} \sqrt{1 + \frac{20}{Bo}\left(1 - \frac{6.8}{Bo}\right)} \quad (2)$$

Thus in a quiescent fluid with moderated viscosities, the velocity U_b can be calculated from a relationship $Fr = f(Bo)$. For Taylor bubbles in co-current flow, the rise velocity can be predicted from Nicklin's equation (Nicklin et al., 1962) $U_b = U_{b_0} + C_0U_m$, where U_m is the mean velocity of liquid flow in the pipe and U_{b_0} is the Taylor bubble velocity in stagnant conditions. Coefficient C_0 takes value of around 1.2 when the liquid flow is turbulent and around 2.0 when it is laminar.

van Hout et al. (2002) were one of the first ones to perform PIV measurements in slug flow for air–water systems, for stagnant water in the pipe. They determined separately the flow pattern around a single gas slug and the bubble shape. In recent works, this subject was studied for the case of Taylor bubble motion in stagnant newtonian and non newtonian liquids (Sousa et al., 2005, Nogueira et al., 2006) and the bubble shape was obtained more precisely by using the simultaneous particle image velocimetry technique (PIV) and pulsed shadow technique (PST).

As reviewed above, several articles have been published on the Taylor bubble motion in vertical tubes in the case of steady flow. However, in almost all the industrial processes, the flow is unsteady, for example when the pipe undergoes vibrations. In this condition the steady models presented in previous works could not be validated. Unfortunately this subject has remained largely unaddressed.

Brannock and Kubie (1996) were the first to perform an experimental investigation on the motion of Taylor bubbles in 2 m long vertically oscillating vertical pipes with internal diameters of 22 and 44 mm. They were subjected to a perfect sinusoidal vertical motion with the oscillation amplitudes b of 50, 100 and 200 mm and acceleration $b\omega^2$ of 0 (stationary vertical pipe), 1, 5, 10 and 15 ms^{-2} with ω the angular frequency. In all these cases, rise velocity decrease with the relative acceleration $a = b\omega^2/g$ was observed. They indicated a good agreement between the experimental data and their semi-empirical approach. In order to predict this decrease, Brannock and Kubie (1996) assumed that the instantaneous bubble velocity, $U_b(t)$, can be deduced from Eq. (1) by replacing g by g_E where g_E is a "pseudo" effective acceleration. They proposed: $g_E = max[(g + b\omega^2 sin\omega t), 0]$. This choice is not very clear and is not based on any scientific argument. Its only interest is to have a positive quantity under the root of Eq. (1) when the relative acceleration a becomes greater than 1. Then the average bubble velocity was calculated by: $\bar{U}_b = (1/T)\int_0^T U_b(t)dt$, where T is the periodic time. Comparing with their experimental results, they found that the "theoretical" results underpredict the reduction in $\bar{U}_b/U_{b_0}$. Thus by considering the bubble nose distortions which become more important at high relative accelerations, they introduced a critical relative acceleration a_c, at which the bubble is completely broken up, in the rise velocity expression and they proposed:

$$\bar{U}_b/U_{b_0} = \left(1 - \frac{a}{a_c}\right)^{\frac{n}{2}} \frac{1}{T} \int_0^T (max[(1 + a\sin\omega t), 0])^{1/2} dt \quad (3)$$

where U_{b_0} is the velocity of the Taylor bubble at $\omega = 0$. The critical relative acceleration, a_c, and the exponent n was found experimentally to be equal to 1.7 and 0.05, respectively. Kubie (2000) also studied experimentally the velocity of long bubbles in horizontally oscillating vertical tubes, but this configuration is different of our investigation. In this last case, Kubie (2000) found that the velocity ratio increases with the relative acceleration, a.

Clanet et al. (2004) developed an analytical model in order to analyze the propagation of Taylor bubble in an oscillating vertical tubes. It should be noted that in their case the surface tension effects are considered to be negligible and the bubble nose is assumed to be undeformable. By projection of the Euler equation onto the interface and by assuming a potential motion along the bubble, they obtained the following differential equation:

$$\frac{dU_b}{dt} + k_0U_b^2 - g(1 - a\sin\omega t) = 0 \quad (4)$$

where $k_0 = 7.66/D$ leading to a $Fr = 0.361$ for steady state regimes. Clanet et al. decomposed the velocity $U_b(t)$ into a mean and fluctuating part: $U_b(t) = \bar{U}_b + U_f(t)$ and used a numerical method in order to determine $\bar{U}_b$. They found that the mean velocity reaches zero for a critical reduced acceleration, a_c of about 1.7 which is in good agreement with the experimental observations of Brannock and Kubie (1996).

Madani et al. (2007) carried out an experimental investigation on the motion of a Taylor bubble moving in water under gravity and vertical oscillating motion generated by a vibrating plate. Their experiments were carried out for different frequencies where the oscillation magnitude b was equal to 5 mm and 20 mm. A very small influence of the oscillation amplitude on the bubble velocity was observed for weak relative accelerations. The evolution of the bubble length for different frequencies were investigated and the small linear evolution of bubble length with the oscillating plate was observed. The effects of quasi-steadiness were also studied by determining Froude and Bond numbers and were found to be more important for high frequencies.

In the present study, this work is extended for different pipe diameters and by using other fluid–gas combinations. As referred above, only two other researchers focused on the unsteady flow of Taylor bubbles and they were only interested in the mean rise velocity of long bubbles. So it appeared legitimate to us to start an experimental study on this topic in order to understand the complex nature of slug flows in quasi-steady conditions. In this work, we carry out an experimental investigation on the motion of a Taylor bubble moving in a non viscous (low viscosity) quiescent liquid under gravity and vertical oscillating motion generated by a vibrating plate. The bubble motion is obtained by using high-speed video tracking and subsequent image processing methods. The average rise velocity, the fluctuating velocity, the phase shift with the oscillating plate are measured. From these results, the effects of quasi-steadiness are studied by defining and determining two unsteady dimensionless numbers: Froude and Bond numbers.

2. Experimental set-up, measurement techniques and data processing

2.1. Experimental set-up

The experimental facility consists of a mechanical system containing a vertically oscillating plate and a closed column filled with a low viscous fluid and a small quantity of gas to generate the Taylor bubble (Fig. 1).