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An experimental investigation on the effect of viscosity on bubbles moving in horizontal and slightly inclined pipes

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ABSTRACT

The motion of long bubbles in horizontal and slightly inclined pipes is a thoroughly investigated phenomenon. However, few results are available in literature for the drift velocity of a gas bubble in viscous liquids.

The aim of this study is to experimentally analyse the effect of viscosity on the drift velocity of an air bubble in horizontal and inclined pipes. Two different measurement techniques are used: five capacitance probes are placed along the pipe to monitor the velocity evolution and image analysis is used to measure the bubble front velocity at two different distances from the outlet. The results of the measurements show that for horizontal case, as opposite to Benjamin (1968), the bubble drift velocity is not constant while the front displaces along the pipe and, in general, the viscosity slows down the propagation rate of the bubble. Finally, two drift velocity closure equations are tested with collected data.

1. Introduction

Few different approaches to slug flow modelling can be found in literature and one of the most used is the slug-unit model. In this formulation, a gas bubble in a slug unit moves with a velocity modelled as the sum of the drift velocity, U_d, and of the mixture velocity, U_m, multiplied by the distribution parameter, C_0. Some authors, Gregory and Scott [13], Dukler and Hubbard [9], and Heywood and Richardson [16] considered a null drift velocity for the slug flow in horizontal or nearly horizontal pipes. However, it has been demonstrated theoretically, Benjamin [6] and Weber [31], and experimentally, Zukoski [33], Bendiksen [5], Weber et al. [32], and Alves et al. [1], that the drift velocity is not zero, even in horizontal flow. Nowadays it is widely accepted, Bendiksen [5], Taitel and Barnea [29], Fabre and Line [10], Andreussi et al. [2], and Hanratty [15], that it should be accounted for in the calculation of the bubble translational velocity.

The pioneering work of Benjamin [6] explores the possibilities of applying the inviscid-fluid theory to steady gravity currents, analysing the problem of an empty cavity advancing along a horizontal pipe filled with liquid. In that analysis, the effect of viscosity and surface tension are neglected. After an initial transient stage, whose analysis is not carried out in the model, the air-filled cavity replacing the out-flowing liquid moves steadily along the tube. Benjamin [6] provided a value for the propagation velocity of the front of the cavity, which depends on the pipe diameter and on the bubble shape. The well-known Benjamin velocity is $U_d = 0.54\sqrt{gD}$ with g and D being the gravitational acceleration and the pipe diameter, respectively. Employing this value in slug flow models for low viscosity and nearly horizontal systems at low mixture velocities is a well established practice, see Taitel and Barnea [29] and Orell [24]. However, when viscous effects become important, inviscid hypothesis may lose its validity and may not be sufficient to properly describe the motion of the bubble.

The first who experimentally investigated the effects of viscosity and surface tension on the motion of long bubbles in horizontal and inclined pipes is Zukoski [33]. In his work, he explained the combined effect of inclination and surface tension.

Wallis [30] indicated three independent dimensionless groups that influence the rising motion of long bubbles in vertical pipes, the Froude number (*Fr*), the Eötvös number (*Eö*) and the Reynonlds number (*Re*); at the same time, Wallis [30] defined three regions of influence, the inertia dominant region, the viscosity dominant region, and the surface tension dominant region. Although he formulated these considerations only for vertical flows, in many works, Gokcal et al. [14], Khaledi et al. [20], Moreiras et al. [22], his approach is followed also to describe horizontal drift velocity, with good agreement with experimental results.

A thorough experimental study on long bubbles in inclined pipes was performed by Bendiksen [5]. In order to take into

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account the effects of inclination, he presented a correlation for the drift velocity, in terms of Fr, at all inclination angles. The correlation combines the Froude number for the two limit cases, horizontal flow (Fr_H) and vertical flow (Fr_V), by means of the cosine and the sine of the inclination angles. As he showed, the correlation is in good agreement with Zukoski's data and his own when *the* Eötvös number is above 100.

Weber et al. [32] proposed an extension of the correlation proposed in Bendiksen [5] to improve its behaviour for $E\ddot{o} > 100$. Weber et al. [32] reduced the error in the drift velocity by a correction term that depends on the difference between Fr_H and Fr_V and on the sine of the inclination angle.

In all experimental studies, the drift velocity is reported to increase as the inclination angle increases, reaching a maximum between 30° and 60°.

An interesting study, both theoretical and experimental, is presented by Baines et al. [4]. They investigated the motion of bubbles in a closed, horizontal, square section tube. Removing a moving wall, they released a fixed volume of air into the duct and observed the evolution of its motion. As they reported, the bubble passes through three different phases: initially, its front displaces with a constant speed, then this speed decreases monotonically and it finally goes toward a series of starts and stops until it comes to rest. Moreover, they classified the shapes of the bubbles into three categories according as the pipe end is completely or partially opened. A smooth steady cavity exists when the pipe end is completely opened while, as it is throttled, an hydraulic jump appears.

Recently, several experimental campaigns have been performed by Gokcal et al. [14], Jeyachandra [17], and Moreiras et al. [22] to investigate the effect of viscosity. In particular, all these works suggested that the viscosity has a deep impact on the value of drift velocity. In Gokcal et al. [14], a procedure similar to that presented in Alves et al. [1] is adapted to compute the total head loss for the horizontal flow and the drift velocity for this inclination. Furthermore, a correlation for inclined flow is presented in a form similar to the one by Bendiksen [5]. Moreiras et al. [22] developed a new approach to model the horizontal drift velocity and, in general, the drift velocity in inclined pipes and it will be discussed in Section 4.

Most of the experimental results regarding drift velocities of viscous fluids available in literature, Zukoski [33] and Weber et al. [32], is obtained in very short pipes and, as already pointed out by Zukoski [33], for these tubes the distance from the bubble front to the exit was not enough for viscous effects to be important. There are some studies that reported experiments carried out with longer pipes, Alves et al. [1], Gokcal et al. [14], and Moreiras et al. [22], however measurements are performed only in one point and there is no evidence of the velocity reduction along the pipe.

Probably the first work to move towards this direction could be found moving to numerical simulations. Andreussi et al. [3] showed that, for large liquid viscosity, the drift velocity of a bubble penetrating in a horizontal draining pipe decreases along the pipe. In this work, different simulations were carried out using the same pipe geometry and different liquid viscosities, showing that the reduction is always present, even for water, and it is more evident as viscosity increases. No further considerations about the influence of surface tension are reported. In line with Andreussi et al. [3], Ramdin and Henkes [25] and Kroes and Henkes [21] reported the results of 2D and 3D simulations performed with a commercial CFD code. In their work they showed that a viscous Benjamin bubble decelerates while it expands along the pipe. The final value of the velocity depends on the viscosity set in the calculation. Moreover, Kroes and Henkes [21] proposed a correlation for the nose displacement as a function of time. The functional dependence is a power law where the power depends the Reynolds number.

Moving from these evidences, the aim of the present work is to experimentally investigate the evolution of the motion of long bubbles intruding in a draining pipe with the use of more than one measuring station. In this manner, the reduction of the velocity of the bubble could be tracked and reported. Few inclinations, including the horizontal condition, will be analysed. Finally, two recently developed drift velocity closure equations will be tested against our results.

2. Experimental set-up

The experimental facility, especially designed to study multiphase flows, consists of a $L = 9$ m long glass pipe with an inner diameter of $D = 0.022$ m. The pipe is formed by six 1.5 m long sections. A sketch of the set-up is given in Fig. 1. The pipe inclination during this work is set between 0° and 5°. Monitoring the pipe inclination is extremely important, in particular for the horizontal case, since the drift velocities we expect to measure are extremely low and, therefore, even a slight deviation from the set inclination can significantly affect the data. The inclination angle is periodically checked with an electronic level sensor, which offers an uncertainty of ±0.1°. Since the facility is composed of six pipes jointed together, some deviations from a perfect alignment of each single section with respect to the previous and the following ones may be present; they are of the same order of magnitude of the level accuracy, i.e. ±0.1°.

Three different paraffin oils are used in these experiments. Their densities are measured by a hydrometer, their viscosities are measured with a rotational rheometer (Ultra Programmable Rheometer LV-DV III+, Brookfield, Middleboro, USA) while their surface tensions are measured by a Wilhelmy plate tensiometer; the values are all reported in Table 1.

According to Kroes and Henkes [21], using dimensionless groups to analyse of the motion of long bubbles in stagnant liquids is helpful for a better understanding of the phenomenon. In particular, a characteristic Reynolds number is defined as $Re = \frac{\rho_l D\sqrt{gD}}{\mu_l}$ and it is used to indicate the effect of viscosity on the bubble motion; note that $\frac{\rho_l D\sqrt{gD}}{\mu_l}$ can be seen as the square root of the Galileo number. The importance of surface tension and pipe diameter is underlined by the Eötvös number defined as $E\ddot{o} = \frac{\rho_l g D^2}{\sigma}$. Using the values from Table 1, the map shown in Fig. 2 is built.

As can be seen from Fig. 2, the conditions investigated in this work are far from those represented by water. The Reynolds numbers are far below the ones for water, showing the predominant influence of viscosity over density. Moreover, the surface tension is the other controlling parameter, since all the oils show an $E\ddot{o} > 100$.

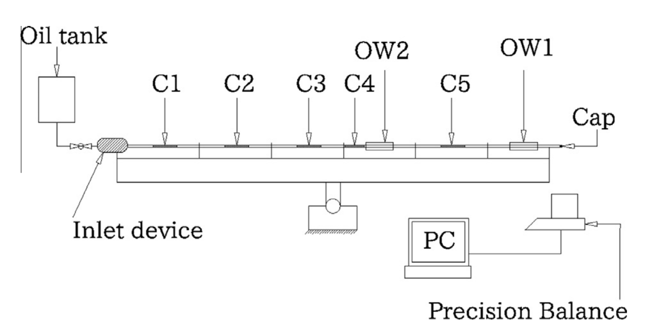

Fig. 1. Experimental multiphase flow set-up. C: capacitance probe; OW: observation window.