Effects of physical properties on the behaviour of Taylor bubbles

V. Hernández-Pérez, L. A. Abdulkareem & B. J. Azzopardi
Department of Chemical and Environmental Engineering,
Faculty of Engineering, University of Nottingham, UK

Abstract

Gas-liquid flow in vertical pipes, which is important in oil/gas wells and the risers from sea bed completions to FPSOs, was investigated to determine the effects of physical properties on the characteristics of the mixture such as void fraction, structure frequency and velocity as well as the shape of 3D structures. These are difficult to visualise using conventional optical techniques because even if the pipe wall is transparent, near-wall bubbles would mask the flow deep in the pipe. Therefore, more sophisticated methods are required. Two advanced wire mesh sensors (WMS) were used and the two-phase mixtures employed were air-water and air-silicone oil.

The effect of fluid properties is accounted for in terms of the Morton number. It was found that the flow pattern is affected by the fluid properties as the results revealed that contrary to what is commonly assumed when modelling pipe flow, the flow is not symmetric, with a lot of distortion, which is even higher for the air-silicone oil mixture.

Keywords: gas/liquid, vertical, wire mesh sensor, slug flow, void fraction, structure velocity.

1 Introduction

One of the most common structures found in gas-liquid flows is the Taylor bubble; it is related directly to the slug flow pattern in upward vertical flow, for instance in oil/gas applications. This bubble occupies the greater part of the pipe cross section. Liquid between the Taylor bubble and the pipe wall flows around this bubble as a thin film. Traditionally the Taylor bubble has been stereotyped as a bullet-shape bubble and most hydrodynamic models of pressure drop for

WIT Transactions on Engineering Sciences, Vol 63, © 2009 WIT Press
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/MPF090301

slug flow take on this shape as suitable, but in reality the behaviour of Taylor bubbles is rather complex and they can adopt different shapes affected by different parameters, such as pipe diameter and fluid properties. Several authors have reported in the literature a lack of slug flow in relatively large pipe diameters. The behaviour of bubbles in turn can affect parameters such as pressure drop and heat transfer coefficients. Of particular importance can be the role that fluid properties play in oil/gas production, where they can vary from one well to another.

The simple change of fluid from one mixture to another can result in the variation of several important properties such as viscosity, density and surface tension. In fact, the viscosities measured for different heavy oils can vary by orders of magnitude. However in the literature, there is a lack of information regarding the effect of fluid properties on the behaviour of Taylor bubbles, particularly at high Reynolds numbers. Most of the work using different gas-liquid mixtures has been directed towards the measurement of average liquid holdup and pressure drop and flow pattern transition, for instance Weisman et al. [1] as well as Nädler and Mewes [2], have studied effect of fluid properties on flow patterns in horizontal two-phase flow. For vertical flow, not surprisingly, most of the extensive work reported has been regarding the motion of single Taylor bubbles using air-water mixtures, as it is the basis for the study of more complicated flows. One of the first investigations on these large bubbles was carried out by Davies and Taylor [3], who carried out viscous potential flow analysis of cap bubbles and found that the terminal rise velocity was simply related to the curvature radius of the cap bubble. However due to disturbances induced by the bubbles in the liquid, it is evident that the Taylor bubbles in a train of bubbles will behave different from a single bubble in static liquid. In general, the theoretical approach has been limited to the low Reynolds number regime and several studies have been published over the years, for instance Moore [4] carried out a study of a gas bubble in a viscous liquid and more recently Tomiyama et al. [5] studied the terminal velocity of a single bubble rising through an infinite stagnant liquid in a surface tension force dominant regime theoretically and experimentally. In many cases investigators have followed the experimental approach in order to tackle the behaviour of Taylor bubbles in more attention demanding problems. Nicklin et al. [6] established a correlation for translational velocity of Taylor bubbles in moving liquid while White and Beardmore [7] used dimensionless groups to account for the combined effect of several variables, including fluid properties. Later developments in instrumentation have allowed researchers to look further at the two-phase flow; Van Hout et al. [8] measured the translational velocity of elongated bubbles in continuous slug flow, Hassan et al. [9] studied two-phase flow field and 3D structures in bubbly flow using particle image velocimetry (PIV). However, no effect of physical properties has been reported. Not until recently have a few studies been presented on numerical simulation of Taylor motion, usually they are limited by the sort of assumptions that need to be made, such as flow symmetry and stagnant liquid. For example Clarke and Issa [10] modelled the motion of a periodic train of Taylor bubbles in vertical flow by imposing cyclic conditions at the inlet and outlet of the slug unit based on the assumption that the flow pattern repeats itself over consecutive slug units. Taha and Cui [11] among others have highlighted the use of dimensionless groups in the study of Taylor bubbles along with the numerical approach, as correlations of experimental data are generally developed in terms of dimensionless groups rather than in terms of the separate dimensional variables in the interests of compactness and in the hope of greater generality.

The shape of the bubbles can change with the local hydrodynamic conditions, adding new degrees of freedom to an already complex problem. Knowledge of the Taylor bubble behaviour in moving liquid is fundamental to our understanding of multiphase flow, particularly when fluid properties are varied.

In this work, a study of the effect of liquid properties on Taylor bubble behaviour is performed based on experimental data obtained at high Reynolds numbers. Particular emphasis is put in the extraction of 3D structures, with the use of advanced instrumentation known as wire mesh sensor, looking forward to use this information for validation of computational models for determination of gas-liquid interface.

2 Experimental facility

Two advanced wire mesh sensors (WMS), developed at Forschungszentrum Rossendorf-Dresden, have been used in a two-phase flow facility at Nottingham. The basic part of the facility has been frequently described elsewhere, for example Hernández-Pérez et al. [12] and Azzopardi et al. [13], and for the sake of simplicity details are omitted here. The sensors are described in detail by Prasser at al. [14] and Da Silva et al. [15] respectively. Both of them have a grid of 24 × 24 measurement points evenly distributed across the pipe cross-section given by a 24 × 24 wire configuration in two planes. The first is based on conductivity measurements and is suitable for water; the second is based on capacitance measurements and works with non-conductive materials such as oil. Figure 1 shows a picture of the wire mesh sensor.

The two-phase mixtures employed were air-water and air-silicone oil. The latter liquid has a surface tension about one third that of water and a viscosity of ~5x water. The physical properties of the fluids used are given in Table 1.

Table 1: Properties of the fluids.

Fluid	Density (kg/m^3)	Viscosity (kg/ms)	Surface tension (N/m)
Air	1.224	0.000018	0.072
Water	1000	0.001	
Silicone oil	900	0.005	0.02

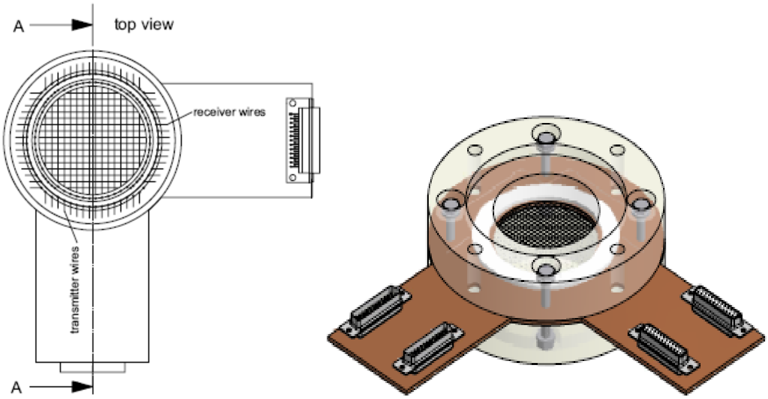


Figure 1: Wire-mesh sensor (2 × 24 electrode wires).

The data were gathered in two campaigns: In the first campaign the air-water mixture was used with the conductivity wire mesh sensor and a pair of capacitance probes in order to obtain structure velocity, as reported by Hernández-Pérez et al. [12]. In the second campaign air-silicone oil was employed with the capacitance wire mesh sensor as well as Electrical capacitance tomography (ECT), as described by Abdulkareem et al. [16]. The test pipe is 6 m long and 67 mm diameter. In both campaigns, the wire mesh sensor was located at 4.92 m from the mixing or inlet section and we focus on vertical flow. Conditions studied were superficial velocities: for air ranging from 0.05 to 4.7 m/s and for liquid from 0.0 m/s to 0.7 m/s for both water and silicone oil. The data were taken at a data acquisition frequency of 1000 Hz over an interval of 40 s for the wire mesh sensors and 200 Hz for both capacitance probes and ECT. In addition, high speed video system was used in order to obtain real images of the flow regimes under different conditions.

3 Results and discussion

The behaviour of the Taylor bubble is described by means of several parameters such as time series of cross-sectional area averaged void fraction. Further analysis of these time series will allow flow patterns and structure frequencies to be extracted and compared. Finally the full 3D structures will be presented.

Applying dimensional analysis, the effect of the properties can be put in terms of dimensionless numbers. For gas bubbles rising in liquids, the viscosity ratio and density ratio tend to be very small and therefore it is generally sufficient to consider only three dimensionless groups, namely the Morton number (*M*), the Eotvos Number (*Eo*) and the Froude number (*Fr*) as identified by White and Beardmore [7]. *M* is also called the properties number and together with the Eötvös number, is useful to characterize the shape of bubbles. These numbers are defined respectively as:

$$M = g\mu_L^4(\rho_L - \rho_G)\big/\rho_L^2\,\sigma^3 \tag{1}$$

$$Eo = g(\rho_L - \rho_G)D^2 / \sigma \tag{2}$$

and

$$Fr = U_{TB} / \sqrt{gD(\rho_L - \rho_G)/\rho_L} \tag{3}$$

Here g is the gravity acceleration, μ is the viscosity, ρ is the density, σ is the surface tension, D is the pipe diameter and U_{TB} is the velocity of a Taylor bubble rising in motionless liquid. The subscripts L and G refer to liquid and gas respectively. Therefore for air-water M = 2.64 10^{-11} and Eo=610.9 whereas for air–silicone oil M = 1.36 10^{-9} and Eo=1970. According to Bhaga and Weber [17], since M for both of the two-phase mixtures employed in this work are lower than 4 10^{-3}, the bubble behaviour is expected to be a function of both Morton and Reynolds numbers. It can be observe from eqn (1) that variations in M are mainly due to the factor, μ^4, since ρ and σ do not vary much from water to silicone oil. Water is usually considered as a low M number fluid.

3.1 Time series of void fraction

The time series of cross sectional average void fraction show in a simple way the occurrence of structures as the gas-liquid mixture flows along the pipe. It also constitutes the raw data for application of statistical analysis to judge the flow behaviour. Figure 2 shows a typical run in which slug flow is present, the appearance of Taylor bubbles can be identified as high void fraction intervals whereas the low void fraction intervals correspond to the liquid slugs. The irregular variation of the void fraction reveals the transient nature of the Taylor bubbles. In addition, the liquid film variation can be observed to have an irregular shape.

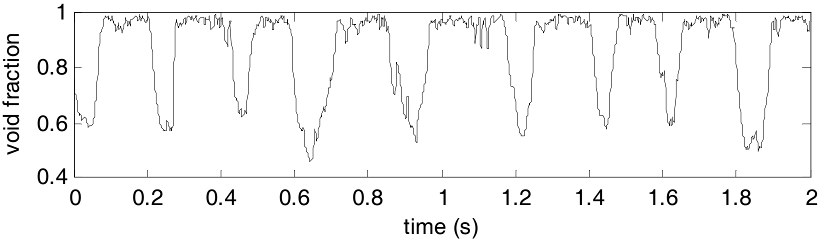
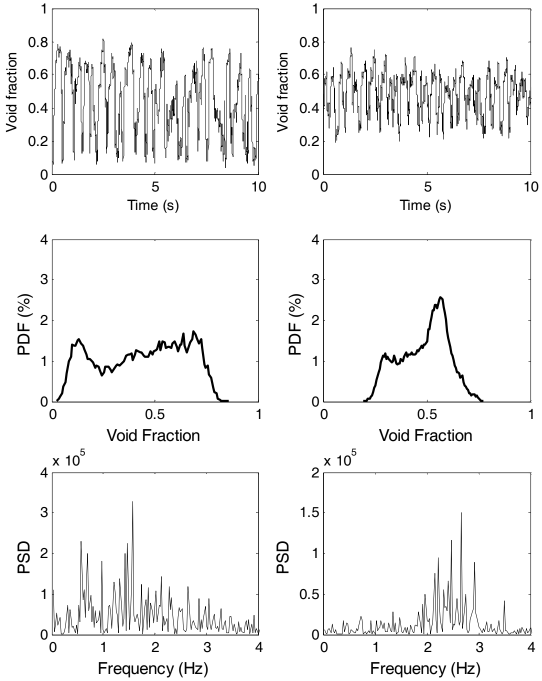


Figure 2: Typical time series of cross-section average void fraction.

3.2 Flow patterns and structure frequency

In considering Taylor bubbles, it is important to know the flow conditions under which these particular structures occur. Statistical analysis of the time series data can provide an insight into flow pattern identification. In this sense, a widely used and accepted method is Probability Density Function (PDF). It is also important to characterise the structures in terms of their occurrence frequency, which was found from the time series utilizing the Power Spectral Density (PSD) technique.

Figure 3 shows the time series, the PDF and the PSD for both two-phase mixtures at a particular flow condition. In this figure a time interval of 10 s is used to plot the time series however for processing the PDF and the PSD, the data gathered in 40 s have been considered. It is apparent from both the time series and PDF plots that the fluctuation amplitude of void fraction is bigger for the case of air-water mixture. Also, the double peak shape of the PDF plot, characteristic of slug flow is not well defined; indeed the flow is greatly distorted as illustrated by the 3D structures in section 3.3.



Air-water

air-silicone oil

Figure 3: Effect of fluid properties on flow pattern transition, liquid superficial velocity 0.2 m/s and gas superficial velocity 0.94 m/s.

Due to the random distortion and fluctuations of Taylor bubbles, in practice, it is usually more convenient to study its behaviour in terms of average parameters such as the frequency. Looking at Figure 3, it can be observed that the frequency of Taylor bubbles is also affected by the change in physical properties of the liquid phase, for a particular condition the structure frequency increases when the viscosity is increased as the dominant frequency predicted with PSD is higher for the case of silicone oil liquid. Also, the liquid film in the Taylor bubble is in general thinner for the case of the air-water mixture. This is in agreement with Goldsmith and Mason [18] who found a similar behaviour.

Figure 4 shows that, the change of liquid from water to silicone oil, which means an increase in the Morton number, keeping the liquid superficial velocity constant produces a displacement of the bubbly-cap bubble boundary towards a higher gas superficial velocity. This behaviour was observed to be evident at higher liquid superficial velocities (0.7 m/s). This is similar to the findings of Weisman et al. [1] in terms of the flow pattern boundaries being affected by the physical properties of the fluids and can be thought of as an indication of a longer development distance required by a more viscous flow. Most of the PDFs in Figure 4 show a shape that corresponds to the cap bubble flow pattern.

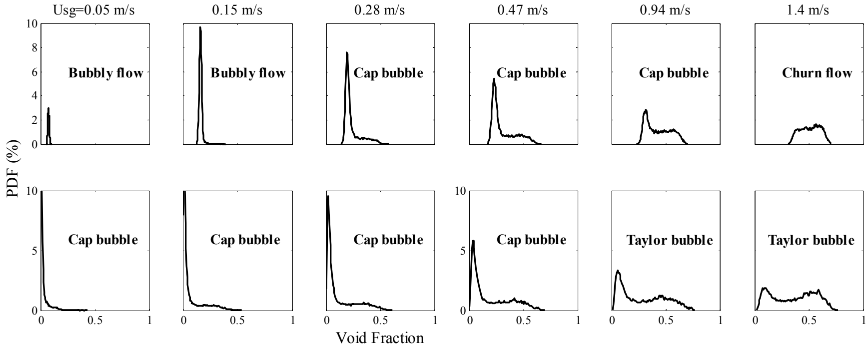


Figure 4: Probability density function of the time series of the cross-section average void fraction at liquid superficial velocity 0.7 m/s. Lower row air-water, upper row air-silicone oil.

3.3 Shape of 3D structures

The detection of the sharp gas-liquid interfaces plays an important role in identification of flow patterns. The wire mesh sensors employed in this study are capable of providing the Taylor bubbles shapes by creating a 3D reconstruction of the flow as shown in Figure 5, where the Taylor bubbles have been brought out for two cases. A time interval of 2 s has been used in both figures 5 and 6. The main features observed in Figure 5 are asymmetry and distortion of the Taylor bubbles, the distortion of bubbles appears to be higher in the air-silicone oil mixture, which can be due to the lower surface tension of the silicone oil, as the surface tension acts as the force that restrains deformation, despite its higher viscosity, as the main effect of viscosity on the displacement of a bubble is the production of a drag force that tends to slow down its relative motion in the surrounding fluid. From the 3D representation in Figure 5 it is clear that the physical properties greatly influence the shape of the structures. For the conditions used in this work the typical Taylor bubble shape is rarely observed for the case of silicone oil.

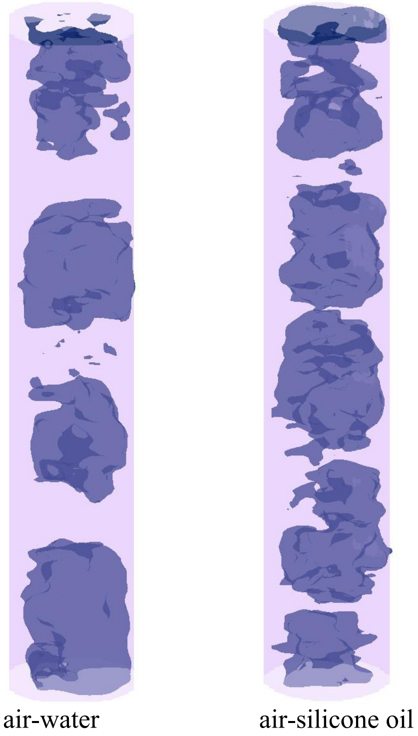


Figure 5: Comparison of Taylor bubble shapes in 3D. Superficial velocities: liquid 0.7 and gas 1.4 m/s.

Both the increase of viscosity and the decrease of surface tension in silicone oil with respect to water contribute to the increase of the Morton number. Therefore the more deformation observed for the air-silicone oil is in agreement with Duineveld [19], who observed that for water, low Morton number, the bubbles rising have relatively low deformation.

The deformation of a Taylor bubble is also related to the stresses generated from the translation movement; as a result, as the mixture velocity increases, it can be observed in Figure 6 that the Taylor bubble is totally broken when the gas superficial velocity reaches 0.94 m/s. This phase interaction mechanism might be the reason why, as reported by Azzopardi et al. [13], liquid structures inside the gas core of the Taylor bubble (Wisps) have been found to exist in the churn flow regime. The deformation due to the high mixture velocity is also related to the high level of turbulence intensity in the flow. The flow conditions employed in the present work, involve large Reynolds numbers. Indeed the classical bullet shape Taylor bubble is rarely observed at the conditions of liquid superficial velocity 0.7 m/s for both water and silicone oil. It is generally accepted that turbulence enhances bubble breakup, however currently turbulence remains an unsolved problem although different turbulence modelling approaches have emerged.

Bubble distortion increases not only with the Morton number but also with Eotvos number, which involves the pipe diameter. This is congruent with the fact that Taylor bubble distortion is proportional to pipe diameter, as it has been reported in the literature.

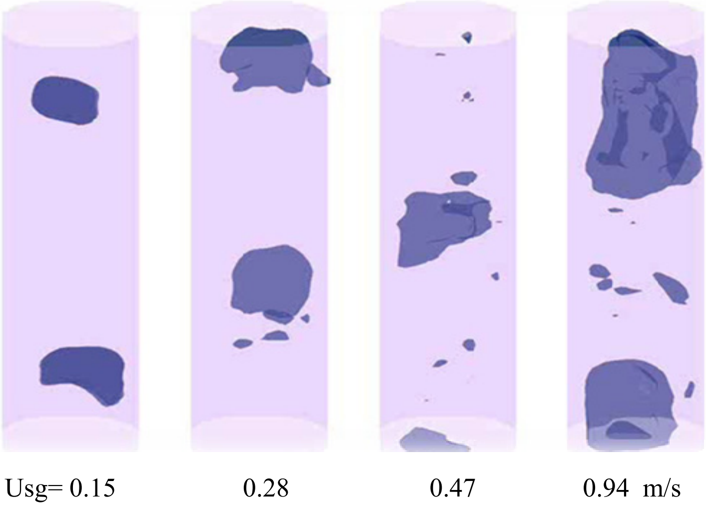


Figure 6: Effect of mixture velocity on Taylor bubble shape, air-water at liquid superficial velocity 0.7 m/s and different gas superficial velocities.

3.4 Translational velocity

The translational velocity, which is an essential parameter to characterise Taylor bubbles, has been obtained by cross correlating a pair of signals delivered by the capacitance probes for the case of air-water and ECT for air-silicone oil. Some of these results are plotted in Figure 7. They show a higher translational velocity for the case of the silicone oil. The higher translational velocity is related to the higher frequency shown in the PSD plot in Figure 3 and the higher overall liquid holdup in the pipe for the air-silicone oil. This finding is in agreement with Van Hout et al. [8], who found that the drift velocity for continuous slug flow is enhanced by the dispersed bubbles in the liquid slug body. Similarly, Hills and Darton [20] found considerable enhancement in the velocity of large bubbles in bubble swarms. Based on observations of Hills [21] who found that when a cap bubble rises in a swarm of small bubbles, the small bubbles never coalesce with the nose of the cap bubble, they suggested that the enhancement is due to the shape change in the cap bubble. However, Hills' arrangement consisted of a two-dimensional bubble column of width so much larger than the cap bubble. Therefore the small bubbles in most cases manage to escape from the cap bubble driven by the liquid velocity field.

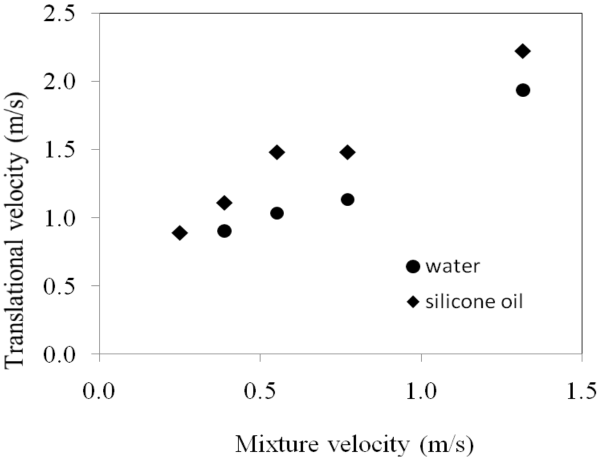


Figure 7: Effect of physical properties on translational velocity. Liquid superficial velocity 0.2 m/s.

4 Conclusion

A study of the effect of the change of fluid properties on Taylor bubble behaviour has been carried out with the use of advanced instrumentation, and a clear effect has been observed. For a higher Morton number, which corresponds to the silicone oil, there is more distortion. Other flow features such as the liquid film and structure frequency are also affected. This comparison shows a remarkable effect of the physical properties on the flow pattern. These results can be used to validate the numerical modelling of Taylor bubbles, which is increasingly gaining popularity, as computational fluid dynamics codes are becoming more widespread.

Acknowledgements

This work has been undertaken within the Joint Project on Transient Multiphase Flows and Flow Assurance. The Authors wish to acknowledge the contributions made to this project by the UK Engineering and Physical Sciences Research Council (EPSRC) and the following: - Advantica; BP Exploration; CD-adapco; Chevron; ConocoPhillips; ENI; ExxonMobil; FEESA; IFP; Institutt for Energiteknikk; PDVSA (INTERVEP); Petrobras; PETRONAS; Scandpower PT; Shell; SINTEF; StatoilHydro and TOTAL. The Authors wish to express their sincere gratitude for this support.

V. Hernández-Pérez was supported by Mexican Council for Science and Technology (CONACyT) with a PhD scholarship. L. Abdulkareem would like to thank The Kurdish Government for supporting his PhD study.

References

[1] Weisman, J., Duncan, D., Gibson, J. and Crawford, T., Effect of fluid properties and pipe diameter on two-phase flow pattern in horizontal lines. Int. J. Multiphase Flow Vol. 5, pp. 437–462, 1979.

[2] Nädler, M. & Mewes, D., Effects of the liquid viscosity on the phase distributions in horizontal gas-liquid slug flow, Int. J. Multiphase Flow, Vol. 21, pp. 253-266, 1995.

[3] Davies, R.M. & Taylor, G.I., The mechanics of large bubbles rising through liquids in tubes. Proc. R. Soc. Lond. Vol. A200, pp. 375–390, 1950.

[4] Moore, D.W., The rise of a gas bubble in a viscous liquid. J. Fluid Mech. Vol. 6, pp 113-130, 1959.

[5] Tomiyama, A., Celata, G.P., Hosokawa, S. & Yoshida S., Terminal velocity of single bubbles in surface tension force dominant regime, Int. J. Multiphase Flow Vol. 28, pp. 1497-1519, 2002.

[6] Nicklin, O.J., Wilkes, J.O., & Davison, J. F., Two-phase flow in vertical tubes, Trans. I. Chem. Engrs. Vol. 40, pp. 61-68, 1962.

[7] White, E.R. & Beardmore, R.H., The velocity of rise of single cylindrical air bubbles through liquids in vertical tubes, Chem. Eng. Sci. Vol. 17, pp. 351-361, 1962.

[8] Van Hout, R., Barnea, D., & Shemer, L., Translational velocities of elongated bubbles in continuous slug flow, Int. J. Multiphase Flow Vol. 28, pp. 1333-1350, 2002.

[9] Hassan, Y.A., Schmidl, W. & Ortiz-Villafuerte, J., Investigation of three-dimensional two-phase flow structure in a bubbly pipe flow, Meas. Sci. Technol. Vol. 9, pp. 309–326, 1998.

[10] Clarke, A. & Issa, R. I., A numerical model of slug flow in vertical tubes”, Computers & Fluids, Vol. 26, pp. 395-415, 1997.

[11] Taha, T. & Cui, Z.F., CFD modelling of slug flow in vertical tubes, Chem. Eng. Sci. Vol. 61, pp. 676-687, 2006.

[12] Hernández-Pérez, V., Azzopardi, B.J. & Morvan, H., Slug flow in inclined pipes. 6th Int. Conf. Multiphase Flow, Leipzig, Germany 5 to 9 July 2007.

[13] Azzopardi, B.J., Hernández-Pérez, V., Kaji, R., Da Silva M.J., Beyer, M., & Hampel, U., Wire mesh sensor studies in a vertical pipe, HEAT 2008, Fifth International Conference on Transport Phenomena in Multiphase Systems, Bialystok, Poland, 2008.

[14] Prasser, H.-M., Bottger, A., & Zschau J., A new electrode-mesh tomograph for gas-liquid flows, Flow Meas. Instr. Vol. 9, pp. 111-119, 1998.

[15] Da Silva, M.J., Schleicher E. & Hampel, U., Capacitance wire-mesh sensor for fast measurement of phase fraction distributions. Meas. Sci. Tech. Vol. 18, pp. 2245-2251, 2007.

[16] Abdulkareem, L.A., Hernández-Pérez, V., Azzopardi, B.J., Sharaf, S., Thiele, S. &Da Silva, M., Comparison of different tools to study gas-liquid flow. ExHFT-7, 28 June – 03 July 2009, Krakow, Poland, (Submitted)

[17] Bhaga, D. & Weber, M. E., Bubbles in viscous liquids: shapes, wakes and velocities. J. Fluid Mech. 105, pp 61-85, 1981.

[18] Goldsmith, H. L. & Mason, S. G., The movement of single large bubbles in closed vertical tubes, J. Fluid Mech. Vol. 14, pp 42-58, 1962.,
[19] Duineveld, P.C., The rise velocity and shape of bubbles in pure water at high Reynolds number, J. Fluid Mech. Vol. 292, pp. 325-332, 1995.
[20] Hills, J.H. & Darton, R.C., The rising velocity of a large bubble in a bubble swarm, Trans. I. Chem. Engrs. Vol. 54, pp. 258-264, 1976.
[21] Hills, J.H., The rise of a large bubble through a swarm of smaller ones, Trans. I. Chem. Engrs. Vol. 53, pp. 224-233, 1975.