Abstract. The development of slug flow along vertical pipes is governed by the interaction between consecutive elongated bubbles. It is generally assumed that the trailing bubble’s shape and velocity are affected by the flow field in the liquid phase ahead of it. To examine this assumption, a facility is used that allows controlled injection of pairs of Taylor bubbles into vertical pipes filled with stagnant or flowing liquid. An experimental approach is developed to perform particle image velocimetry measurements of the velocity field in front of the trailing Taylor bubble, simultaneously with video imaging of Taylor bubble pairs, to be able to relate the instantaneous parameters (shape and velocity) of the trailing bubble to the instantaneous velocity distribution in liquid ahead of it. Experiments are performed in pipes of two diameters and for a number of Reynolds numbers based on mean water velocity, corresponding to both laminar and turbulent background flows. A model relating the propagation velocity of the trailing Taylor bubble to the local mean centerline velocity of the leading bubble is suggested and verified experimentally. The effect of the velocity fluctuations in the leading Taylor bubble’s wake on the instantaneous propagation velocity of the trailing bubble is studied.
1. INTRODUCTION

Slug flow is one of the basic gas-liquid flow patterns that occur naturally inside pipes over a wide range of flow parameters. The phenomenon of slug flow plays an important role in a variety of industrial applications.

Vertical slug flow is characterized by quasi-periodic alteration of large, axisymmetric, bullet-shaped Taylor bubbles that occupy most of the pipe cross section and by regions of continuous liquid phase, or liquid slugs, which may be aerated. In developed slug flow, the Taylor bubbles move upward with a constant velocity. The liquid around the elongated bubbles moves downward as a thin falling film. The liquid velocity in the film is usually several times larger than the mean velocity of the liquid in the slug, forming a circumferential wall jet. The velocity field in the wake of the Taylor bubble is complicated and has been subject to numerous investigations (van Hout et al. 2002, Shemer et al. 2005, 2007).

The translational velocity of a Taylor bubble $U_{tr}$ can be seen as a superposition of its rise velocity in stagnant liquid due to buoyancy, the so-called drift velocity $U_0$, and the contribution due to the mean liquid velocity in the slug $U_{\text{mean}}$:

$$U_{tr} = CU_{\text{mean}} + U_0$$  \hspace{1cm} (1)

The drift velocity $U_0$ is determined by the three-dimensional flow at the front of the bubble. For potential flow, the drift velocity of an elongated bubble rising in a vertical pipe is (Dumitrescu 1943, Davies and Taylor 1949)

$$U_0 = k \sqrt{gD}$$  \hspace{1cm} (2)

where the value of $k$ in Eq. (2) is about 0.35.

The coefficient $C$ in Eq. (1) is generally assumed to depend on the velocity profile in the liquid ahead of the bubble and can be seen as the ratio of the maximum to the mean velocity in the profile; hence for developed turbulent flows, $C \cong 1.2$, while for laminar flow, $C \cong 2$. Nicklin et al. (1962), Grace and Clift (1979), and Fabre and Liné (1992), among others, obtained these values experimentally. Collins et al. (1978) arrived at very close values. Polonsky et al. (1999) carried out simultaneous measurements of the velocity profiles ahead of the Taylor bubble using particle image velocimetry (PIV) and of the bubble propagation velocity in undeveloped laminar and turbulent pipe flow. The measured values of the coefficient $C$ vary from 1.1 to 2.0, in good agreement with the ratio of the maximum to the mean velocity in the profile ahead of the Taylor bubble. Visualization of the velocity profiles behind elongated bubbles (Shemer and Barnea 1987) revealed that the tip of the trailing bubble in the wake of the leading one follows the location of the maximum instantaneous velocity in the wake.

In fully developed slug flow, the distance between any two consecutive bubbles is supposed to be large enough for the trailing bubble to be unaffected by the wake of the leading one. The very existence of such a flow remains questionable, in part since the volume of the gas phase within the pipe necessarily varies due to the pressure changes along the pipe; pressure variations are most significant in vertical slug flow. In the entrance region of the pipe, the distance between the bubbles is not sufficiently
large, and thus bubbles move in the wake of their predecessors, resulting in merging of bubbles and variation of the flow structure along the pipe (Moissis and Griffith 1962, Taitel and Barnea 1990). The merging process results in decreasing the frequency of slugs along the pipe and in increasing the length of both elongated bubbles and liquid slugs (van Hout et al. 2002).

Data on the rise velocity of the trailing Taylor bubble in air-kerosene slug flow were presented in Hasanein et al. (1996) as a function of the separation distance between the leading and the trailing bubbles. Pinto and Campos (1996) and Pinto et al. (1998) measured the coalescence of pairs of gas bubbles rising in vertical columns of liquids covering a wide range of viscosities by means of instantaneous pressure variation measurements at a number of locations along the pipe. More recently, Pinto et al. (1998) and Aladjem Talvy et al. (2000) carried out experiments with two consecutive bubbles injected into pipes with a stagnant or flowing liquid and determined the translational velocity of the trailing bubble as a function of the separation distance between the bubbles using pressure transducers and image processing techniques, respectively.

In the present study, an experimental approach is developed to relate the detailed information on the velocity field in the wake of the leading elongated bubble and the instantaneous translational velocity of the trailing bubble.

2. EXPERIMENTAL FACILITY

Experiments were carried out in a specially designed facility that consists of an air and water supply systems and a test section made of 6-m-long vertical Perspex pipes. Pipes with internal diameters of 0.014 m and 0.026 m were used in this study. Filtered tap water flowing in a closed loop was used as the working fluid. Water flow rate was measured by a set of rotameters. The accuracy of each rotameter was 1.6% of the full scale. Air was supplied from a central compressed air main. Individual air bubbles were injected via a computer-controlled solenoid-activated ball valve from a common manifold through separate pipes with internal diameters identical to those of each test section. Adjustment of the air pressure in the manifold and the valve opening duration allowed controlling the length of the injected bubbles. Each test section was surrounded by a rectangular transparent box filled with water to reduce image distortion. The distance between the injection and the measurement point was 4 m.

Axial and radial liquid velocities in the leading Taylor bubble wake were determined using PIV. The measuring station was located at the distance of $\Delta h = 4$ m above the injection point. The PIV system used a Kodak ES 1.0 camera with a maximum frame rate of 14 frame pairs per second and illumination by a pulsed double-head Nd:yytrium/aluminum/garnet MiniLase III PIV-15 laser. A vertical laser sheet was generated at the pipe axis by a sequence of spherical and cylindrical lenses. The sheet thickness was about 1 mm at the measurement position. Neutrally buoyant fluorescent particles with a diameter not exceeding 80 mm were added to water for the PIV measurements.

The components of the measuring system were synchronized by an external synchronizer unit. The acquisition process was initiated by an optical sensor placed upstream of the measuring station. The sensor generated a trigger pulse at the passage
of the Taylor bubble bottom. It was estimated that the inaccuracy in the determination of the Taylor bubble bottom location due to its oscillations does not exceed $0.1 D$. The synchronizer unit, triggered by the optical switch, generated a trigger signal to the frame grabber and a sequence of trigger signals at a prescribed frequency to the PIV camera. On receiving the trigger signal, the PIV camera, besides capturing the images, returned a pulse to the synchronizer unit, which in turn triggered the two laser heads at a specified time delay between the laser pulses. Each illumination pulse in the pair was captured by the camera in a different frame, and the resulting image ($1008 \times 2036$ pixels) contained a pair of frames (each of the size of $1008 \times 1018$ pixels). The accuracy of the local instantaneous PIV velocity measurements for the operational conditions of the present study was estimated to be better that 1 mm/s. For more details about the experimental facility and PIV measurements, see van Hout et al. (2002) and Shemer et al. (2007).

To measure the instantaneous shape variation and the velocity of the trailing bubble, a fast digital Pixelink video camera was used that recorded the instantaneous location of the leading edge of the trailing Taylor bubble. The operation of this camera was also synchronized with the leading Taylor bubble passage by the trigger signal generated by the optical switch. A number of broad-spectrum halogen lamps provided illumination for the instantaneous bubble shape determination from a sequence of shadowgraphs recorded by the Pixelink camera. Contrary to the velocity measurements were performed in the diameter plane of the pipe illuminated by the laser sheet, the trailing bubble’s shadowgraphs recorded the extreme points of the bubble’s interface. The instantaneous velocity of the trailing bubble was determined from the sequence of locations of the most protruding interface points. An orange light (580–590 nm) band-pass filter corresponding to the wavelength emitted by the fluorescent particles was attached to the PIV camera objective lens. High-pass filter transmitting light with wavelength exceeding 550 nm prevented the green laser light from reaching the Pixelink camera. Since both the Pixelink and PIV cameras were synchronized, the instantaneous translational velocity of the trailing bubble derived from the Pixelink camera images can be related to the instantaneous velocity field ahead of the trailing bubble obtained by simultaneous PIV measurements. In addition, each pair of injected bubbles was recorded at the inlet of the pipe by a stills digital camera. The images recorded by this camera provide information on the spacing between consecutive bubbles at the bottom of the pipe. The accuracy of determination of the bubble separation distance at the inlet was limited by the leading bubble bottom oscillation and the variation in shape of the trailing bubble head and was estimated to be better than $0.15 D$.

3. RESULTS

3.1 Movement of a single Taylor bubble

The front part of a single Taylor bubble rising in a steady flow, either laminar or turbulent, maintains a constant shape, and the bubble propagates with a constant velocity. When a pair of bubbles is injected into the pipe, the front bubble remains unaffected by the trailing one and retains its shape and propagation velocity. The shape and motion of the trailing bubble are, however, strongly affected by the wake of the
leading bubble, as shown in Fig. 1. The trailing bubble’s nose is deformed, and its shape changes rapidly in the course of the bubble approach (Aladjem Talvy et al. 2000).

As suggested in Shemer and Barnea (1987) and Polonsky et al. (1999), the trailing bubble tip follows the location of the maximum liquid velocity in the profile ahead of the bubble. In the near-wake, the strong velocity fluctuations characteristic for this region are randomly distributed in the whole pipe cross section. The location of the maximum instantaneous velocity thus varies as well. Owing to strong velocity fluctuations, the value of the maximum instantaneous velocity in the near-wake always exceeds the translational velocity of the leading bubble, causing eventual coalescence between the two bubbles. Away from the near-wake region, the variation of the mean axial liquid velocity along the pipe, where the velocity attains its maximum value within a given cross section, is of particular importance. The detailed information on the mean velocity field in the wake of a single Taylor bubble accumulated in experiments carried out in the present facility is presented elsewhere (Shemer et al. 2007). This data on the mean and instantaneous velocity field in the Taylor bubble wake is now applied to study the propagation of the trailing Taylor bubble. The measured mean axial velocity at the centerline $U_{CL}$ is presented in Fig. 2 as a function of a distance from the Taylor bubble bottom. These results were obtained by ensemble averaging the PIV-measured velocities.

![Figure 1](image_url)

**Figure 1** A snapshot of the trailing bubble in the wake of the leading one. Pipe diameter $D = 0.026$ m; $Re = 820$. 
Figure 2  Centerline velocity $U_{CL}$ as a function of the distance from the Taylor bubble bottom: a) near-wake region and b) far-wake region.

in the Taylor bubble wake. The ensemble size was about 200 individual injected bubbles for each set of experimental conditions.

The dominant velocity that can be used for the scaling purposes is different in the near- and far-wake regions. Close to the Taylor bubble bottom, the liquid velocity in the central part of the pipe cannot differ significantly from the translational velocity of the Taylor bubble $U_{tr}$, as follows from continuity. The measured $U_{tr}$ is used as a scaling velocity in this domain. The flow just below the Taylor bubble bottom is characterized by a circumferential downward wall jet. The combined effect of the wall jet with the upflowing liquid behind the bubble results in a toroidal vortex that has a longitudinal length scale of about one pipe diameter $D$ (Shemer et al. 2005). The mean centerline velocity $U_{CL}(x)$ in the near-wake region is plotted in Fig. 2a. The distribution of $U_{CL}$
is affected by the toroidal vortex so that the values of $U_{CL}$ increase initially, attaining a maximum at about $x/D = 1$, and then decrease.

In the far-wake region, the mean liquid velocity $U_{mean}$ is used as a scaling parameter. This velocity is always lower than $U_{tr}$, as follows from Eq. (1). The distribution of $U_{CL}$ in this region is presented in Fig. 2b. It is clear from this figure that fully developed flow in turbulent background flow is attained at distances that exceeds 25–35 pipe diameters, while in the laminar background flow, the fully developed conditions with $U_{CL} = 2U_{mean}$ are not observed even at the end of the measurement domain at $x/D = 70$.

3.2 Trailing bubble velocity determination from sequences of video images

Video images of the trailing elongated bubble motion are processed to determine its shape and translational velocity. The processing of the images is performed in a number of stages. The quality of each image is first improved by application of a sequence of filters. The coordinates of the bubble’s edge are then calculated using the edge detection procedure. The instantaneous propagation velocity of the bubble’s nose at each radial location separately is then calculated as the shift between the nose profiles in two consecutive frames divided by the time elapsed between those frames. These values are then averaged over all radial positions, yielding the averaged cross-sectional nose velocity. The averaging procedure is required in view of the variation of the shape of the trailing bubble’s nose, as shown in Fig. 1. A number of approaches to determine the velocity of the trailing bubble were compared in Aladjem Talvy et al. (1999). The average over the nose profile velocity used here constitutes a more stable and robust estimate of the trailing bubble instantaneous velocity.

3.3 Movement of two consecutive bubbles

While the leading bubble propagates along the pipe with a constant velocity $U_{tr,1}$, given by Eq. (1), the trailing bubble velocity $U_{tr,2}$ is affected by the varying velocity field in the leading bubble’s wake. The dependence of the trailing bubble velocity on the separation distance is a key parameter for modeling undeveloped slug flow. To examine this effect, the velocity of the trailing bubble and its distance from the bottom of the leading Taylor bubble were measured simultaneously.

Figures 3 ($D = 14$ mm) and 4 ($D = 26$ mm) present the ratio of the instantaneous translational velocity of the trailing bubble $U_{tr,2}$, derived from the processed sequences of video images, to the constant leading bubble velocity $U_{tr,1}$, as a function of the separation distance between the two bubbles. In all cases, a notable scatter in the measured instantaneous velocities $U_{tr,2}$ can be attributed to the strong velocity fluctuations in the wake region. The amount of experimental data on the trailing bubble velocity for separation distances below about $5D$ is limited as a result of the coalescence of bubbles injected with a short time delay prior to arriving at the measurement station. It is well established (Moissis and Griffith 1962, Pinto and Campos 1996, Pinto et al. 1998, Aladjem Talvy et al. 2000, van Hout et al. 2001) that for short separation distances (up to five to eight pipe diameters), the trailing Taylor
Figure 3  Translational velocity of the trailing bubble, $D = 14$ mm: a) in stagnant liquid; b) $Re = 700$; and c) $Re = 7800$. 
Figure 4  Same as Fig. 3, but for a 0.026-m pipe: a) in stagnant liquid; b) Re = 820; and c) Re = 7500.
bubble on the average rises faster than the leading one. For stagnant water in both pipes, even at distances exceeding about 10D, the trailing bubble’s velocity usually somewhat exceeds that of the leading one. Contrary to the stagnant column case, for laminar and turbulent background flows in both pipes, the translational velocity of the trailing bubble is generally lower than that of the leading one at separation distances exceeding about 7D. These results can be related to the distribution of the experimentally determined mean axial liquid velocity at the centerline of the pipe (Fig. 2b). In laminar background flow, the mean $U_{CL}$ remains below the axial velocity in fully developed Poiseuille pipe flow for all distances covered in this figure, whereas in turbulent background flow, it attains values corresponding to fully developed flow only at distances from the bubble $x/D$ exceeding about 25 to 35.

The assumption that the velocity of the trailing bubble can be seen as a superposition of the measured maximum mean liquid velocity in front of the bubble and the drift velocity of the bubble $U_0$, given by Eq. (2), is examined in Figs. 5 and 6. Note that for distances beyond 5D from the trailing bubble bottom, the maximum velocity is replaced here by the mean liquid velocity at the centerline of the pipe $U_{CL}$, presented in Fig. 2. The symbols in Figs. 5 and 6 present the measured instantaneous translational velocity of the trailing bubble as a function of the separation distance from the leading one for 0.014-m (Fig. 5) and 0.026-m (Fig. 6) pipes. The data in these figures were acquired for bubbles about 4D long. The solid lines show the variation along the wake of the sum of $U_{CL}$ and $U_0$.

As in Figs. 3 and 4, the scatter in the measured instantaneous velocities is mainly due to the strong liquid velocity fluctuations in the wake region. Those fluctuations decay with the distance from the leading Taylor bubble, the decay being somewhat more pronounced in laminar background flow. The experimentally determined trailing bubble velocities in Figs. 5 and 6 compare well with the calculations based on the adopted assumption. Only a very limited number of measurements of the trailing bubble velocity at separation distances below about $x/D = 5$ could be performed as bubble coalescence occurs at the measurement station for short separations at the injection. Note that strong variations of the centerline velocity occur in this region. The experimentally determined values of the trailing bubble velocity in Figs. 5 and 6 decrease from their maximum at about 1D from the bubble bottom to a certain minimum and then increases again. For larger distances from the leading bubble bottom, the effect of the leading bubble wake on the trailing bubble’s velocity is considerably weaker.

The accumulated evidence on the relation between the trailing bubble velocity and the mean centerline velocity in the leading bubble wake ahead of it prompted an attempt to predict the bubble separation at the measuring location, based on the distance between the bubbles at the injection point, 4 m below the measuring station. The experimental data on the centerline velocity distribution along the Taylor bubble wake are used to examine the effect of the wake of the leading bubble on the trailing one. In Fig. 7, the separation between the bubbles at the observation point located at $\Delta h = 4$ m above the injection point $L_M$ is plotted as a function of the distance between the bubbles at the injection point $L_I$. The symbols in Fig. 7 represent the experimental data points accumulated by injecting more than 100 bubble pairs for each set of experimental conditions.
Figure 5 Variation of the trailing bubble velocity as a function of the separation distance for the 0.014-m pipe: a) in stagnant liquid; b) Re = 700; and c) Re = 7800. Solid lines are $U_{CL} + U_0$; symbols $U_{tr,2}$ were measured from the video image sequences.
Figure 6 Same as Fig. 5, but for a 0.026-m pipe: a) in stagnant liquid; b) Re = 820; and c) Re = 7500.
For separation distances at the injection point $L_I$ below $5D - 10D$, all pairs of bubbles arrive at the observation location after coalescence. Contrary to that, for relatively large initial separations, the distance between the bubbles in most cases increases up to the observation point. The notable exception is the case of two bubbles rising in stagnant columns.

To model this phenomenon, an assumption validated by the results of Figs. 5 and 6 at the observation station is generalized to the whole pipe. It is assumed that the local translational velocity of the trailing bubble at any distance $L$ from the leading one, $U_{tr,2}(L)$, is a superposition of the local mean axial flow velocity ahead of the bubble at the central line of the pipe $U_{CL}(L)$ and the bubble drift velocity $U_0$, as given by Eq. (2):

$$U_{tr,2} = 0.35\sqrt{gD} + U_{CL}(L(t))$$

Since the leading bubble propagates with a constant velocity $U_{tr,1}$ given by Eq. (1), during a time increment $dt$, the separation between the bubbles changes by

$$dL = (U_{tr,1} - U_{tr,2}(L))dt$$

Thus, at the observation point at a distance $\Delta h$ from the injection location, the spacing between the two bubbles is

$$L_M = L_I + U_{tr,1}\Delta t - \int_{0}^{\Delta t} U_{tr,2}(L(t)) dt$$
\[ \Delta t = \Delta h / U_{tr,1} \]

is the duration of the leading bubble motion from the injection up to the measurement point. The lines in Fig. 7 represent results of the calculations based on Eq. (5). The variation of the mean axial flow velocity \( U_{CL}(L) \) as a function of the separation distance \( L \) from the leading bubble for each set of flow conditions is taken from the PIV results on the flow field behind a single Taylor bubble (see Fig. 2).

For short separation distances between the bubbles at the injection point, the bubbles arrive at the observation location after coalescence due to high local instantaneous velocities in the liquid in front of the trailing bubble. At separation distances up to about \( 2D \), the mean axial liquid velocity at the centerline of the pipe \( U_{CL} \) increases significantly and is higher than the translational velocity of the leading bubble \( U_{tr,1} \). The excessive velocity of the trailing bubble over the leading one leads to coalescence of most bubbles with a small initial spacing at the injection location \( L_I \).

When the initial separation distances are increased, both the experimental and model results show that the distance between the bubbles increases at the observation point. This is again consistent with the measured mean axial liquid velocity at the centerline of the pipe (Fig. 2b). The results of this figure demonstrate that following the initial increase in the near-wake region, the centerline velocity may fall below the maximum liquid velocity for a developed velocity profile \( C U_{mean} \) (Polonsky et al. 1999). The consequence of this is that the trailing bubble’s velocity, which, according to Eq. (3), depends on the liquid axial velocity ahead of it, is smaller than the translational velocity of the leading bubble, so the distance between the two consecutive bubbles increases for these separation distances. The calculated and measured data agree well, except for the near-wake region for turbulent background flow, where the instantaneous fluctuations are important. The thick solid line in Fig. 7 corresponds to the case when the trailing and leading bubbles move with identical velocities. Bubbles injected into stagnant water at initial distances exceeding about \( 10D \) approach this line from below, indicating that they still move somewhat faster than the leading bubbles. For laminar background flow, the thick line is attained at \( L_I > 70D \), while for the turbulent background flows, the trailing bubble’s motion becomes unaffected by the leading bubble when the initial separation distance \( L_I \) exceeds about \( 35D \). These results confirm the conclusion that the mean velocity field in the laminar background flow remains affected by the Taylor bubble up to very large distances, whereas in turbulent background flow, the fully developed velocity profile is attained somewhat faster.

The results of Fig. 7 indicate that the ensemble-averaged centerline velocity indeed plays a dominant role in determining the variation of the bubble separation as the bubbles propagate along the pipe and that Eqs. (3)–(5) are generally valid beyond the near-wake region. The observed differences in the bubbles’ spacing in laminar and turbulent background flows are correctly presented in the model results. Moreover, variation of the distance at the measuring location with the initial bubbles’ spacing predicted by the model is in general quantitative agreement with experiments for all sets of the flow conditions.

In spite of this generally satisfactory agreement, a significant scatter in the experimental results is observed in Fig. 7. As mentioned in discussion of Figs. 3–6, this scatter suggests that the trailing bubble velocity is affected not just by the mean, but also by the instantaneous velocity ahead of the bubble, which varies in
For the pipe diameters considered here, those turbulent fluctuations may be significant in the near-wake region, even in laminar background flow. This stems from the fact that the dominant velocity in this domain is the leading bubble propagation velocity $U_{tr,1}$ resulting in a Reynolds number above the critical (Shemer et al. 2006). In laminar background flow, the turbulent fluctuations decay fast with the distance from the Taylor bubble bottom $x/D$. At higher liquid flow rates, the turbulent structure of the flow undergoes considerable variation with $x/D$, and the turbulent structure gradually adjusts itself to the equilibrium state appropriate for a fully developed turbulent pipe flow.

The liquid velocity fluctuations encountered by the trailing Taylor bubble lead, apart from propagation velocity fluctuations, also to variations in its instantaneous shape, which do not necessarily remain symmetric. The relation of the instantaneous velocity field immediately ahead of the trailing bubble and its instantaneous shape is examined in Fig. 8 for a pipe diameter of $D = 14$ mm and in Fig. 9 for $D = 26$ mm. The right vertical axis in those figures represents the distance from the leading bubble bottom of the trailing bubble’s interface, while the left axis is the liquid velocity ahead of it. The examples in those figures represent cases when the extreme trailing bubble profile occurred in the plane illuminated by the laser light sheet. Our earlier flow visualization experiments using a hydrogen bubble technique (Shemer and Barnea 1987) suggested that the bubble nose follows the local maximum velocity in the pipe cross section. As can be seen from the figures, the present results support this assumption. Note that in the case of laminar background flow in 14-mm pipe, the effect of the leading bubble wake on the shape of the trailing bubble nose at $x/D = 20$ (Fig. 8b) is notably weaker than closer to the leading bubble bottom (Fig. 8a). The effect of the leading bubble’s wake on the trailing bubble shape in the larger pipe with $D = 26$ mm is quite visible in all cases presented in Fig. 9. Both Figs. 8 and 9 demonstrate the qualitative similarity between the appropriately scaled shape of the trailing bubble nose and the axial velocity profile in the liquid just ahead of it.

The randomness of turbulent fluctuations in the liquid ahead of the trailing bubble leads to fluctuations in the trailing bubble propagation velocity $U_{tr,2}$ around the value given by Eq. (3). As a result of those fluctuations in $U_{tr,2}$, the bubbles injected at a given distance from the leading bubble arrive at the measuring station at distances that can vary within quite a wide range. This phenomenon is studied in Fig. 10 for a variety of Reynolds numbers of the background flow. The figure shows histograms representing the frequencies of appearance of the separation distances between two consecutive bubbles at the measurement location $L_M$ and at the injection point $L_I$. The distances $L_I$ were derived from processing images recorded by the still camera, while the corresponding separation distances $L_M$ were determined using sequences of video images recorded by the Pixelink camera. The total ensemble size in Fig. 10 ranged from about 100 to more than 200 bubble pairs for each flow condition. Contrary to the experiments involving liquid velocity measurements by PIV technique, where the whole experiment was computer controlled, the time delay between bubbles’ injection within each pair in each realization was controlled manually. This time delay for each set of flow conditions was selected to be sufficient to ensure that in most realizations, two separate bubbles arrived at the observation point. However, since the effect of the
leading bubble’s wake on the trailing bubble is apparently stronger for shorter bubble separations, an attempt was made to get sufficiently small separation distance between the bubbles at the injection point.

The bubble pairs that arrive to the measurement point after coalescence are denoted in the histograms as zero separation. Figure 10 demonstrates that coalescence occurred for about 10–20% of the injected bubble pairs. The mean separation distance at the
Figure 9  Instantaneous parameters of the trailing bubble in a 0.026-m pipe: a) bubble rising in stagnant liquid; b) upflowing liquid with Re = 820; and c) upflowing liquid with Re = 7500.
Figure 10  Distribution of the separation distances within bubble pairs at the injection (open columns) and at 4 m from the injection (filled columns) in a 0.014-m pipe: a) in stagnant liquid; b) Re = 700; and c) Re = 7850.
MOVEMENT OF TAYLOR BUBBLES

Injection $L_I$ is also given in Fig. 10. In all cases, the mean value of $L_I$ was about $10D$. The mean value of $L_M$ is also specified. Two values of mean $L_M$ are presented: the one that takes into account all pairs of bubbles, including those that underwent coalescence up to the measuring location, and an additional mean $L_M$, where only those pairs that remained separated were considered.

Generally speaking, the distributions at the measurement station are wider than those at the injection location, and the mean values of $L_M$ are higher than those of $L_I$, even when the coalesced bubble pairs are not accounted for. Only for bubbles injected into water columns with stagnant liquid does the mean separation distance not change significantly along the pipe, in agreement with Fig. 7. In all cases with flowing liquid, the distribution of $L_M$ is wider than that of $L_I$. Comparison of Fig. 10b with other cases clearly indicates that both the separation distance distribution widening and the increase in the mean $L$ along the pipe are much more apparent in laminar background flow. As discussed with respect to Fig. 7, this result can be explained by more notable variation with the distance from the leading bubble’s bottom of the velocity profile in general, and of the centerline velocity, in particular, in the laminar case. The presented results show that widening of the distribution at the measurement point is more pronounced for turbulent background flow, supporting the conjecture that the instantaneous trailing bubble velocity has an oscillatory character.

4. CONCLUSIONS

Interaction between two consecutive Taylor bubbles rising in laminar and turbulent background flows in vertical pipes is studied quantitatively using the image processing technique to investigate the instantaneous shape and propagation velocity of the trailing Taylor bubble, simultaneously with the PIV measurements of the velocity field ahead of this bubble. It is demonstrated that an unsteady velocity field in the liquid ahead of a trailing bubble affects both its propagation velocity and shape. A qualitative similarity is observed between the shape of the trailing bubble nose and the instantaneous velocity profile of the water flow just ahead of it.

Contrary to a single Taylor bubble that travels with a constant velocity, the trailing bubble has a velocity that is no longer constant and undergoes fluctuations. The velocity fluctuations in the liquid slug ahead of the trailing bubble can either accelerate its propagation or slow it down. It is a quite common concept that the trailing bubble moves faster than the leading one and eventually overtakes it and coalesces (Pinto and Campos 1996, Aladjem Talvy et al. 2000). The present results demonstrate that this concept is only partially valid. For relatively short initial separations, the experimental results of Fig. 7 as well as the histograms of Fig. 10 indicate indeed that most pairs of initially close bubbles will coalesce after traveling a relatively short propagation distance. This can be attributed to strong velocity fluctuations in the near-wake region, necessarily resulting in a high local instantaneous axial velocity component somewhere in the liquid cross section ahead of the trailing bubble. The present results support the conjecture that the trailing bubble velocity can be estimated as a superposition of the maximum velocity in the liquid ahead of it and the bubble drift velocity due to
buoyancy. The presence of high instantaneous velocity anywhere in the cross section leads therefore to faster movement of the trailing bubble and eventual coalescence.

The situation is, however, quite different in flowing liquid when the initial spacing between the bubbles is larger than about 7–10 pipe diameters. The present results reveal that in this case, the distance between the bubbles will most probably increase in the process of their propagation along the pipe. It is argued here that this increase in the separation distance stems from the variation of the maximum liquid velocity, presented by the centerline velocity, in the liquid ahead of the trailing Taylor bubble. When the experimentally determined variation of the centerline velocity along the leading bubble’s wake is used as an input into the model that predicts the variation of the bubbles’ spacing with the axial pipe coordinate, good agreement is obtained between the model predictions and the experimental results.

This agreement, however, only holds with respect to mean values. In individual realizations, a wide range of possible separation distances was observed for identical initial bubble spacing. The unsteady velocity field in the leading Taylor bubble’s wake strongly affects the propagation velocity of the trailing bubble. A statistical approach therefore should be applied; the fully deterministic model for the determination of the bubble spacing along the pipe as a function of mean flow parameters suggested here is valid only on the average.

These conclusions are of major importance for the development of comprehensive models for prediction of slug flow parameters.

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NOMENCLATURE

\begin{itemize}
  \item \( C \) coefficient in Eq. (1)
  \item \( D \) pipe diameter m
  \item \( g \) acceleration due to gravity m/s\(^2\)
  \item \( h \) height above the injection point m
  \item \( k \) coefficient in Eq. (2)
  \item \( L \) bubble separation distance m
  \item \( t \) time m
  \item \( U \) velocity m/s
  \item \( x \) distance from the Taylor bubble bottom m
  \item 0 drift velocity
  \item 1 first bubble
  \item 2 second bubble
  \item CL centerline
  \item I injection location
  \item M measuring station
  \item tr translational
\end{itemize}
REFERENCES


