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# INVESTIGATION OF BUBBLE BREAKUP IN SUDDEN EXPANSIONS AND CONTRACTIONS

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**Abstract.** *The dynamics of bubble breakup and coalescence in expansions and contractions located in vertical pipes are studied in this work. The experimental apparatus has a total of 10.5 m height and is composed by sudden expansion followed by a contraction. Three gas flow rate conditions are selected for the investigation of the properties of the two-phase flow across two consecutive local accidents. In particular, flow pattern transitions due to breakup and coalescence are studied. Particle Image Velocimetry and Shadow Sizing techniques were used to characterize the continuous and dispersed phases, respectively. Information about bubble velocity, velocities of the nose, body and tail of Taylor bubbles, bubble size, statistics of diameter and mean liquid velocity are presented in this work. Turbulence statistics are developed to identify areas of high turbulent kinetic energy and compare them with the breakup locations.*

**Keywords:** *Two-phase flow, expansion, contraction, breakup, coalescence.*

## 1. INTRODUCTION

In industry, every hydraulic installation requires the use of bends, valves, junctions and pipe enlargements and restrictions. These local accidents may induce bubble breakup or coalescence phenomenon, depending on the effects exerted on the flow, such as turbulence, pressure gradient and acceleration.

Many studies in the literature developed models for the prediction of flow patterns and properties in expansions and contractions, without focus on breakup and coalescence mechanisms (Schmidt and Friedel, 1997; Attou and Bolle, 1999; Ahmed *et al.*, 2006, 2007). Experimental studies in vertical pipes (Rinne and Loth, 1996) used local measurements of bubble velocity and size distributions to predict the local interfacial area concentration.

Aloui *et al.* (1999) attributed a 20% bubble diameter decrease to the increase in the dynamic pressure across an expansion, located in a horizontal pipe. Ahmed *et al.* (2008) observed the relation between the void fraction of the incoming flow and the downstream flow patterns in a horizontal air-oil pipe flow across an expansion.

Galinat *et al.* (2005) studied the drop breakup in a vertical pipe flow across a restriction, showing that breakup probability could be modeled as a function of a global Weber number based on the maximum pressure drop across the orifice.

In this work, the main objective is to understand the mechanism of bubble breakup and coalescence across a sudden change in the pipe cross section. In particular, the influence of the high shear region that bounds the recirculation zone downstream of the expansion and the effect of the *vena contracta* that is formed at the contraction, are investigated. To fulfill this purpose, high-speed filming, Shadow Sizer technique and Particle Image Velocimetry have been used to fully characterize the properties of the continuous and dispersed phases.

Bubble size and velocities distributions, mean liquid velocity fields and turbulent statistics have been measured at different sections along pipeline.

## 2. EXPERIMENTAL PROCEDURE

The experimental set up consists of a 10.5 m long pipe divided in three sections with diameters of 19 mm, 44 mm and 19 mm, respectively (Fig. 1). The test section is supplied with water and gas through a "T" junction located on bottom part of the flow loop. The water is feed by a progressive cavity pump, and an air compressor provides the

dispersed phase. The gas and water flow rates were measured with a rotameter and an electromagnetic flow meter, respectively. The experimental conditions are shown in Tab. 1.

Table 1. Flow measurement conditions.

FLOW PATTERN TRANSITION	Liquid flow rate [m <sup>3</sup> h <sup>-1</sup> ]	Gas flow rate [m <sup>3</sup> h <sup>-1</sup> ]
Single phase flow	2.0	0.0
Bubble-bubble-bubble	1.24	0.12
Slug-bubble-slug	1.24	0.27
Slug-slug-slug	1.24	0.69

Celis *et al.* (2016) conducted an extensive experimental campaign to characterize the three different flow patterns along the vertical pipe where a sudden expansion was followed by a sudden contraction (see Table 1 and Figure1). In total, 16,400 high-speed images were acquired with a sampling rate of 1400 Hz. A Shadow Sizer System from Dantec Dynamics was used for the characterization of the dispersed phase. The images were processed by a contour detection algorithm, as described by Matamoros *et al.* (2014). Mean velocity and turbulent statistics of the continuous phase were measured through a 2D Particle Image Velocimetry. Analysis of the images provided information about the statistics of the flow in the positions  $z = -1100$  mm, 100 mm, 3500 mm and 5500 mm.

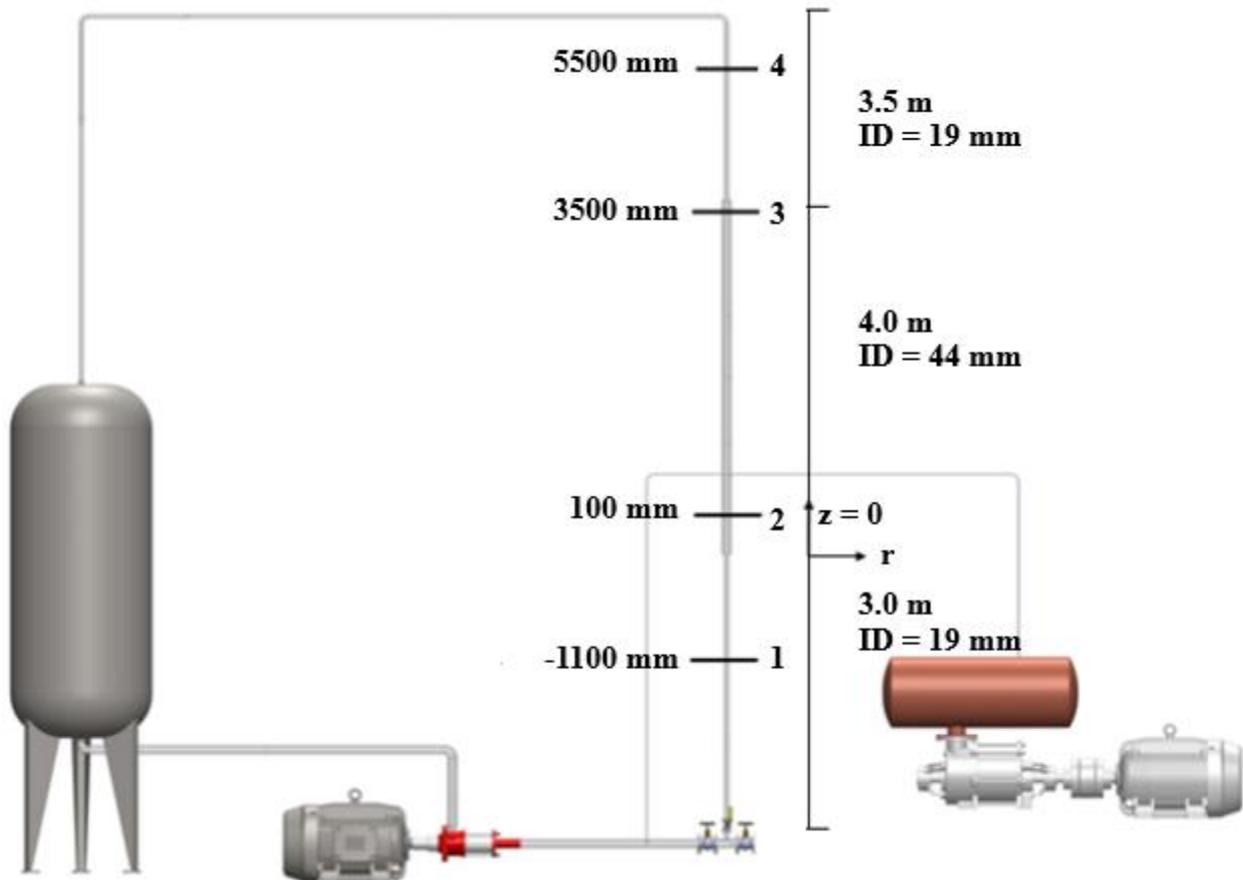


Figure 1. Diagram of the experimental apparatus and positions of measuring stations

### 3. BUBBLY FLOW ACROSS A SUDDEN EXPANSION FOLLOWED BY A CONTRACTION

The bubble breakup in a sudden expansion is illustrated in Fig. 2. To have a better visualization of the phenomenon, just the contours of the breaking bubble and the pipe wall are shown in Fig. 3. The time evolution (left to right) in Fig. 3 is uniform with interval between frames equal to  $10\Delta t$  ( $\Delta t = 1/1400$  s). In Fig. 3, at Frame 1, a small gas bubble located near the pipe wall reaches the expansion and then it enters the high shear layer that bounds the recirculation region, denoted by the dashed line (Fig. 3, Frame 2). The shear stresses elongate the bubble until it break up (Fig. 3, Frames 3-4). The fragmented new bubble is smaller in size than the remaining one, and can be eventually captured by the separation region. The smallest bubble continues into the recirculation zone, assuming negative velocity values. In the contraction, as shown in Figs. 4-5, for  $Q_g = 0.12$  m<sup>3</sup>h<sup>-1</sup>, the time interval between frames is  $4\Delta t$ . High velocity gradients,

especially near to the pipe wall, promote bubble elongation in the *vena contracta* (Fig. 5, Frames 2-3) and then, it breaks up resulting in three daughter bubbles (Fig. 5, Frames 4-6).

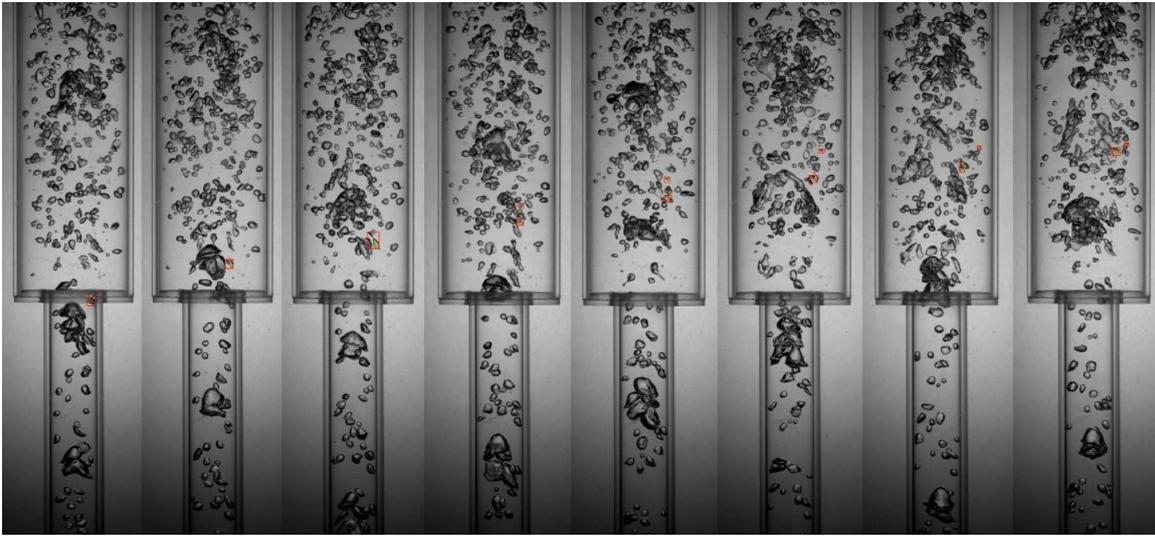


Figure 2. Time evolution of a bubbly flow along a sudden expansion.  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ ,  $Q_g = 0.12 \text{ m}^3\text{h}^{-1}$

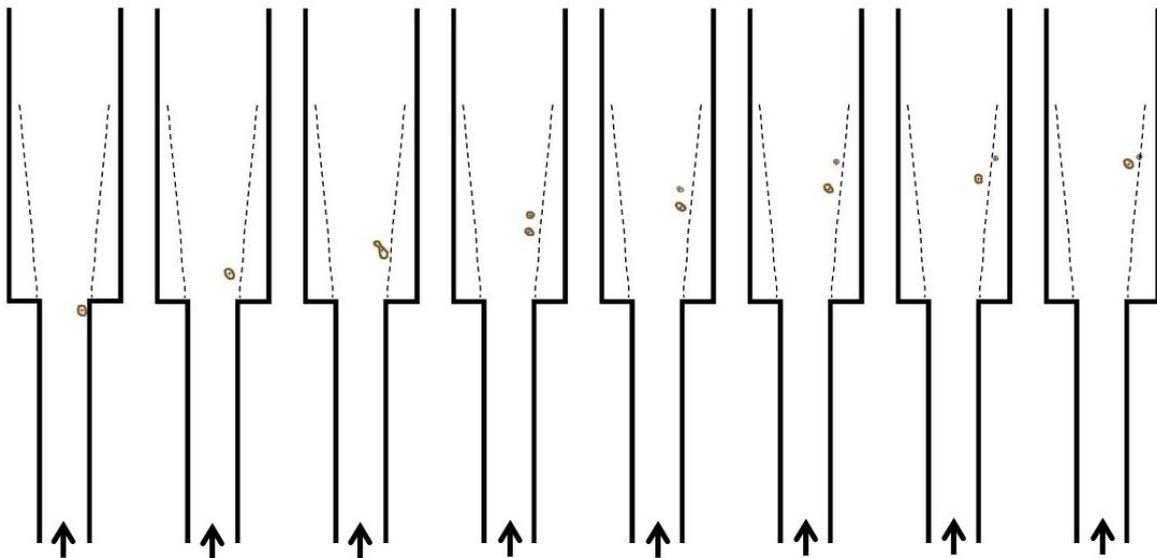


Figure 3. Time evolution of a small bubble entering a sudden expansion. Time interval between Frames  $10\Delta t$ , ( $\Delta t = 1/1400 \text{ s}$ ).  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ ,  $Q_g = 0.12 \text{ m}^3\text{h}^{-1}$



Figure 4. Time evolution of a bubbly flow along a sudden contraction.  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ ,  $Q_g = 0.12 \text{ m}^3\text{h}^{-1}$

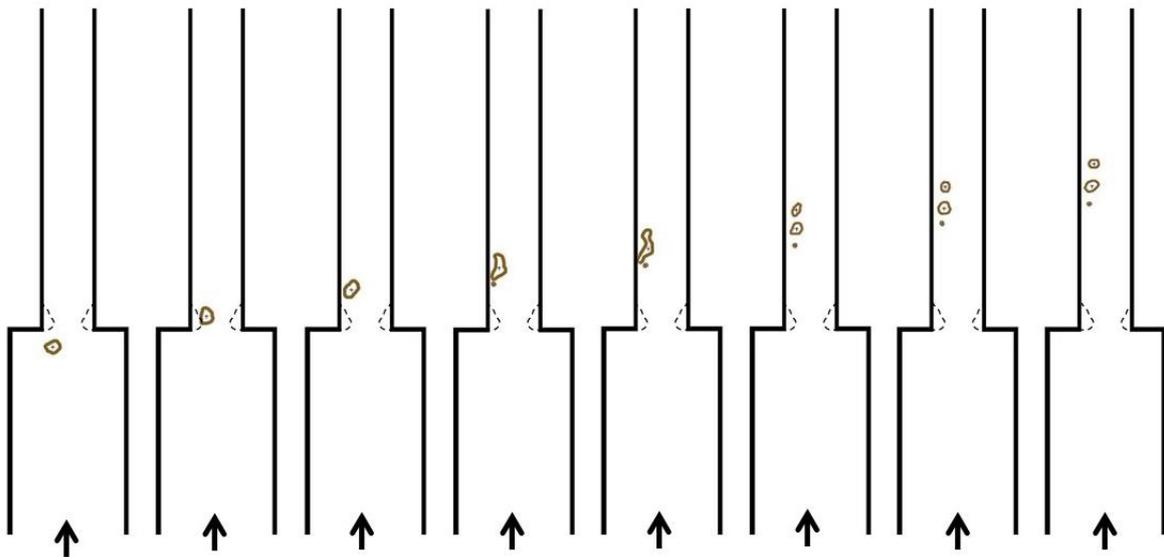


Figure 5. Time evolution of a small bubble entering a sudden contraction. Time interval between Frames  $4\Delta t$ , ( $\Delta t = 1/1400 \text{ s}$ ).  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ ,  $Q_g = 0.12 \text{ m}^3\text{h}^{-1}$

#### 4. SLUG FLOW ACROSS A SUDDEN EXPANSION FOLLOWED BY A CONTRACTION

Figures 6-7 illustrate the behavior of a slug flow across a sudden expansion. The Taylor bubble is observed to break up at two instants of time. Instabilities on the bubble surface are increased as it flows along the neighboring shear layer. These instabilities give origin to elongated shapes and thin films that will disrupt into daughter bubbles (Fig. 7, Frames 5-7).

The lengths of the incoming and fragmented bubbles are shown in Fig. 8a. The bubble nose reaches the located at  $z = 0 \text{ mm}$  and then stretches from  $l_f = 95 \text{ mm}$  at  $z = -10 \text{ mm}$  to  $l_f = 125 \text{ mm}$  at  $z = 30 \text{ mm}$ , getting an almost stable length around  $120 \text{ mm}$ . Then, at position  $z = 94 \text{ mm}$ , the first break up appears, this is represented by the discontinuity in the filled dots, and the appearance at position  $34 \text{ mm}$  of a second bubble (half filled dots) of length  $58 \text{ mm}$ . The first bubble is observed to experience a sudden change in size, from  $115$  to  $63 \text{ mm}$ . The second bubble initially keeps a relatively stable length, which is followed by a sharp rise in size and a second break up at  $z = 70 \text{ mm}$ . The size of the second bubble then reduces from  $78$  to  $24 \text{ mm}$ . The third bubble (empty filled dot) appears at  $z = 40 \text{ mm}$ , with a size of  $28 \text{ mm}$ .

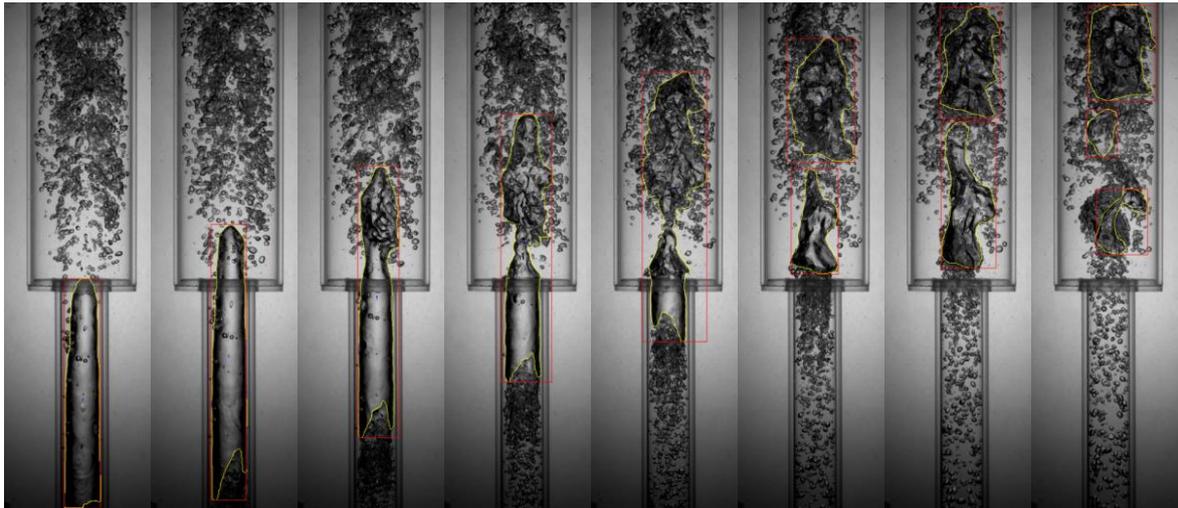


Figure 6. Time evolution of a Taylor bubble entering a sudden expansion.  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ ,  $Q_g = 0.69 \text{ m}^3\text{h}^{-1}$

Figure 8b shows the centroid velocities of the incoming and fragmented bubbles. Once a bubble breaks, the two new centroids provoke discontinuities in the velocity as compared to the original centroid. The top portion of the bubble results in a sharp increase in velocity (positive velocity), whereas the bottom portion results in a sharp decrease in velocity (negative velocity). Figure 8b shows the velocities of the centroids and, thus, the discontinuity locates the position of bubble break up. Figure 8c shows the nose, body and tail velocities of the incoming bubble. Nose velocity does not change abruptly as a result of the breakup process, but body and tail velocities do, mainly because of the tail turbulence and resulting instabilities.

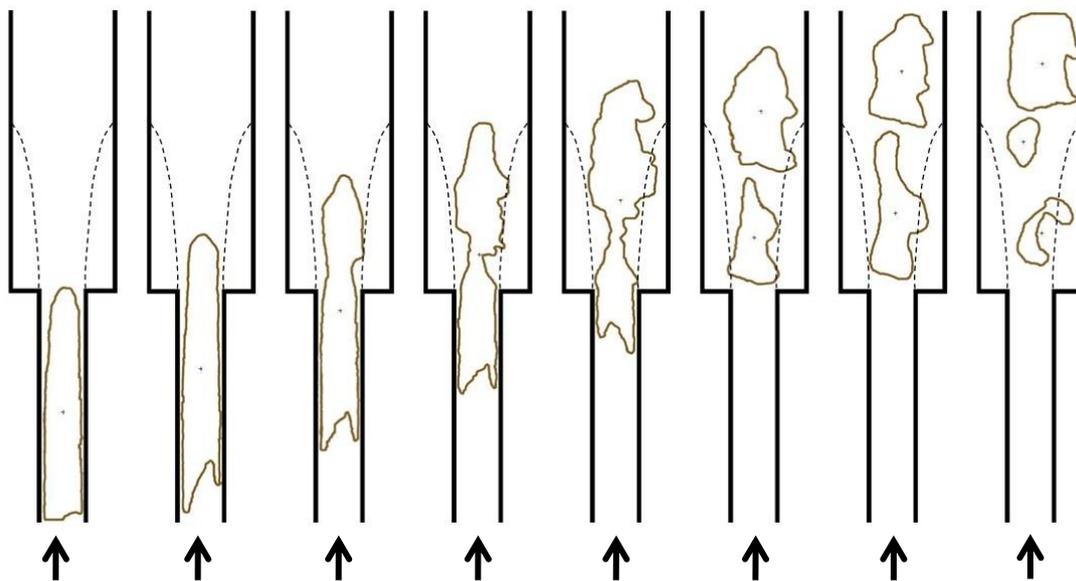


Figure 7. Time evolution of a large bubble entering a sudden expansion. Time interval between Frames  $8\Delta t$ , ( $\Delta t = 1/1400 \text{ s}$ ).  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ ,  $Q_g = 0.69 \text{ m}^3\text{h}^{-1}$

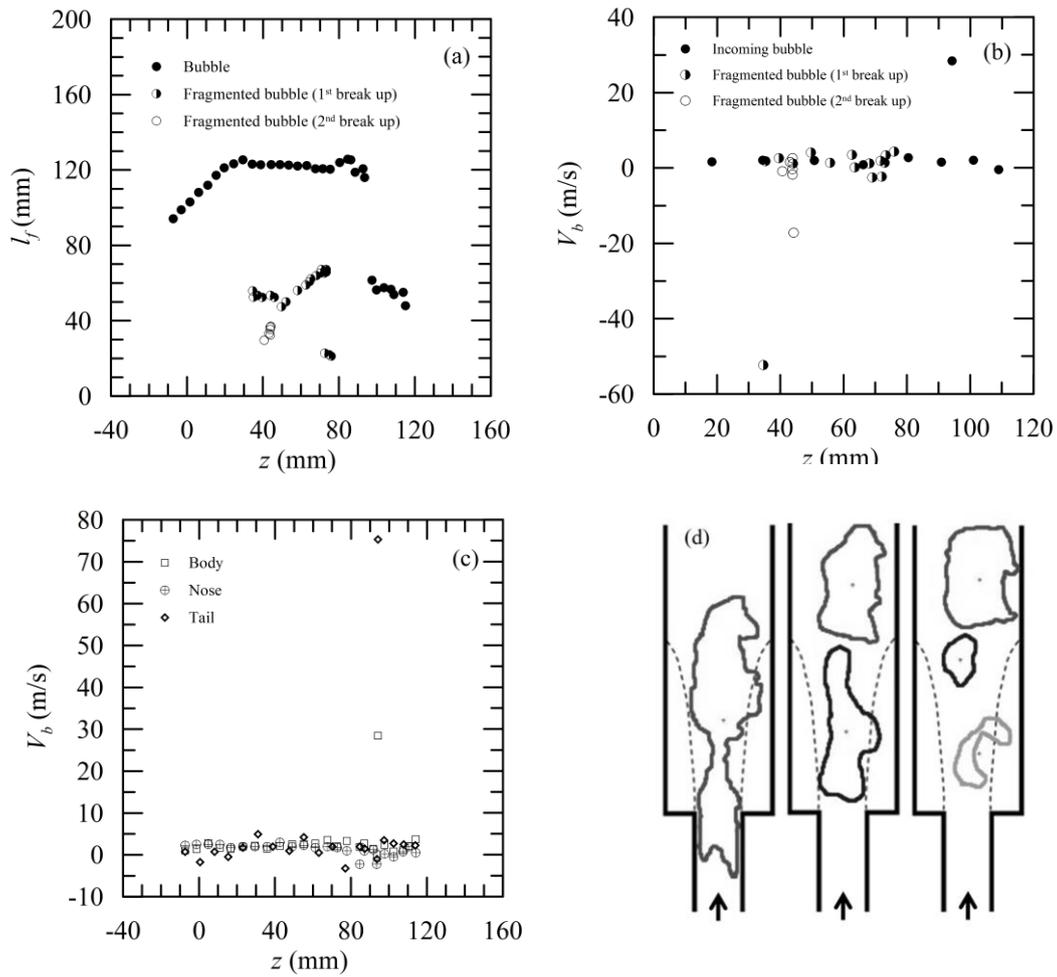


Figure 8. Length and velocity of a Taylor bubble moving across a sudden expansion. The expansion is located at  $z = 0$  mm. In (b),  $V_b$  denotes the velocity of the centroids of the bubbles.  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ ,  $Q_g = 0.69 \text{ m}^3\text{h}^{-1}$

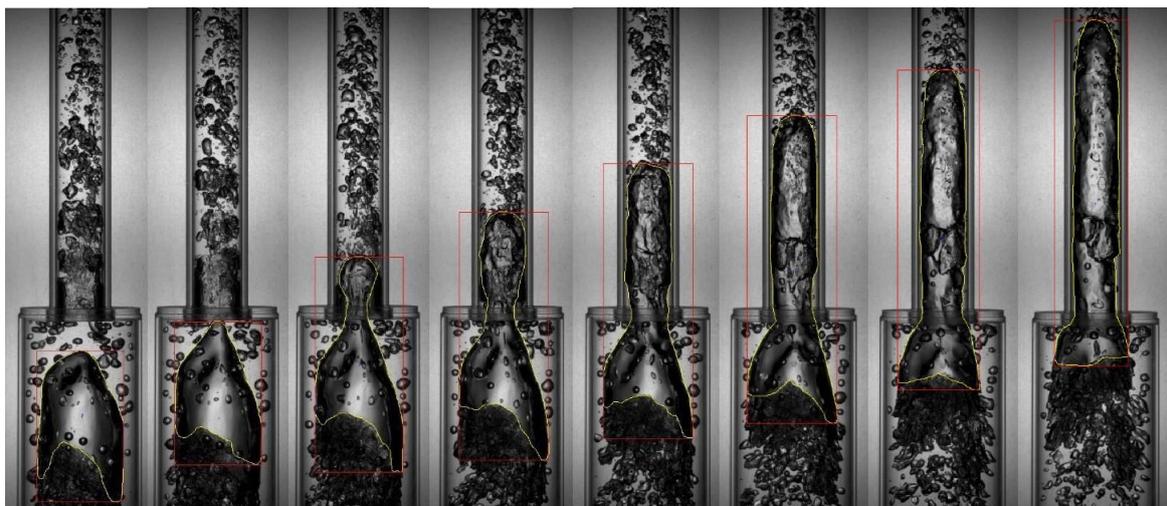


Figure 9. Time evolution of a large bubble entering a sudden contraction.  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ ,  $Q_g = 0.69 \text{ m}^3\text{h}^{-1}$

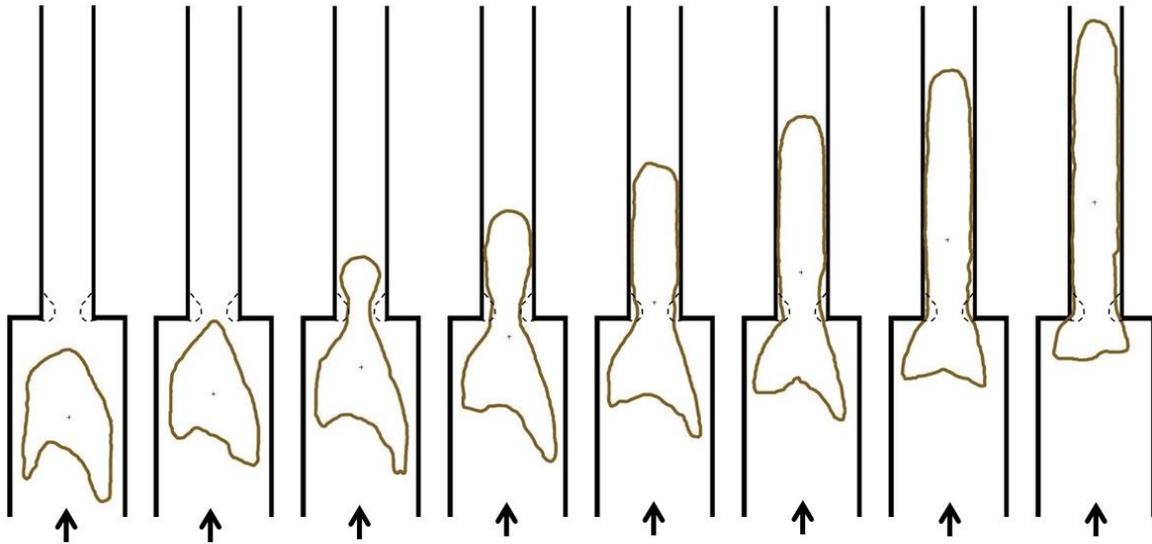


Figure 10. Time evolution of a large bubble entering a sudden contraction. Time interval between Frames  $6\Delta t$ , ( $\Delta t = 1/1400$  s).  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ ,  $Q_g = 0.69 \text{ m}^3\text{h}^{-1}$

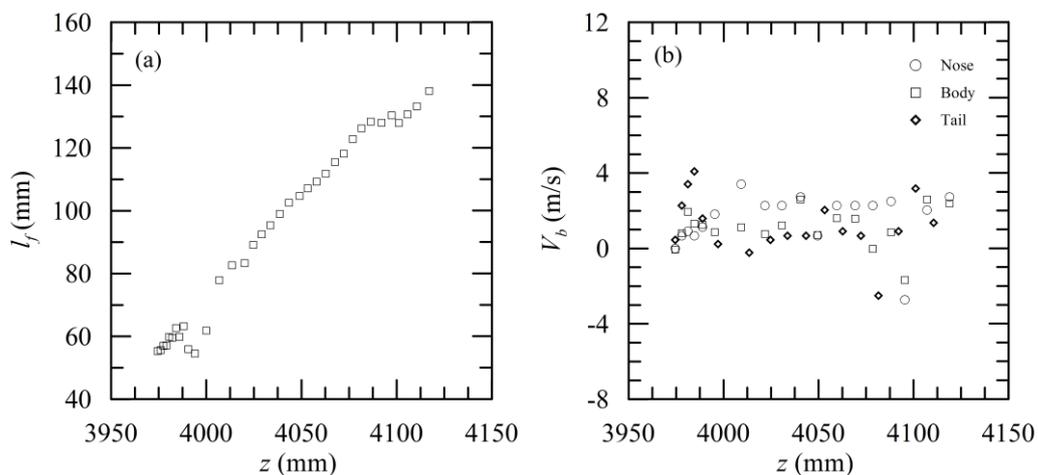


Figure 11. Length and velocity of a Taylor bubble moving across a sudden contraction. The contraction is located at  $z = 4000$  mm.  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ ,  $Q_g = 0.69 \text{ m}^3\text{h}^{-1}$

At the contraction, the large Taylor bubble squeezes into the smaller pipe diameter, increasing its length continuously (Fig. 9-10). The time interval between Frames is equal to  $6\Delta t$ . The velocity of the nose increases to a maximum at the *vena contracta* formed by the two short recirculation regions at the entrance of the contraction, relaxing further downstream to an almost constant value (Fig. 11a). The tail position is given by the lowest bubble point in the pipe. The nose velocity is higher than the tail velocity, resulting in a stretching bubble without breakup (Fig. 11a,b).

## 5. MEAN LIQUID VELOCITY PROFILES, BUBBLE SIZE AND VELOCITY DISTRIBUTIONS

Bubble size distributions are presented in Fig. 12 for the three gas flow rates. Between positions -1100 mm and 100 mm, upstream and downstream of the expansion, the recirculation zone favours bubble break up, and the bubble size decreases. Then, in the position 3500 mm, further downstream of the expansion, the process of coalescence is observed and the bubble size increases. Finally, at station  $z = 5500$  mm, bubbles flow through the *vena contracta*, where some of them break up and the bubble size decreases again. Comparing the results for the three gas flow rates, the biggest bubble size is always observed for the smallest gas flow rate. For stations  $z = -1100$  and 5500 mm, it can be shown that the distributions peaks lies around the same bubble size.

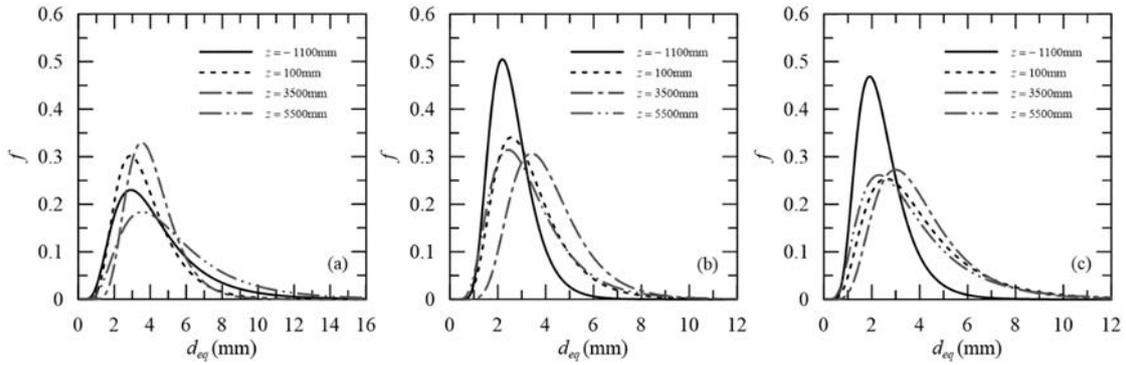


Figure 12. Bubble size distributions at different stations along the expansion and contraction for  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ , and: a)  $Q_g = 0.12 \text{ m}^3\text{h}^{-1}$ , b)  $Q_g = 0.27 \text{ m}^3\text{h}^{-1}$ , c)  $Q_g = 0.69 \text{ m}^3\text{h}^{-1}$

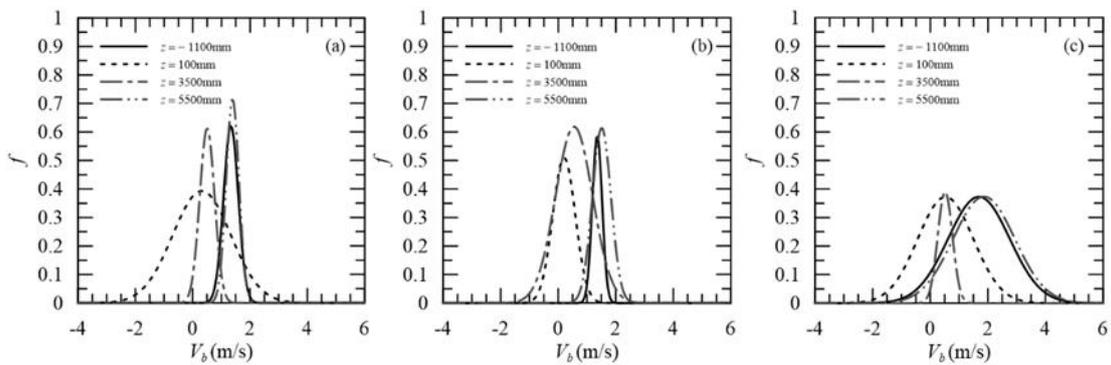


Figure 13. Bubble velocity distributions at different stations along the expansion and contraction for  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ , and: a)  $Q_g = 0.12 \text{ m}^3\text{h}^{-1}$ , b)  $Q_g = 0.27 \text{ m}^3\text{h}^{-1}$ , c)  $Q_g = 0.69 \text{ m}^3\text{h}^{-1}$

The bubble velocity distributions measured through the Shadow Sizer System are shown in Fig. 13. All the profiles exhibit the same behavior. The results show that a velocity reduction and increase are observed in expansion and contraction, respectively. The velocity distribution at section 5500 mm (downstream of the contraction) reaches the same value as those observed at  $z = -1100 \text{ mm}$ . Mean velocity profiles were taken in different positions near the contraction and the expansion. Positions investigated are given by  $z = -25 \text{ mm}$ ,  $-10 \text{ mm}$ ,  $25 \text{ mm}$  and  $65 \text{ mm}$  for the expansion; and  $3975 \text{ mm}$ ,  $3995 \text{ mm}$ ,  $4015 \text{ mm}$  and  $4030 \text{ mm}$  for the contraction. Particle Image Velocimetry results for the mean velocity profiles in the expansion (Fig. 14) provided a thorough characterization of the recirculation region, showing negative mean velocity values near the wall. For higher positions in the pipe, the recirculation region influence is weaker, resulting in positive mean velocity values near the wall.

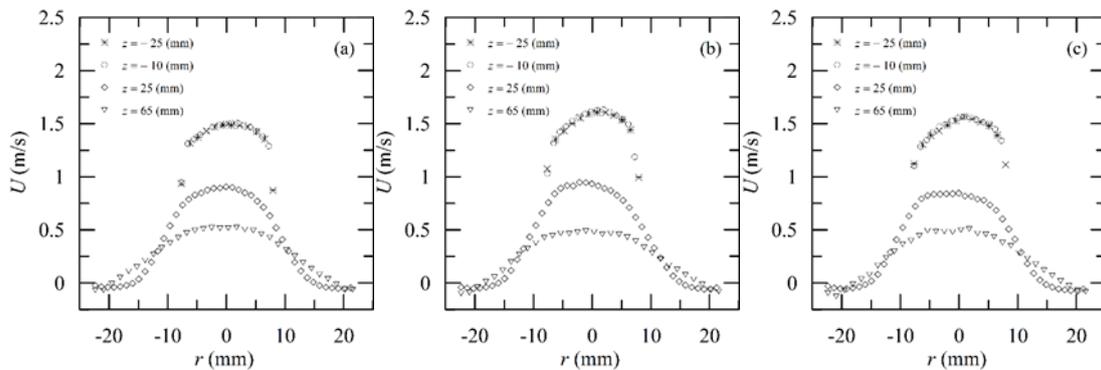


Figure 14. Mean liquid velocity profiles along the expansion for  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ , and: a)  $Q_g = 0.12 \text{ m}^3\text{h}^{-1}$ , b)  $Q_g = 0.27 \text{ m}^3\text{h}^{-1}$ , c)  $Q_g = 0.69 \text{ m}^3\text{h}^{-1}$

Mean liquid velocity profiles at the contraction are shown Fig. 15. Bubbles start to accelerate closer to the restriction, showing a deformation in the profile. The influence of the gas flow rate is most noticeable downstream of

the contraction, where the large bubbles are squeezed causing an obstruction for the liquid flow. Lower mean velocity values are shown for higher gas flow rates.

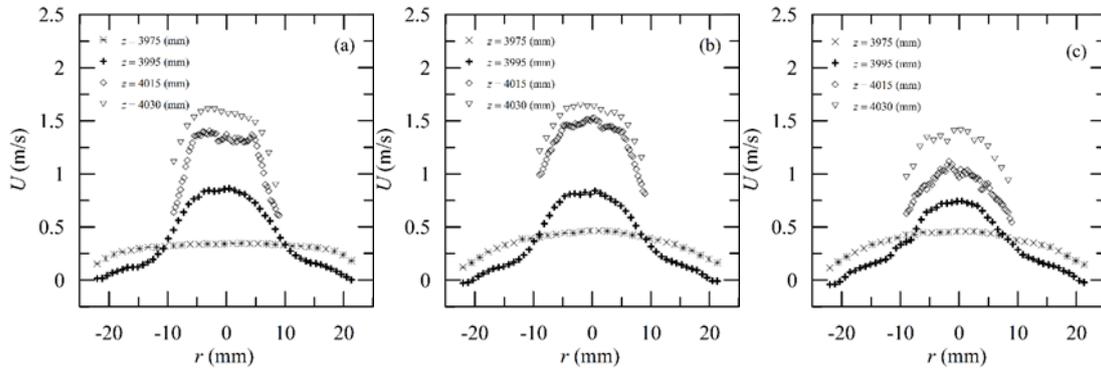


Figure 15. Mean liquid velocity profiles along the contraction for  $Q_l = 1.24 \text{ m}^3\text{h}^{-1}$ , and: a)  $Q_g = 0.12 \text{ m}^3\text{h}^{-1}$ , b)  $Q_g = 0.27 \text{ m}^3\text{h}^{-1}$ , c)  $Q_g = 0.69 \text{ m}^3\text{h}^{-1}$

## 6. BREAKUP LOCATION AND TURBULENT KINETIC ENERGY RELATION

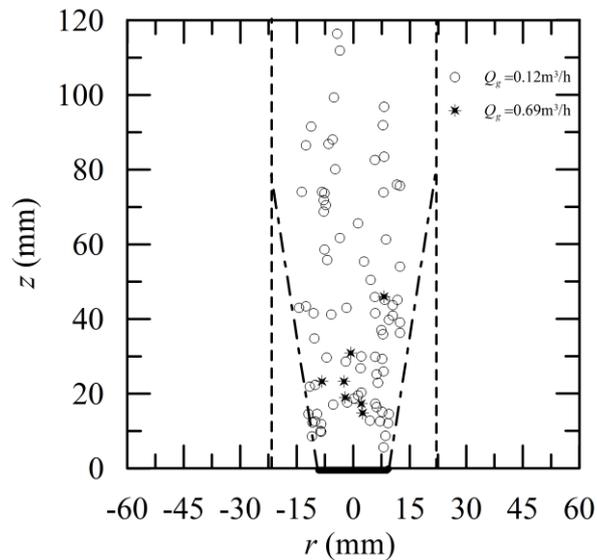


Figure 16. Break up location for small and large bubbles downstream of an expansion. Dashed lines represent the 19 mm pipe walls and the dot-dashed lines illustrates the region of the recirculation region

Figure 16 shows the small and large bubble breakup locations for the lowest and highest gas flow rates, respectively. Dashed lines represent the 19 mm diameter pipe, and dot-dashed lines represents the recirculation region limits. It is observed that bubble breakup happens immediately downstream of the expansion and along the high shear layer on the recirculation limits. No occurrence of bubble breakup in the recirculation zone is observed.

## 7. CONCLUSIONS

Statistics and dynamics of the two-phase flow across a sudden expansion and contraction are presented. These statistics show that bubble size and bubble velocity distributions change along the restrictions. However, one interesting observation is that the distributions measured downstream of an expansion followed by a contraction always return to a value close to the upstream undisturbed flow. For higher gas flow rates, Taylor bubbles break up in many little bubbles, resulting in a higher distribution peak for smaller bubble sizes. The influence of the recirculation zone and the *vena contracta* is also discussed. Bubble breakup happens in regions of higher turbulent kinetic energy, but not inside the recirculation region. Therefore breakup is essentially due to the velocity gradient resulting from the restrictions.

## 8. ACKNOWLEDGEMENTS

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