

# EXPERIMENTAL ASSESSMENT OF TWO-PHASE FLOW ACROSS SUDDEN EXPANSIONS AND CONTRACTIONS

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**Abstract:** *Local and global statistical measurements of a vertical upward two-phase flow in a ten-meter column across a sudden expansion followed by a contraction are presented. The work studies the transition of two different two-phase flow patterns through the singular accidents, specifically bubble/bubble/bubble and slug/bubble/slug transitions. The phenomenology of bubble break up and coalescence is particularly discussed. Properties and parameters of both phases, including the translational gas velocity, bubble diameter distribution, pressure drop and void fraction were characterized. The continuous phase properties were assessed through Particle Imaging Velocimetry and Laser-Doppler Velocimetry. The dispersed phase was characterized with the Shadow Sizing technique.*

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

## 1. INTRODUCTION

Industrial hydraulic installations routinely present changes in pipe diameter. Irrespective of the reason, these changes imply that transitions must be applied consisting of expansions or contractions.

The details of the flows in singularities – expansions or contractions – are of complex description and for this reason have motivated many works. For single-phase flows, theoretical (including numerical) and experimental works are abundant. The emphasis in most works is on determining the pressure recovery across singularities. Some of the developments are the simplest possible, based on a straightforward application of the conservation equations to a control volume. Even so, various simplifying hypotheses need to be considered which strictly do not correspond to reality.

Unfortunately, in many technological applications two-phase flows are the prevalent flow pattern. The implication is that the complexity of flows in singularities is much complicated by the unknown spatial and temporal distribution of the distinct phases. The void fraction changes play an essential role in the determination of pressure changes and this is not easy to incorporate into models.

Many early models for pressure change of two-phase flows in singularities do not consider the slip between phases; they consider that the gas and liquid decelerations are the same and this is a gross simplification of the actual phenomenon. Some models (Lottes, 1961) go as far as neglecting the gas flow rate so that all losses are presumed to occur in the liquid phase. Other authors consider a constant void fraction across the expansion or single-phase correlations with a corrector (Ahmed *et al.*, 2006, 2007).

Recently, authors have attempted to incorporate information on the flow pattern into predictive correlations. Examples for bubbly flow (Petrick and Swanson, 1959; Attou and Bolle, 1999) and annular mist flow can be found in the literature (Schmidt and Friedel, 1997).

The objective of the present work is to study the phenomenology of gas-liquid flows in sudden expansions or contractions. The work, in particular, discusses the flow changes undergone by bubbly and slug flows in singularities. Of particular concern is a discussion on changes of void fraction as a result of the processes of bubble break up and coalescence. This is a subject that has been deficiently discussed in literature (Rinne and Loth, 1996; Bertola, 2003).

The work introduces the flow statistics for bubbly and slug flows in a vertical pipe that is fitted with an expansion and a contraction in succession. The statistics include mean and fluctuating velocities, pressure, void fraction and bubble size distribution. The measurements resorted to PIV, Shadow Sizing and LDV (Silva *et al.*, 2006; Ozalp *et al.*, 2007; Celis *et al.*, 2014).

## 2. EXPERIMENTAL SET-UP

The experiment consists of a transparent vertical pipe, 10.5 meters in length and internal diameters of 19 and 44 mm. The pipe is divided into three characteristic sections of respectively 19, 44 and 19 mm in diameter, all connected in succession to define the expansion and the following contraction (Fig 1).

The test section is supplied with water and gas at the bottom through a “T” junction, connected directly to cavity progress pumping and an air compressor. The water flow rate was measured through an electromagnetic flow meter; the gas flow rate was obtained from reading of a rotameter. On the top of the column a liquid-gas gravitational separator was installed. The separated air is directly released to the atmosphere; the water is returned back to a reservoir. The lengths of the characteristic sections were designed to guarantee fully developed flow; the recommended aspect ratio ( $L/D$ ) was considered from (Collier, 1981).

The flow conditions are shown in Table 1. They were chosen on the basis of the visualization study reported in (Celis

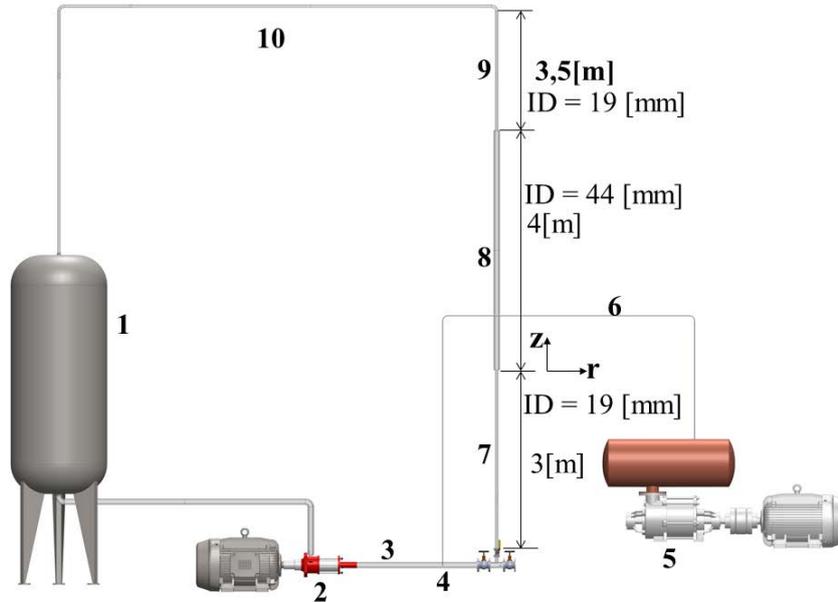


Figure 1: Diagram of the experimental apparatus. 1) Storage liquid tank; 2) volumetric pump; 3) electro-magnetic flow meter; 4) air-water mixing region; 5) supply air compressor; 6) rotameter; 7) upstream expansion; 8) downstream expansion; 9) downstream contraction; 10) return pipe.

Table 1: Flow measurements conditions

Flow pattern transitions	Liquid flow rate $m^3/h$	Gas flow rate $m^3/h$
Single phase flow	2.0	0.0
Bubbly/Bubbly/Bubbly	1.26	0.12
Slug/Bubbly/Slug	1.26	0.27

*et al.*, 2014). The liquid and gas flow rates aim at permitting a flow pattern change at the sudden expansion from bubbly flow to bubbly flow, and slug flow to bubbly flow. Transitions from slug flow to slug flow were not observed for any of the other tried conditions. In vertical flows, as we shall see, transitions from slug to slug flow are difficult to observe for water and air flows at relatively large flow rates.

The flow positions where the measurements were made are shown in Fig. 2.

The PIV system is composed by a Litron DualPower 135 laser with  $532mw$ , a SpeedSense M310 camera with resolution of  $1200 \times 800$  pixels and acquisition frequency of 1500 Hz in double frame mode. A synchronization software developed by *Dynamic Dantec* was used to measured the single phase flow of Table 1. Rhodamine particles with  $15\mu m$  in diameter were used as tracers. For the other two flow conditions (Table 1), a Shadow Sizing System was used to characterized the disperse phase.

Measurements at Stations 1 and 6 in Fig. 2 were made simultaneously, with a synchronized system of two cameras in single frame mode. The system recorded a total of 16400 images at  $1400Hz$  for each camera, resulting in a sampling time interval of 11.71 seconds. At both stations, an acrylic box filled with water was installed to reduce image distortion.

The single-phase flow velocity profiles were measured through laser-Doppler velocimeter. An one-component Dantec laser-Doppler system was used with a 400 mW Ar-ion tube laser that operated in the forward-scatter mode. The two light beams that emerged from the 60 mm diameter FiberFlow probe were made to pass through a beam expander with expansion ratio of 1.98. This optical component was used to increase the beam spacing so providing a measurement volume of dimensions  $49.6 \mu m \times 49.9 \mu m \times 150 \mu m$ . Front lens with 310 mm focus length were mounted on the probe to accurately position the measurement volume on the centerline of the pipe. The signals from the photo-multipliers were digitized and processed through a burst spectrum analyzer BSA P60 operating in single measurement per burst mode. The Dantec BSA Flow Software 4.50 was used to calculate the Doppler frequencies and the resulting velocity samples. A series of LDV biases were avoided by adjusting the strictest parameters on the data processor and software.

### 3. RESULTS

Some of the flow statistics are presented next. Then, a short qualitative description of the flow behavior in the expansion and contraction regions is make. The section follows with a quantitative presentation of the flow properties in the expansion and contraction for single and two-phase flows.

Table 2 shows the statistics of the flow upstream of the expansion and downstream of the contraction, for the two

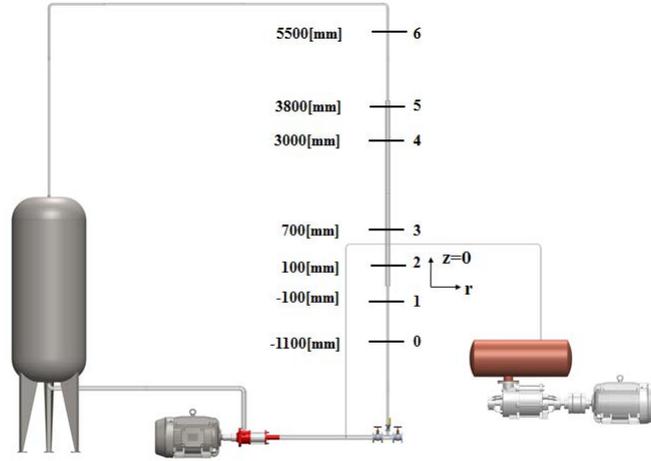


Figure 2: Position of measuring stations.

Table 2: Flow patterns observed across the singularities

Flow Pattern transition	Position [mm]	Number of Slug	Frequency [Hz]	Mean Length [mm]	Mean Velocity [m/s]
Bubbly	-1100	-	-	3.29	1.405
Bubbly	3500	-	-	4.34	0.484
Bubbly	5500	-	-	4.26	1.356
Slug	-1100	83	16.93	34.21	1.87
Bubbly	3500	-	-	5.87	0.49
Slug	5500	14	3.63	122.69	2.01

changes of pattern described in Tab. 1. For bubbly flow, “mean length” stands for the average equivalent diameter of the bubbles. For slug flow, the “mean length” is the average length of a Taylor bubble.

### 3.1 Pattern changes in bubble flow at an expansion followed by a contraction

The changes experienced by bubble flow in a contraction/expansion system are shown in Fig. 3. The pipe diameters are not in scale. To every picture, the smaller diameter represents the 1” pipe.

At position  $z = -1100$  mm the dispersed bubbles have an average diameter of 3.29 mm. At the expansion position  $z = 0$ , the gas and liquid deceleration induce bubbles to agglomerate and coalesce. The flow recirculation region induces the appearance of a shear flow layer that stretches and breaks bubbles. The combination of the merging and tearing up processes results in a new bubble diameter distribution with average 4.34 mm at position  $z = 3500$  mm. At  $z = 4000$  mm, a ring of gas is formed at the wall as a result of the small recirculation region just downstream of the contraction point. The length of the gas film is about 1”. Past the film, the diameter distribution of the bubbles has an average value of 4.26 mm, a value very close to that at  $z = 3500$  mm.

### 3.2 Pattern changes in slug flow at an expansion followed by a contraction

The pattern changes undergone by slug flow in a contraction/expansion system are shown in Fig. 4. The pipe diameters are not in scale. To every picture, the smaller diameter represents the 1” pipe.

At  $z = -1100$  mm, the long bubbles have an average length of 34.21 mm. At the expansion,  $z = 0$ , the gas bubble is strongly decelerated by the sudden increase in pressure. The following liquid slug on the other hand keeps a higher momentum due to inertial effects. The large difference in velocities causes the slug to hammer the Taylor bubble breaking it into small pieces. Thus, in a short downstream distance of the expansion the Taylor bubble is reduced to a swarm of small bubbles that at  $z = 3500$  mm have an average diameter of 5.87 mm. The shear flow layer formed by the recirculation region further breaks up bubbles. At the contraction  $z = 4000$  mm, the small bubbles squeeze into the 1” pipe, quickly coalescing to a large Taylor bubble with an average 122.69 mm in length.

### 3.3 Single-phase flow changes

The typical single-phase flow behavior at the expansion is shown in Figs. 5 and 6. The full mean velocity profile at position  $z = -100$  mm develops at  $z = 100$  mm to a Gaussian profile with tails distributed in the flow recirculation region so that  $u \approx 0$  (but slightly negative). The turbulence intensity at  $z = -100$  mm shows a high peak close to wall due to the high flow shear. At  $z = 100$  mm, the turbulence level is raised throughout the cross section of the flow, with two peaks clearly defined by the shear layers that limit the recirculation region of the flow.

At the contraction, at  $z = 3960$  mm, the mean velocity profile distorts to move past the regions of flow recirculation



Figure 3: Bubble flow changes at an expansion followed by a contraction. Stations (from left to right):  $z = -1100, 0, 3000, 4000, 5500$  mm.

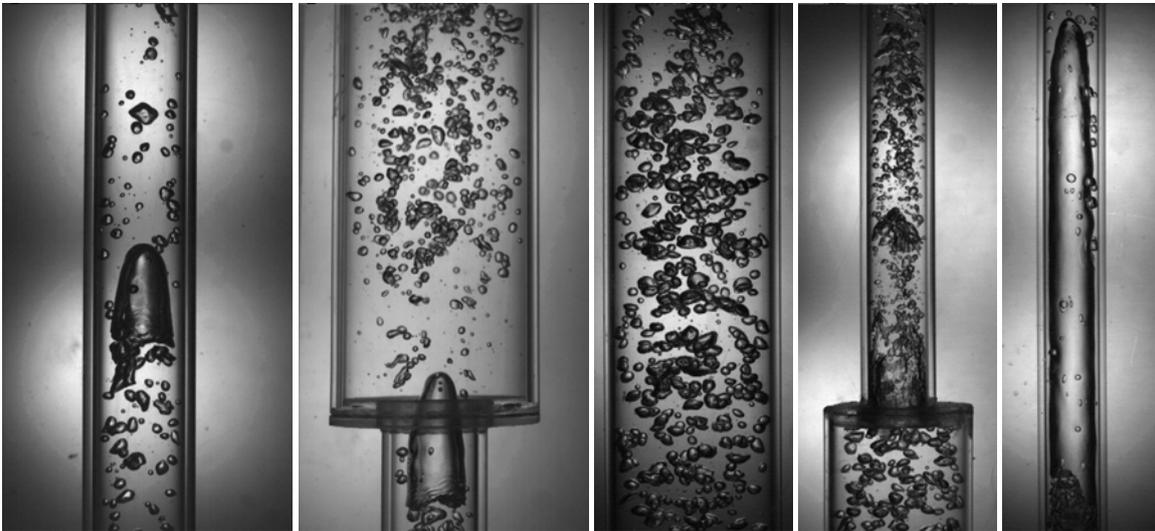


Figure 4: Slug flow changes at an expansion followed by a contraction. Stations (from left to right):  $z = -1100, 0, 3000, 4000, 5500$  mm.

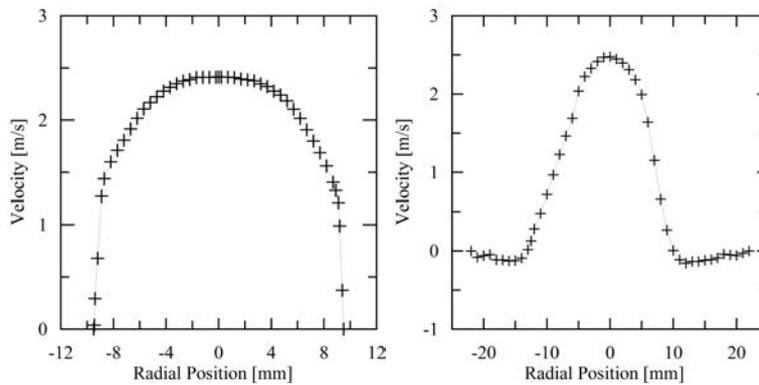


Figure 5: Mean velocity at the expansion.  $z = -100, 100$  mm.

(Fig. 7), yielding a level of turbulence intensity ( $Tu$ ) that is high and about 0.3 across the pipe (Fig. 8). Following the change in pipe diameter the flow accelerates resulting in a  $Tu$ -profile with a very high peak at the wall (Figs. 7, 8).

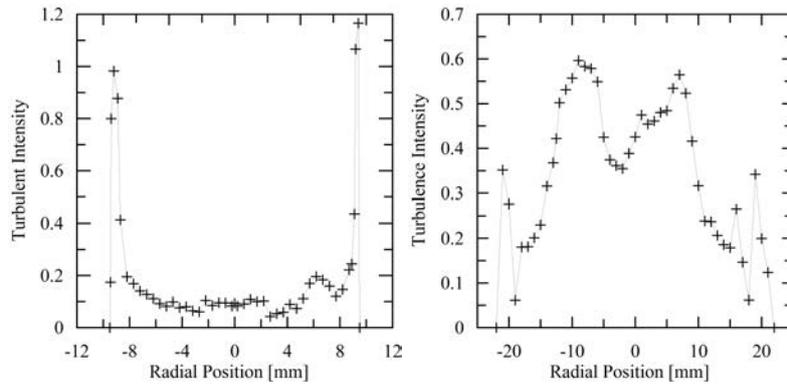


Figure 6: Turbulence intensity at the expansion.  $z = -100, 100$  mm.

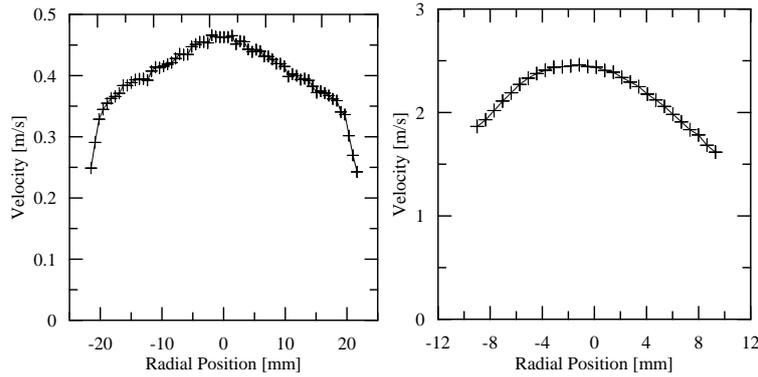


Figure 7: Mean velocity at the contraction.  $z = 3960, 4050$  mm.

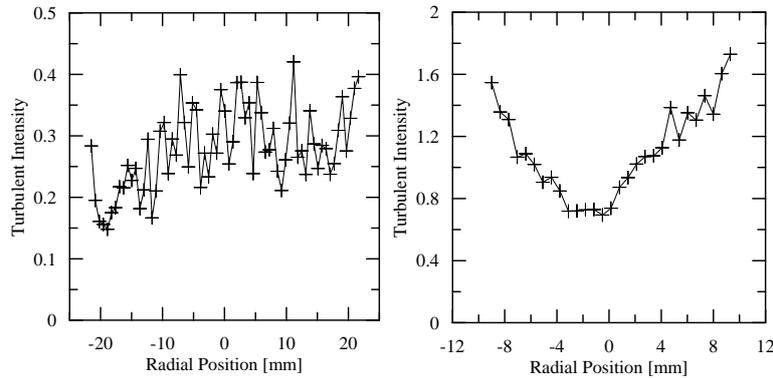


Figure 8: Turbulence intensity at the contraction.  $z = 3960, 4050$  mm.

### 3.4 Two-phase flow changes

For bubble flow, the changes in velocity profile and bubble diameter distribution are discussed next. The flow conditions at the inlet were  $Q_l = 1.26$ ,  $Q_g = 0.12 \text{ m}^3\text{h}^{-1}$  (Table 1).

The changes in the mean velocity of the dispersed phase are shown in Fig. 9. The mean velocity distributions were taken at the pipe centerline and illustrate the intermittent velocity at the expansion. The statistics at stations  $z = -1100$  and  $5500$  mm are about the same showing the recovery of the mean velocity profile to its previous undisturbed values.

The diameter distribution shown in Fig. 10 makes clear that the expansion promotes bubble coalescence. The contraction on the other hand tends to reduce the diameter of the bubbles, but with a mean compared to the value at  $z = 3800$ .

### 3.5 Pressure changes

The pressure changes are shown in Figs. 11 and 12 for the expansion and the contraction respectively. The global pressure (singular + gravitational) evidently always decreases as  $Q_g$  increases.

For  $Q_l = 1.26 \text{ m}^3\text{h}^{-1}$ , the singular pressure drop is relatively small for all gas flow rates. However, for  $Q_l = 2 \text{ m}^3\text{h}^{-1}$ , the singular pressure drop can be as high as 50 mbar for the two highest gas flow rates.

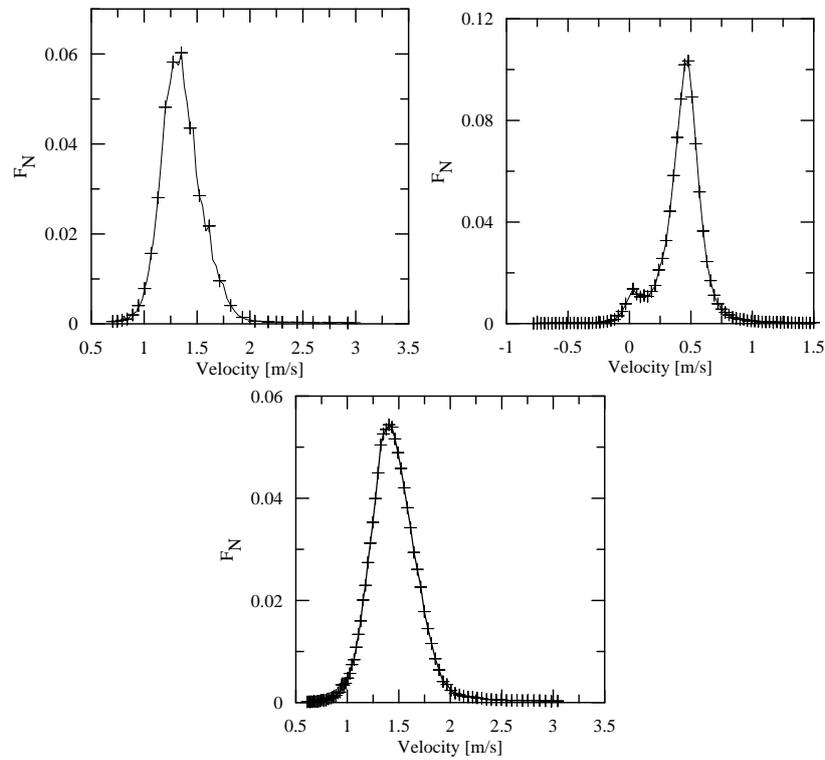


Figure 9: Mean velocity distribution of the bubbles at positions  $z = -1100, 3800, 5500$  mm.

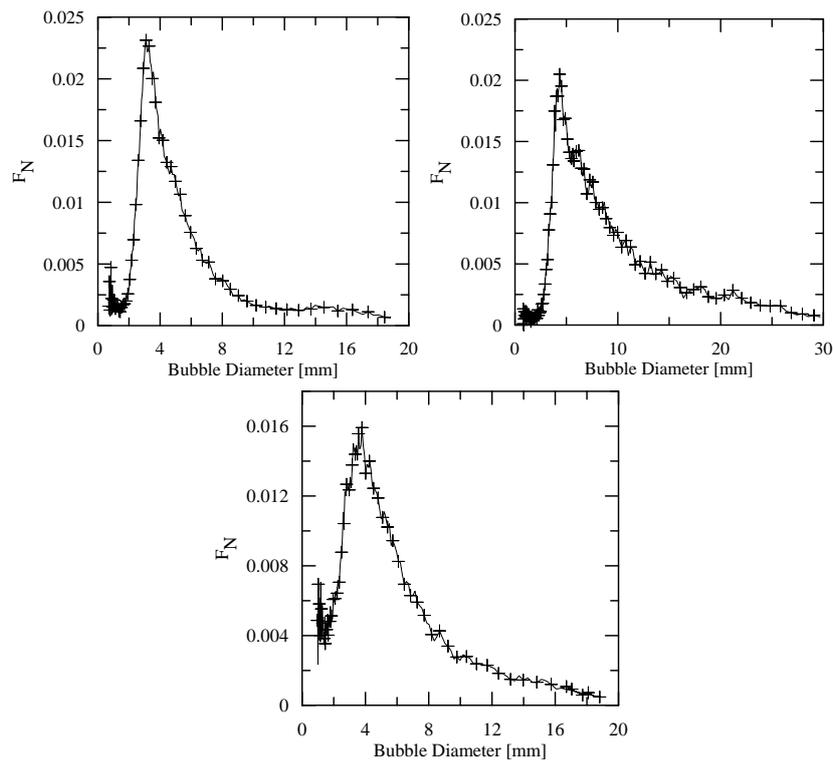


Figure 10: Bubble diameter distribution at positions  $z = -1100, 3800, 5500$  mm.

At the contraction, the gas presence changes the trends in pressure behavior. For single-phase flow the pressure decreases continuously due to flow acceleration. The turbulent agitation resulting for the gas/liquid interaction, however, increases the pressure. For the highest gas flow rate,  $Q_g = 2 \text{ m}^3\text{h}^{-1}$ , the pressure increase is about 30 mbar.

For the highest liquid and gas flow rates, the pressure difference at the contraction increases to about 60 mbar.

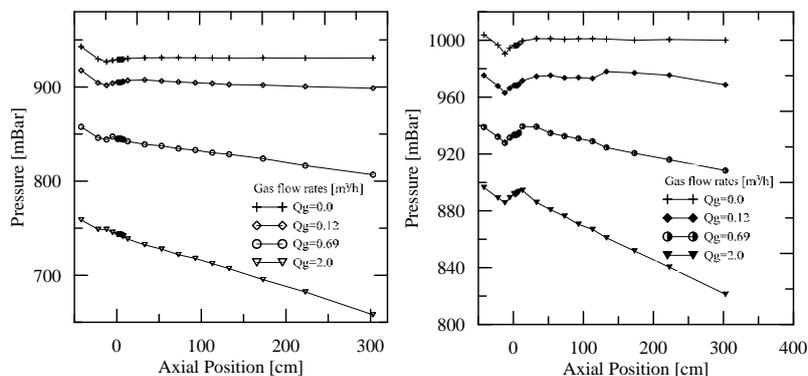


Figure 11: Pressure distribution for the expansion,  $Q_l = 1.26$  and  $2.00 \text{ m}^3\text{h}^{-1}$ .

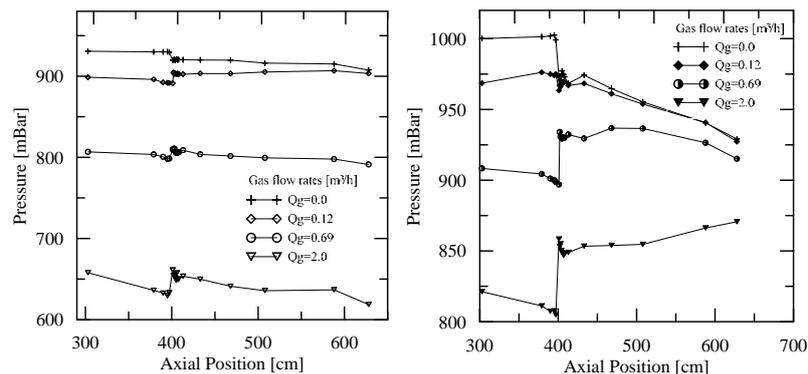


Figure 12: Pressure distribution for the contraction,  $Q_l = 1.26$  and  $2.00 \text{ m}^3\text{h}^{-1}$ .

#### 4. FINAL REMARKS

The work has discussed the phenomenology of two-phase flow past expansions and contractions. Of special interest is the discussion on bubble break up and coalescence as a result of the liquid slug hammer on the Taylor bubble in an expansion. Results on the distribution of bubble diameter were presented for bubble/bubble/bubble and slug/bubble/slug transitions.

Further results are currently been obtained for a better characterization of the break up and coalescence processes in the expansion and the contraction.

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