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EXPERIMENTAL STUDY OF GAS-LIQUID FLOW SEPARATION AT AN INCLINED T-JUNCTION WITH A VERTICAL UPWARD BRANCH

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Abstract. The separation of gas-liquid flows in the oil industry requires the use of large vessels, where the flow mixture should rest for a while so that gravity forces can act and promote phase separation. New separation strategies are being investigated in order to perform on line separation inside compact equipment. The separation of two-phase flows at a T-Junction is a common feature in this industry. When a gas-liquid mixture flows through a junction, the phases are separated unevenly such that the qualities in the downstream pipes are unequal. This work is focused on the experimental characterization of the dynamical properties of gas-liquid flow separation using visualization techniques. The geometrical configuration investigated in the present work has an inlet pipe of 70 mm inclined downwards (10°) and a vertically upward branch of 50 mm. Air and water flow rates were varied to simulate different flow patterns. The mean velocity and turbulent statistics of the liquid phase were characterized by means of Particle Image Velocimetry (PIV). A Shadow Sizer system and laser-based techniques were used to quantify the properties of the gas phase, such as bubble length and bubble velocity.

Keywords: T-junction, gas-liquid separation, two-phase flow, PIV, Shadow Sizer

1. INTRODUCTION

New processing separation strategies of gas-liquid flows in the oil industry are being investigated in order to promote on line separation. One of this technological solution is based on the optimization of gravitational effect through a set of pipes and T-junctions. Named generically of tubular separators, these equipment can be made in vertical, horizontal or inclined geometries (Wren and Azzopardi, 2004), (Baker *et al.*, 2007).

When two-phase gas-liquid flow enters a T-junction, the phases tend to divide between the lateral branch and the main pipeline. The separation will hardly be uniform, with phase division in equal quantities. Depending on the input conditions, the liquid phase may or may not flow through the lateral branch (Shoham *et al.*, 1987). Different flow patterns at the junction entrance and different geometries adopted affect the separation. Therefore, it is of great importance to study the mechanism of phase distributions for different geometries.

The quantitative and qualitative flows visualization has developed considerably in the last decades. This measurement technique allows to infer information about the flow velocity field and the phase distribution. Fu *et al.* (2011) have studied the break up process of bubbles in a T-junction microchannel. Štigler *et al.* (2012) have used visualization techniques in an single-phase flow to obtain the velocity profiles in a T-junction.

The purpose of the present investigation is to understand the behaviour of a two-phase flow mixture across a very particular configuration of T-junction using visualization techniques, in order to understand the separation mechanisms. A special flow loop was modified to allow the present study. Gas-liquid two phase flow is connected to the entrance of a downward inclined pipe, which side arm is located in the middle-length of the inclined pipe and is positioned in the vertical upward direction. Global measurements of flow rate, Shadow Sizer Technique and Particle Image Velocimetry (PIV) have been performed.

The present work has developed an extremely accurate experimental database that include global and local properties of the gas and liquid phases, such as pressure drop, mass flow rates at the entrance and outlets, length and velocities of gas bubbles and mean and turbulent statistics of the continuous phase. These results enlighten our understanding of gas-liquid separation at junction flows and will be a valuable reference dataset for numerical validation purposes.

2. EXPERIMENTAL SET-UP

The experiments were conducted at the Laboratory of Compact Separators of the Interdisciplinary Center for Fluid Dynamics (NIDF/UFRJ). Figure 1 shows an overview of the experimental set up used for the present investigation.
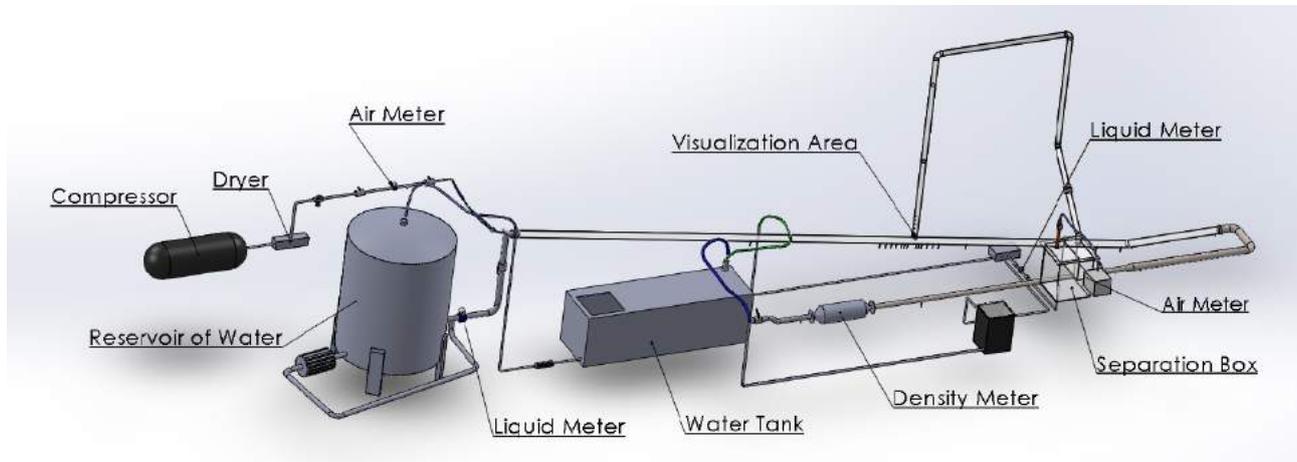

Figure 1: Overview of the experimental set-up used for the T-junction experimental investigation.

3. EXPERIMENTAL PROCEDURE

The present study presents two widely used techniques for visualizing gas-liquid two-phase flows. A Shadow Sizer System was used to quantify the bubble size distribution on the liquid outlet. Besides that, the mean velocity and turbulent statistics of the liquid phase were characterized by means of Particle Image Velocimetry (PIV).

For the Shadow Sizing and PIV techniques, the inlet gas flow rates were varied from 0.07 to 0.27 m^3/h in steps of 0.07 m^3/h while the inlet liquid flow rates were varied from 6.0 to 13.65 m^3/h in steps of 2.0 m^3/h, approximately. These flow rates gave origin to different flow patterns on the inclined pipe. Figure 2 illustrate some of the observed patterns and Table 1 describes the present experimental conditions. All pressure transducers and flow meters used in the present work have been calibrated against reference instruments.
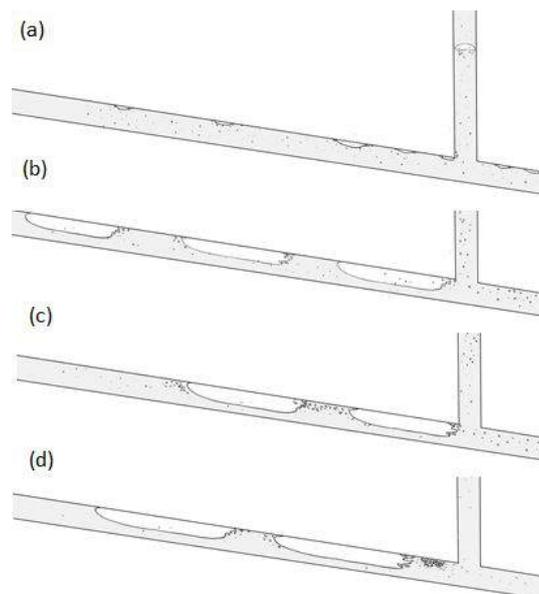

Figure 2: Typical flow patterns before the T-junction for $Q_{liq} = 10.09\ m^3/h$. Experimental conditions: (a) 6 ($Q_{gas} = 0.07\ m^3/h$), (b) 7 ($Q_{gas} = 0.13\ m^3/h$), (c) 8 ($Q_{gas} = 0.20\ m^3/h$) e (d) 9 ($Q_{gas} = 0.27\ m^3/h$).

Regarding the optical measurements, to avoid optical distortions due to the pipe curvature, the T-Junction was placed inside a rectangular acrylic box.

Table 1: Characterization of the Flow Pattern for Visualization Tests

Configuration	Q_{liq} (m^3/h)	1º Bubble (cm)	1º Slug (cm)	2º Bubble (cm)	2º Slug (cm)	3º Bubble (cm)
$Q_{gas} \approx$ **0,13** m^3/h						
1	6,07	386	30	218 (until the T-Junction)	-	-
2	8,05	132	43	117	43	90 (until the T-Junction)
3	10,09	112	58	101	63	177 (until the T-Junction)
4	11,19	91	-	-	-	-
5	13,65	-	-	-	-	-
$Q_{liq} \approx$ **10,09** m^3/h						
Configuration	Q_{gas} (m^3/h)	1º Bubble (cm)	1º Slug (cm)	2º Bubble (cm)	2º Slug (cm)	3º Bubble (cm)
6	0,07	-	-	-	-	-
7	0,13	112	58	102	63	117 (until the T-Junction)
8	0,20	145	58	132	-	-
9	0,27	168	58	178	-	-

For the Shadow Sizer measurement, a light diffuser was placed between the acrylic box and the light source, in order to obtain a uniform illumination on the entire image. The intensity of the LEDs and lens aperture are adjusted so that the acquired image does not show over or under exposure, generating a clear and uniform image. The software used allows to make changes of coordinates from pixels to the metric system, through a process of calibration by scale. After these adjustments, 1,000 background images (single-phase system) with a sampling frequency of 500 Hz were acquired before starting the two-phase flow tests.

After the acquisition of the two-phase flow data, it was made an image post-processing step with the aid of a subroutine using *MatLab*. The objective of this routine is to make the recognition of the gas phase in the system, where, through the application of filters and the subtraction of the characteristic background (image of the pipe filled with water only) generate a greater contrast between the bubbles, in order to binarize the image, resulting in a white background and black bubbles. This processing is based on contour detection algorithms, which together with *Dantec Dynamics Software* provide results as equivalent diameter, area, perimeter, as well as velocity vectors for each measured bubble. To characterize the bubble that arrives at the T-junction, the same technique developed by Matamoros *et al.* (2013) was adopted.

In order to isolate the bubble effects in the continuous phase for the determination of the velocity field in a two-phase flow, it is necessary to combine two visualization techniques: the Particle Image Velocimetry, PIV, and the Shadow Sizing technique. For these tests, both measurement techniques have been used simultaneously. Rhodamine particles, that scatter the laser light in the red wavelength, have been used to seed the liquid phase. A red filter was placed on the camera lens, so it was possible to capture the image of the bubbles together with the identification of the PIV particles. The obtained data are processed by the *Dynamics Studio Software*.

4. RESULTS AND DISCUSSION

Each experimental condition of flow splitting resulted in different flow behaviours near the T-junction. Figures 3 and 4 illustrate the different bubble shapes and the post processing area where bubbles that were not separated by the T-Junction are analysed.

4.1 Shadow Sizing Analyses

Initially, the equivalent diameters and velocities of the non-separated phase by the T-junction were determined. Figures 5a and 5b represents the frequency of equivalent diameter distribution of the not separated bubbles.

For both fixed gas flow and fixed liquid flow configurations, the mean diameter of the non separated bubbles are similar, with larger amounts of bubbles having a diameter of approximately 2 mm. When the gas flow rate is fixed (Figure 5a), it can be observed that for the configurations of 6.0, 8.0 and 10.1 m^3/h, there is a greater dispersion of bubbles not separated. This fact is due to the presence of a fixed bubble in the entrance region of the T-junction, as illustrated in Figure 3. For flow configurations of 11.2 and 13.7 m^3/h (Figure 5b), a larger frequency of bubbles of smaller diameters
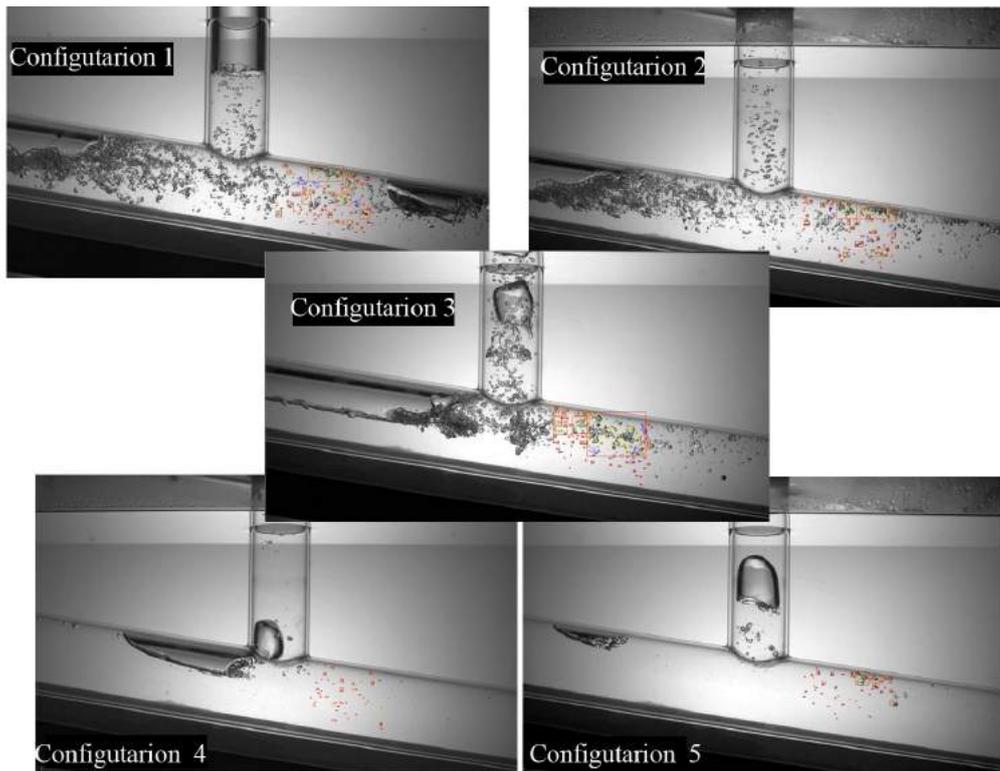
Figure 3: Flow profile close to T-junction for flow configurations from 1 to 5.
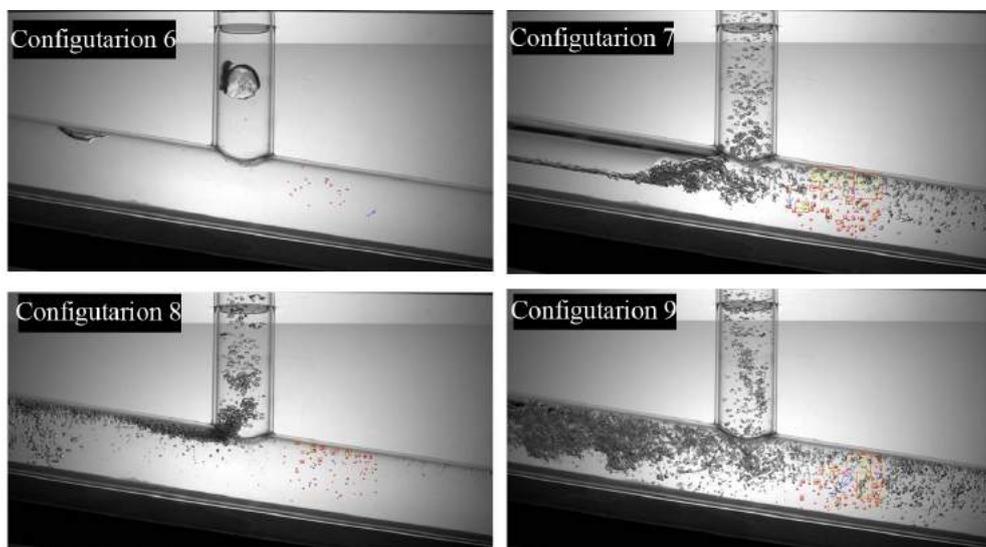

Figure 4: Flow profile close to T-junction for flow configurations from 6 to 9.

is observed, this is also due to the inlet condition of the flow. For such flow configurations there is no formation of fixed bubbles upstream of the T-junction, and thus, the amount of smaller bubbles that are not separated increases.

Regarding the diameters for a fixed liquid flow at the T-junction, it is noted that there is a similarity in the distribution of the non separated bubble diameters, so it can be concluded that the liquid flow directly influences the separation, as faster the flow is (greater liquid flow in the inlet), the lesser time the gas phase will be exposed to the T-junction, thereby reducing the separation efficiency.

Another result obtained by the Shadow Sizing technique is the velocity of the non separated bubbles. Because the flow of this work occurs in a inclined pipe, the velocity of the bubbles has two coordinates, one in x (U_b) and other in y (V_b), where the reference for the x-axis is given from left to right and the y-axis from bottom to top. The Figures 6a, 6b, 7a and 7b presents these results.

For all configurations tested, the velocity V_b on the y-axis is predominantly negative, just as the velocity U_b on the x-axis is predominantly positive. This happens due the fact that the flow occurs in a downwardly inclined pipe. The
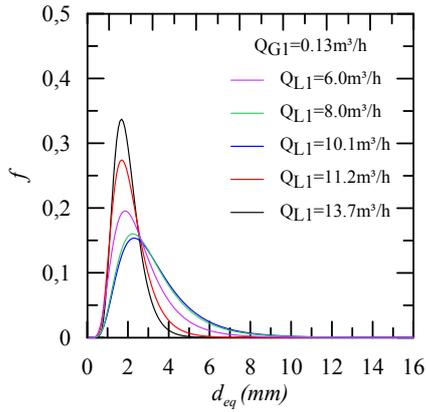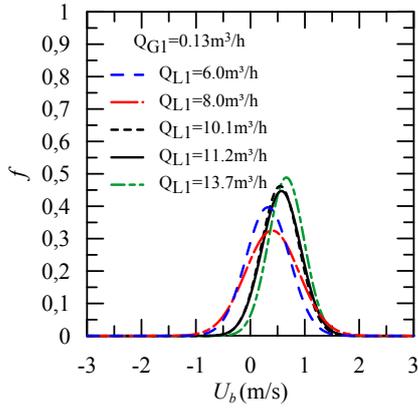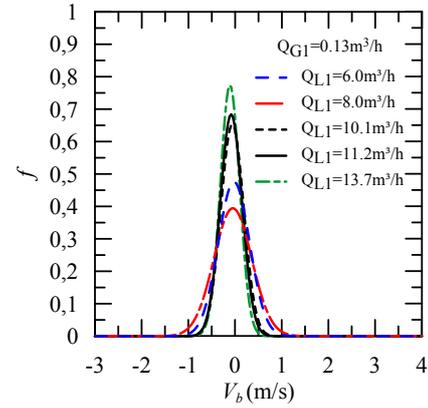
(a) Gas fixed flow.
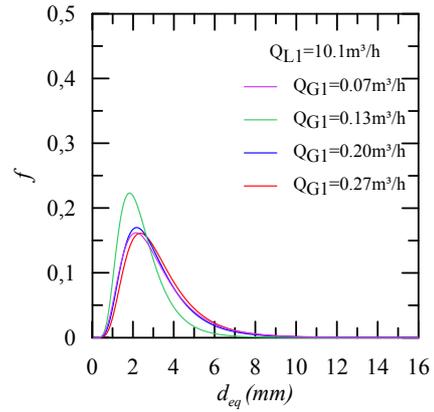
(b) Liquid fixed flow.

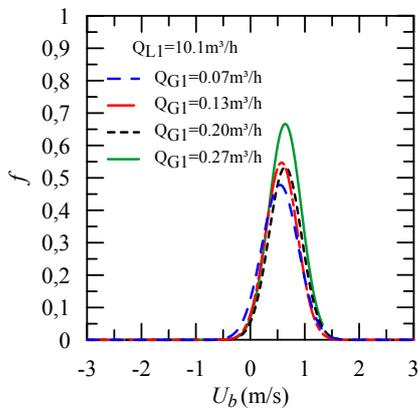Figure 5: Equivalent diameters of *Shadow Sizing* analyses.
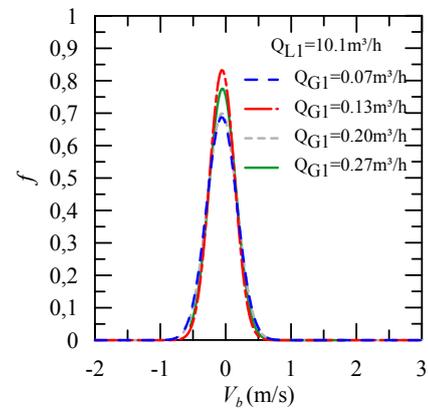

(a) x-axis velocity

(b) y-axis velocity

Figure 6: Bubble velocities for gas fixed flow configurations.

(a) x-axis velocity

(b) y-axis velocity

Figure 7: Bubble velocities for liquid fixed flow configurations.

positive velocities at y and negative at x are because the effect of bubble recirculation after the T-junction.

Flow configuration 4, 5 and 6 did not present a fixed bubble before the T-junction, only small bubbles that moved with the nose pointed against the direction of the main flow. For this configurations, bubbles were characterized: frequency of bubbles, velocity, length, volume, dry area and wet area. The mean results are shown in Table 2.

Table 2: Bubble Characterization

	Configuration 4	Configuration 5	Configuration 6
Frequency ($bubble/s$)	3,33E-01	1,04E+00	7,03E-01
Mean Velocity (m/s)	2,42E-01	4,58E-01	3,19E-01
Mean Length (m)	1,39E-01	8,20E-02	6,16E-02
Mean Volume (m^3)	1,32E-04	4,88E-05	2,72E-05
Mean Dry Area (m^2)	8,84E-03	4,38E-03	3,07E-03
Mean Wet Area (m^2)	2,18E-02	1,41E-02	1,05E-02

Configuration 4 and 5 have the same amount of gas flow. Since the liquid velocity in configuration 5 is greater than in configuration 4, the bubble velocity also exhibited the same tendency. Unlikely, the mean volume and mean length, once the liquid flow increases for the same gas flow rate, there is a decrease of the bubbles formed before the T-junction, this fact occurs because the gas phase is dragged by the liquid phase.

Is possible to observed that in configuration 6, since the gas flow is lower than the others configurations, the size of the bubble is the smallest. Because of this, the mean velocity is bigger when compared to configuration 4, even thought the liquid velocity is higher.

The analysis of single bubbles for the different configurations implies that the variation of dry and wet area has a linear tendency when compared with the volume (Figures 8a and 8b).
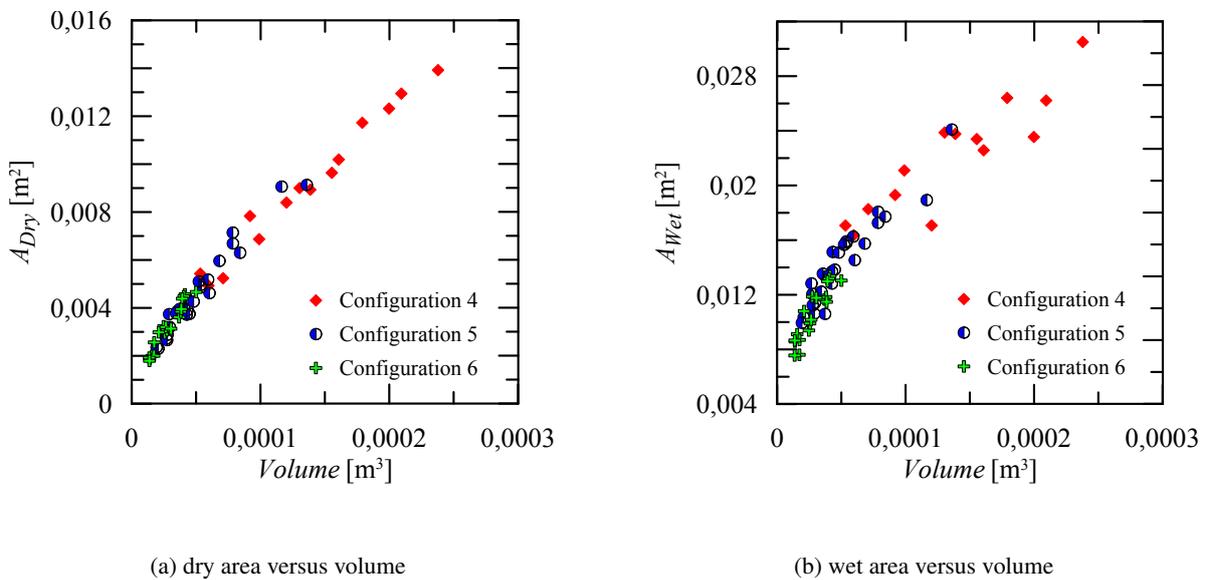

(a) dry area versus volume   (b) wet area versus volume

Figure 8: Single bubbles: areas versus volume.

4.2 Shadow Sizing and PIV Analyses

The flow configurations studied are the same listed previously in the table 1. The application of the Particle Image Velocimetry in the vertical section of the T junction proved to be infeasible, since the laser illumination plane is located in the same direction of the flow (from the bottom-up), so when bubble goes through this section, shadows were formed in the region of continuous phase, preventing the visualization of the Rhodamine particles.

Initially, the results of flow configurations that resulted in fixed bubbles before the T-junction will be presented, where the tail and the waist of these bubbles are captured in the tests performed (configurations 1, 2, 3, 7). Subsequently, the images of the configurations 8 and 9, where the gas flow rate was larger than those tested in the other runs, were analysed, $Q_{G1} = 0.20m^3/h$ and $Q_{G1} = 0.27m^3/h$, respectively. Finally, configurations 4, 5 and 6, where there is no formation of fixed bubbles in the slope upstream of the joint, were studied.

Figures 9, 10 and 11 illustrate examples of the observed flow pattern and measured mean velocity field. The color scale of the velocity vectors in m/s is also illustrated.
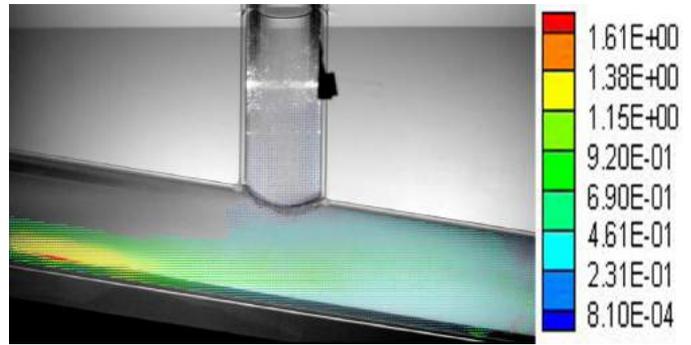
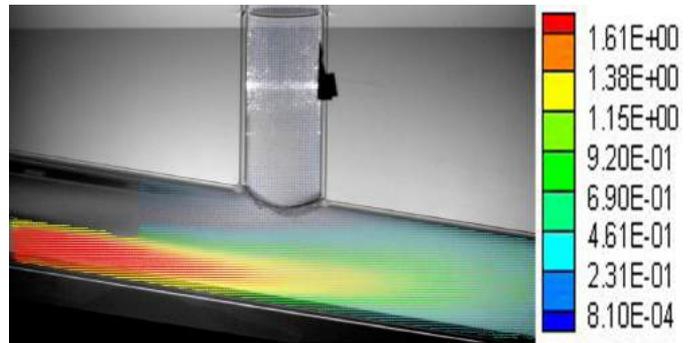(a) Feature image.   (b) mean velocity field over the average image.

Figure 9: Configuration 1 ($Q_{L1} = 6.0m^3/h$ and $Q_{G1} = 0.13m^3/h$).
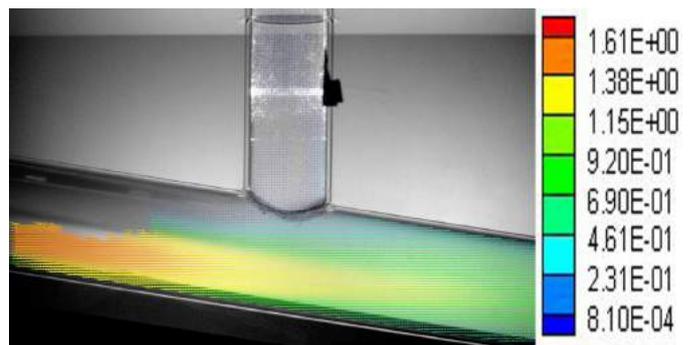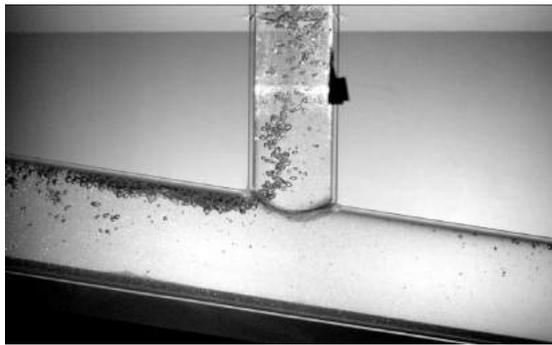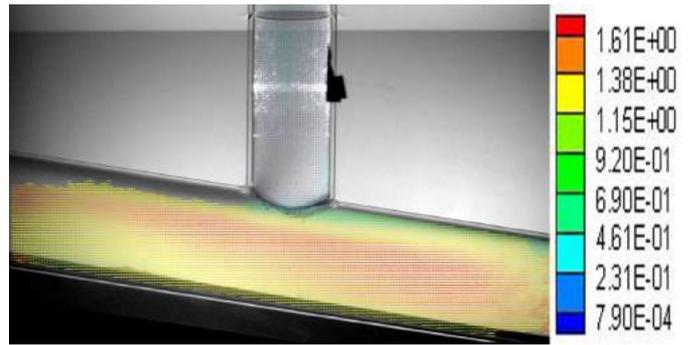

(a) Feature image.   (b) mean velocity field over the average image.

Figure 10: Configuration 2 ($Q_{L1} = 8.0m^3/h$ and $Q_{G1} = 0.13m^3/h$).

(a) Feature image.   (b) mean velocity field over the average image.

Figure 11: Configuration 3/7 ($Q_{L1} = 10.1m^3/h$ and $Q_{G1} = 0.13m^3/h$).

It was observed for configurations 2 and 3/7 that there is a difference in the height of liquid occupied in the inclined section just downstream of the bubble. In configuration 2, the bubble has a larger diameter than in the 3/7 experiment, this fact contributes to the velocity increase observed in the images.

Examples of the observed pattern and the mean velocity field of the flow for configurations 8 and 9 are given in Figures 12 and 13, respectively. At configuration 8, the flow pattern is similar to a single phase flow near to the T-Junction. Moreover, configuration 9 presents a significant amount of dispersed bubbles near to the T-junction and this fact change substantially the mean velocity field.

For configurations 4, 5 and 6, the Taylor bubbles was observed to be captured by the junction, with the characteristic images and mean velocity fields being shown in Figures 14, 15 and 16.
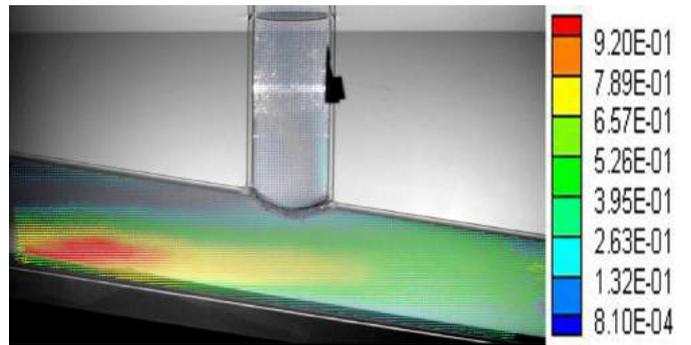
(a) Feature image.   (b) mean velocity field over the average image.

Figure 12: Configuration 8 ($Q_{L1} = 10.1 m^3/h$ and $Q_{G1} = 0.20 m^3/h$).
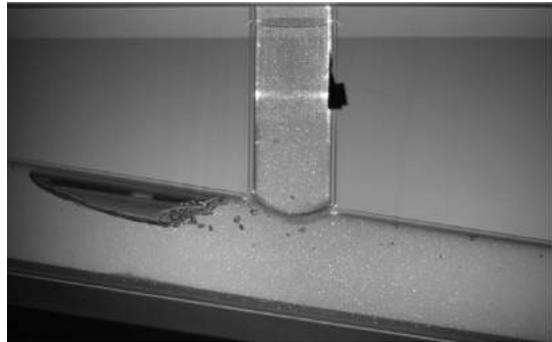

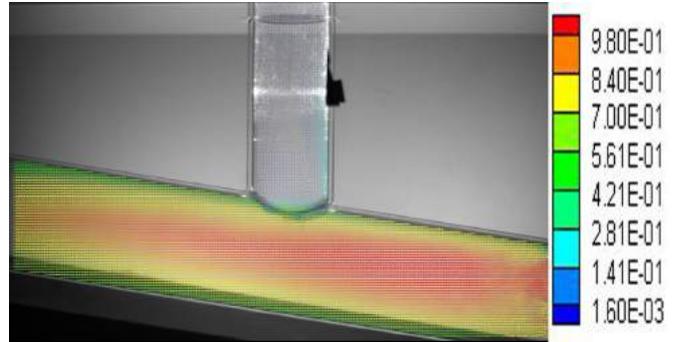(a) Feature image.   (b) mean velocity field over the average image.

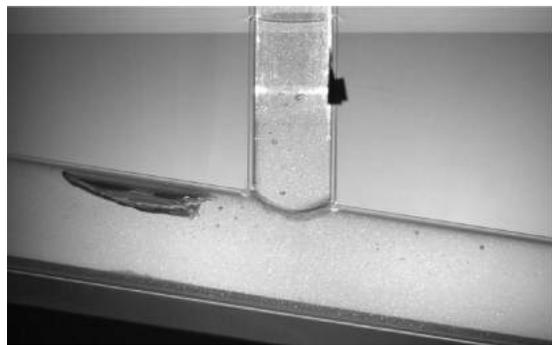Figure 13: Configuration 9 ($Q_{L1} = 10.1 m^3/h$ and $Q_{G1} = 0.27 m^3/h$).
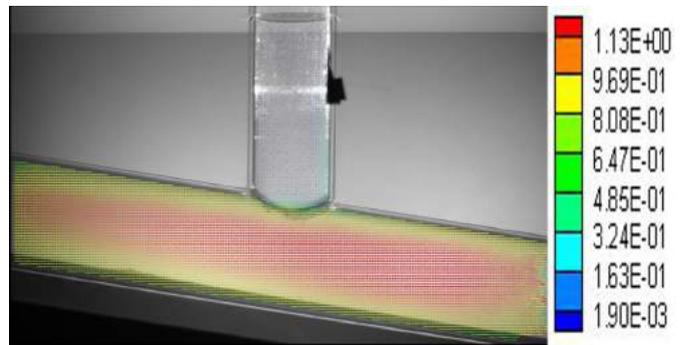

(a) Feature Bubble   (b) mean velocity field over the average image.

Figure 14: Configuration 4 ($Q_{L1} = 11.2 m^3/h$ and $Q_{G1} = 0.13 m^3/h$).
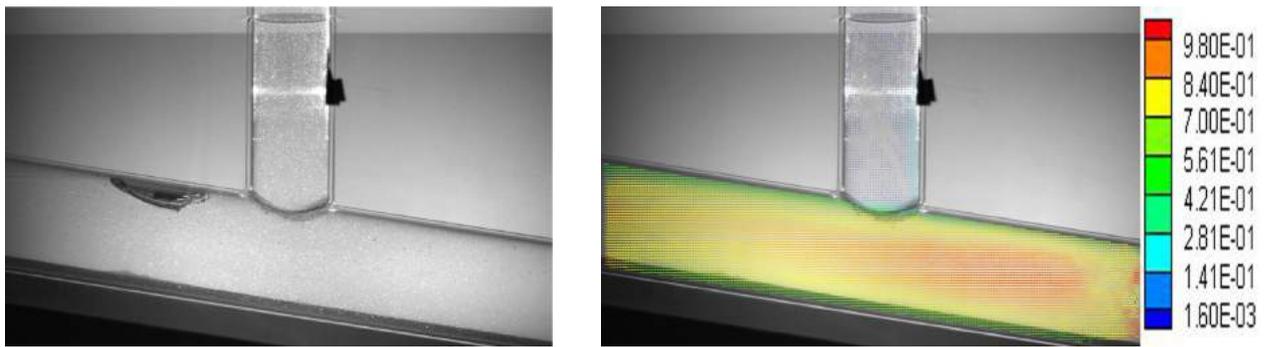

(a) Feature Bubble   (b) mean velocity field over the average image.

Figure 15: Configuration 5 ($Q_{L1} = 13.7 m^3/h$ and $Q_{G1} = 0.13 m^3/h$).

5. CONCLUSIONS

The purpose of this work was to study a very particular configuration of T-junction flow. Gas-liquid two-phase flow is connected to the entrance of a downward inclined pipe, which side arm is located in the middle-length of the inclined

(a) Feature Bubble   (b) mean velocity field over the average image.

Figure 16: Configuration 6 ($Q_{L1} = 10.1 m^3/h$ and $Q_{G1} = 0.07 m^3/h$).

pipe and is positioned in the vertical upward direction. This investigation is dedicated to understanding the separation mechanisms in order to maximize gas separation. Global measurements of flow rate, Shadow Sizer Technique and Particle Image Velocimetry (PIV) have been performed. Different configurations of inlet gas-liquid flow were tested to provide a variety of bubble distributions before the T-junction. The non-separated phase was characterised by the equivalent diameter and velocities. For some configurations it was possible to characterize the bubble velocity, length, volume, dry area and wet area. Also, the mean velocity distribution and turbulent statistics of the liquid phase were characterized by means of Particle Image Velocimetry.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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