EXPERIMENTAL STUDY OF GAS-LIQUID FLOW SEPARATION AT A T-JUNCTION

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Abstract. *The separation of two-phase flows at a T-Junction is a common feature in many industrial processes, such as oil field flow lines, pipeline networks and refinery streams to divide or combine flows. When a gas-liquid mixture flows through a junction, the phases are separated unevenly such that the qualities in the downstream legs are unequal. This work is focused on the experimental characterization of the dynamical properties of gas-liquid flow separation in a T-junction composed by a horizontal inlet pipe of 70 mm in diameter and an upward vertical branch of 44 mm in diameter. The fluids used were air and water. Different combinations of gas and liquid flow rates were used to simulate stratified smooth and slug flow patterns. The inlet pipe and the vertical branch arm were pressure-tapped to enable measurement of pressure distribution in each arm.*

Keywords*: T-junction, gas-liquid separation, two-phase flow*

1. INTRODUCTION

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. These new solutions are typically based on cyclonic effects that maximize separation through centrifugal effects in very slim cylindrical equipment. Another technological solution, however, resorts to the intensification of gravitational effects in pipes and T-junction flows (Wren, (2004), Baker et al. (2007)).

In fact, T-junction flows have received much attention in the literature over the last twenty years (Lahey (1986). Until nowadays it is not a fully understood problem since almost all geometrical parameter of a T-junction can affect flow split. Lahey (1986) as well as Azzopardi (2000) stated that no satisfactory model exists for the prediction of phase separation over a range of flow conditions and geometrical shapes.

The full description of a T-junction is done by specification of the inlet, outlet and branch side arm diameter, and their associated angles. The three angles to consider are: the angle of the main pipe from the horizontal, the angle of the side arm from the main pipe and the orientation of the side arm, which can take any angle between -90^o, for a vertically downward side arm, and $+90^o$ for a vertically upward one. Azzopardi and Smith (1992) investigated the influence of side arm orientation and downstream geometry on the characteristics of flow separation. The authors observed that the amount of liquid separated depended not only on geometry but also on the inlet flow pattern.

The dominant forces that will affect the phase split at a T-junction (Baker (2003)) are gravity, inertia and pressure. Gravity will act mainly on the liquid phase, pushing the liquid downwards and minimizing the amount of liquid taken upwards. Since the axial momentum of the liquid is higher that the gas, the liquid is forced to continue along the pipe, bypassing the entrance to the side arm. When the side arm diameter is small, this effect becomes more pronounced since liquid will have a small time to be influenced by gravity. Typical pressure drop in a T-junction shows a loss between the inlet and the side arm and a recovery inside the run arm. This effect is due to a decrease in the mixture velocity in the run arm, which according to Bernoulli leads to an increase in pressure.

Another critical characteristic of T-junction flows is its transient effects. As remarked by Baker et al. (2008), the literature has very little work conducted over transient flow conditions. As such, further investigation is still necessary to elucidate the dynamics that occur when transient two-phase mixtures flow across T-junctions.

The purpose of this work is 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 pipe and is positioned in the vertical upward direction. After a thorough literature review no similar T-junction flow could be found. This investigation is dedicated to understand the separation mechanisms in order to maximize gas separation. A special flow loop was modified to allow this present study. Global measurements of flow rate, pressure drop and void fraction have been performed. The transient behavior of the flow loop was quantified by pressure and density measurements.

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.

2.1 T-junction set up

The water flow is driven by a progressive cavity pump to an ultrasonic flowmeter and then follows to a horizontal pipe where there is an air-water mixer. A frequency inverter connected to the progressive cavity pump is used to control and adjust the water flow rate. The gas phase is provided by a compressed air line equipped with a drying system and pressure regulator valves. The gas flow rate in the inlet section is measured by a rotameter.

The water and air feeding lines are mixed in the horizontal pipe at a point located two meters upstream of the T-test section. The T-junction is composed by an inlet pipe inclined 10^o downwards, which is connected to a side branch arm oriented vertically upwards. The inlet inclined pipe has 70 mm in internal diameter, while the vertical branch arm has 50 mm internal diameter. The flow that is separated at the vertical branch arm is directed to a separator, to retain the liquid phase, and then to a diaphragm gas flow meter. The pipes are made of Plexiglas in order to allow the use of optical measurement techniques. However, to avoid leakages and vibrations, the T-junction and the connections located at the corners were made of stainless steel.

A control valve located at the gas outlet can be used to adjust the pressure drop on the vertical branch arm. The mixture that flows along the inclined pipe goes through a Coriolis flow equipped with a densimeter, so that both the gas and liquid phases can be quantified. The water goes to a secondary reservoir where a level-driven centrifugal pump returns the liquid to the main reservoir.

The experiment was planned so that flow rates of each phase could be measured on the inlet and on the gas (upward) and liquid (downward) outlets. Absolute and differential pressure transducers were also installed at these specific locations, as well as on the bottom of the T-junction. A Pitot tube sensor was installed at the top of the vertical branch arm in order to be a redundant measurement of the diaphragm gas flow rate at the vertical outlet. Naturally, the Pitot tube readings were considered only for the cases when no liquid water content was carried with the gas phase.

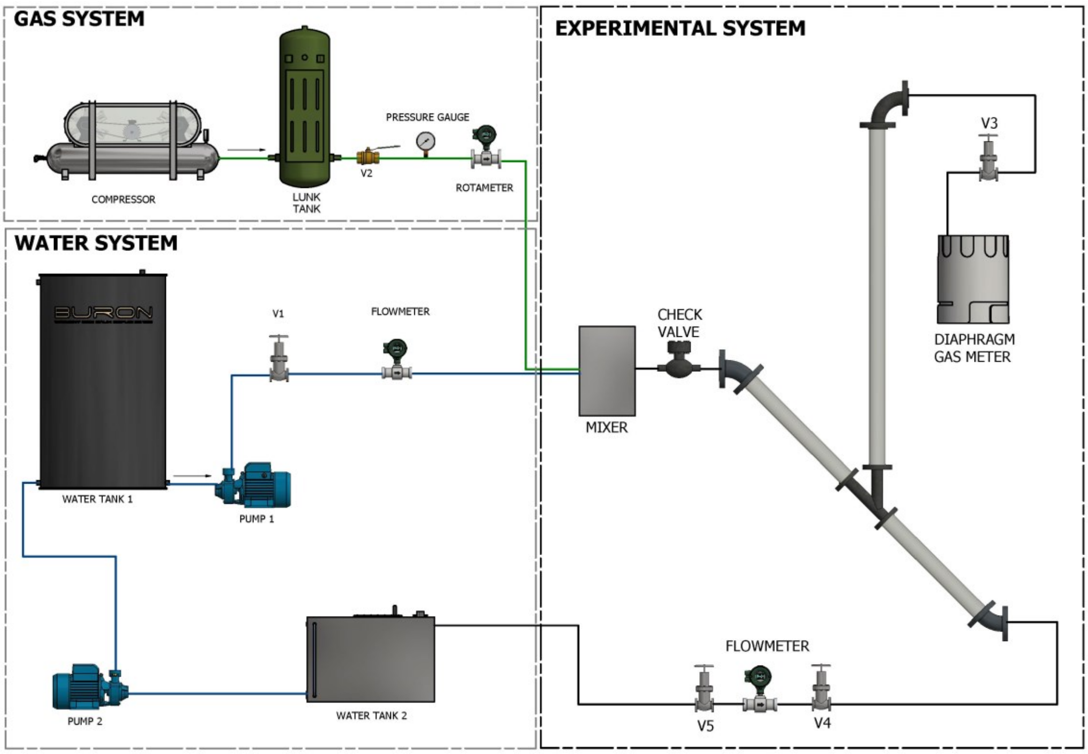

Figure 1. Overview of the experimental setup used for the T-junction experimental investigation.

2.2 Instrumentation

A Shadow Sizer System, from Dantec Dynamics, was used to quantify the bubble size distribution on the liquid outlet. This system is composed by the high speed camera SpeedSense M310, with resolution of 1024x1024 pixels and maximum frame rate of 5 kHz. The light source is provided by a Constellation led light, made by a matrix of 32 x 32 individual white leds. A diffusive paper should be positioned in front of the led array in order to provide a diffusive background illumination to the droplet particles. The software Dynamic Studio version 3.20 was used for image treatment and diameter calculation. Typically, image background subtraction was applied to increase contrast. Afterwards, a median filter is applied, followed by a binarization step. The Shadow Sizer processing is based on contour detection algorithm and then furnishes equivalent diameter, area and perimeter, as well as velocity vector for each measured droplet. This information can be used as a redundant measurement to the gas fraction calculated from the Coriolis data.

2.3 Experimental conditions

The objective of the present investigation is to understand the behavior of a two-phase flow mixture across a T-junction, in order to maximize gas-liquid separation. With that purpose, a range of inlet flow conditions was observed. More specifically, the measured liquid flow rates were varied between 5.0 to 6.5 m^3/h in steps of 0.5 m^3/h. For each liquid flow rate, the gas flow rate was varied in the range of 0.86 to 4.4 m^3/h. These flow rates gave origin to a stratified flow pattern on the inclined pipe. The specific experimental conditions investigated are listed in Table 1.

Table 1. Experimental conditions.

Experimental run	Q_{liq} inlet		Q_{gas} inlet		Q_{gas} inlet (corrected)	
1	5,00	m³/h	1,0	Nm³/h	0,86	m³/h
2	5,00	m³/h	2,0	Nm³/h	1,61	m³/h
3	5,00	m³/h	2,5	Nm³/h	2,19	m³/h
4	5,00	m³/h	3,8	Nm³/h	3,30	m³/h
5	5,50	m³/h	1,0	Nm³/h	0,87	m³/h
6	5,50	m³/h	2,0	Nm³/h	1,74	m³/h
7	5,50	m³/h	3,0	Nm³/h	2,59	m³/h
8	5,50	m³/h	5,0	Nm³/h	4,43	m³/h
9	6,00	m³/h	1,0	Nm³/h	0,86	m³/h
10	6,00	m³/h	1,6	Nm³/h	1,01	m³/h
11	6,00	m³/h	1,6	Nm³/h	1,01	m³/h
12	6,00	m³/h	3,2	Nm³/h	1,85	m³/h
13	6,00	m³/h	3,0	Nm³/h	2,62	m³/h
14	6,00	m³/h	4,0	Nm³/h	3,50	m³/h
15	6,50	m³/h	1,4	Nm³/h	0,85	m³/h
16	6,50	m³/h	1,4	Nm³/h	0,85	m³/h
17	6,50	m³/h	2,0	Nm³/h	1,70	m³/h
18	6,50	m³/h	2,0	Nm³/h	1,70	m³/h
19	6,50	m³/h	2,0	Nm³/h	1,69	m³/h
20	6,50	m³/h	2,0	Nm³/h	1,76	m³/h

All pressure transducers and flow meters used in the present work have been calibrated against reference instruments. In the present work, the rotameter has been calibrated through a comparison of its readings to the total volume measured by the diaphragm flowmeter.

3. RESULTS

For each experimental condition listed in Table 1, the measurement of gas and liquid volumes on the upper and lower exits of the T-junction has been made. Since a stratified flow was always observed at the inlet section, the range of experimental conditions investigated was very favourable to gas separation at the branch arm. This result can be seen in Figure 2, where the gas volume measured at the inlet of the inclined pipe is compared to the gas volume separated at the vertical branch arm. In this picture, the continuous line indicates a straight line that crosses the origin and has angular coefficient 1. This line physically represents the condition when all the gas at the inlet is separated at the branch arm. Fig. 2 shows that only a small percentage of the gas is carried with the liquid to the lower exit.

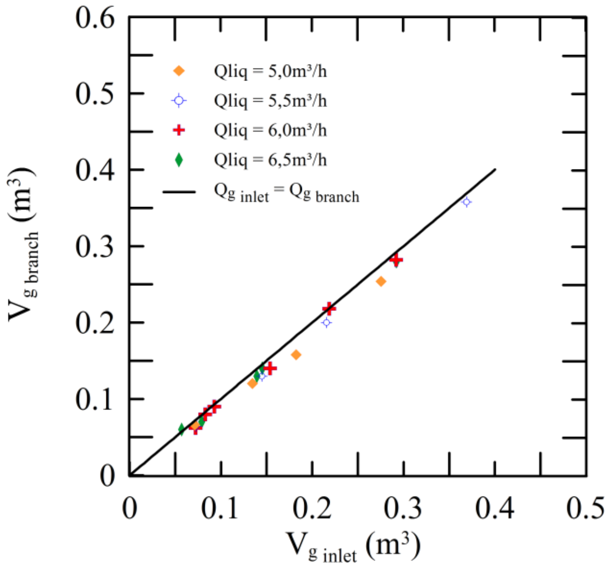

Figure 2. Comparison between the volume of gas that enters the T-juntion and the volume of gas that is separated at the branch vertical arm.

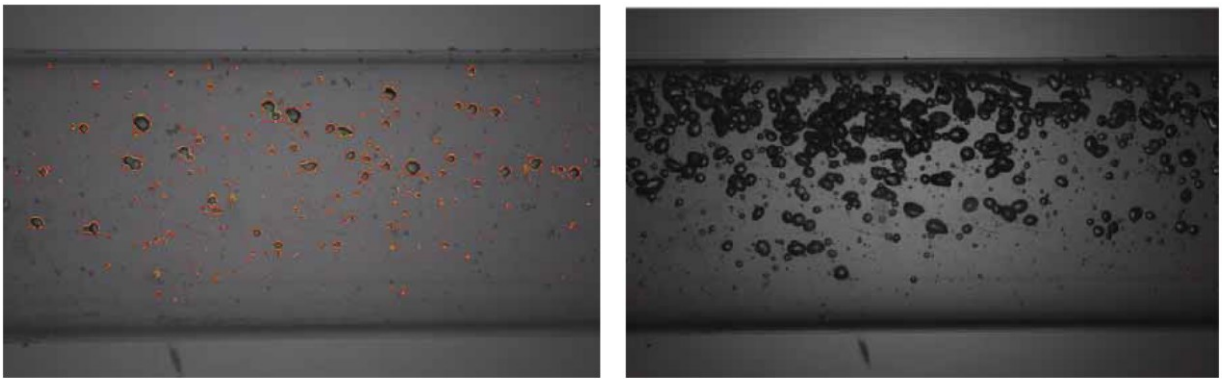

Figure 3. Shadow Sizer images measured for void fraction calculation at the lower liquid exit of the T-junction.

Figure 3 shows typical images obtained with the aid of a Shadow Sizer system at the liquid exit of the T-junction. It can be seen the small bubbles that are carried with the liquid phase.

During the experimental measurements, a liquid column filled the vertical branch arm. The flow patter on the vertical branch varied from dispersed bubbles to slug flow, depending on the inlet flow rates. As a consequence of the separation process, a lower density level indicated at the Coriolis flowmeter is intrinsically related to the passage of bubbles along the horizontal pipe that is considered the liquid outlet. Since the flow is highly intermittent, as reported by Baker et al. (2008), the gas is accumulated on the lower section of the T-junction until a huge bubble is formed on the downstream portion of the inclined pipe. This bubble eventually rised counter-current and escaped through the vertical branch, resulting in a higher value of density measured at the liquid outlet, since a smaller quantity of gas bubbles scape during the rise of the air bubble in the vertical branch.

This intermittent phenomenon has been observed for some given combinations of liquid and gas flow rates. Figure 4 shows this transient regime observed at the liquid outlet of the T-junction for two different liquid flow rates on the entrance of the T-junction. For Q_L = 6.0 m^3/h (Fig. 4a) it can be noticed that only one specific gas flow rate (Q_g = 1.85 m^3/h) induces an intermittent behaviour, quantified as the temporal variation of the density measurement on the liquid outlet pipe. A small increase of the liquid flow rate on the entrance of the T-junction, Q_L = 6.5 m^3/h (Fig. 4b), results in transient behavior for all the gas flow rate conditions investigated.

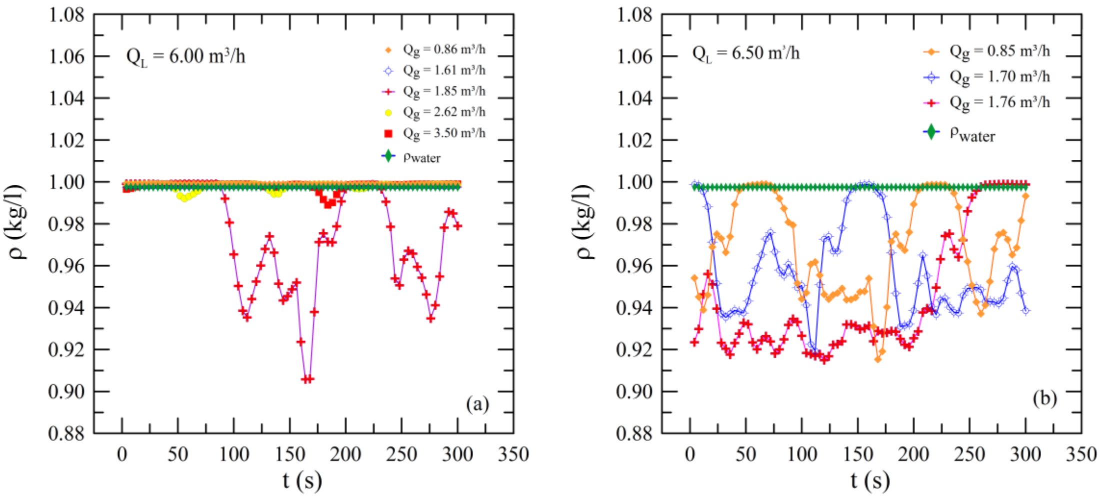

Figure 4. Temporal distribution of the density measured at the liquid outlet of the T-junction.

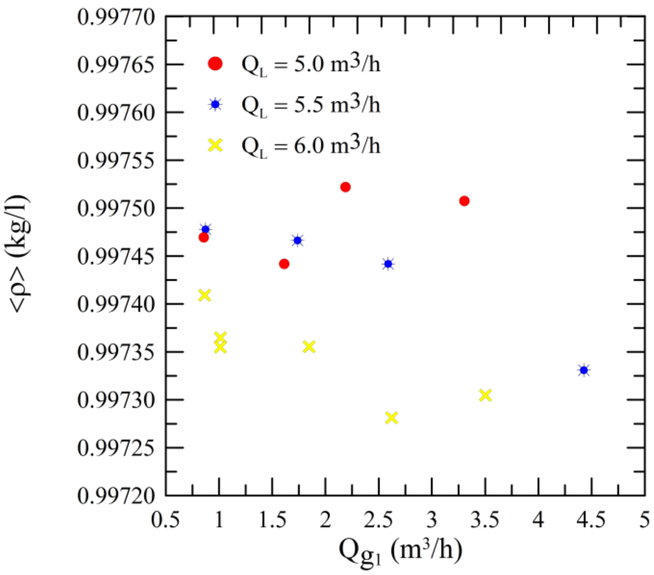

Figure 5. Mean value of the density measured at the liquid outlet of the T-junction for different liquid flow rates.

The mean value of the density measurements for different gas and liquid flow rates is shown in Figure 5. For the liquid flow rate of Q_L = 5.0 m^3/h, the range of gas flow rates investigated has not shown considerable influence on the gas carried to the liquid outlet. However, for the liquid flow rates of 5.5 m^3/h and 6.0 m^3/h, there is a clear effect of gas entrainment for higher gas flow rates.

4. FINAL REMARKS

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 pipe and is positioned in the vertical upward direction. After a thorough literature review no similar T-junction flow could be found. This investigation is dedicated to understand the separation mechanisms in order to maximize gas separation. A special flow loop was modified to allow the present study. Global measurements of flow rate, pressure drop and void fraction have been performed. The transient behavior of the flow loop was quantified by pressure and density measurements. This intermittent phenomenon is being further investigated through the aid of particle image velocimetry and high speed cameras.

5. ACKNOWLEDGEMENTS

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