Training period at the Microgravity Lab of the Technical university of Catalonia

On ground experiments with a T-shaped device for bubble injection for microgravity applications

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This report contains the description of the experimental work I have done during my training period from Jun 30th to August 31st 2008 in the Microgravity Laboratory at the Castelldefels School of Technology (EPSC) of the Technical University of Catalonia (UPC). My work consists of the on ground characterization of a gravity insensitive T-shaped device to generate bubbles for microgravity applications. The study focuses on the generation of air bubbles in water and on the different flow regimes which can take place. Results are obtained by means of the analysis of recorded movies corresponding to each regime of interest.

Keywords: Bubbles generation, Two-phase flow, Microgravity, Slug flow, Annular flow, Bubbly flow
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1. Introduction

1.1. Presentation of the Microgravity Lab

The Microgravity Lab is a small laboratory attached to the Technical University of Catalonia (UPC) located at Castelldefels, near Barcelona. Composed by a dozen of people, this research group focuses both on fundamental and technological aspects of microgravity research in the fields of materials science and fluid physics. The Microgravity Lab was created in 2005 and is currently moving to a new location in the same campus.

1.2. Objectives

The general aim of research in microgravity conditions is to determine the role played by gravity on physical processes and develop the design of space systems to be used as space hardware. The study presented here is included in this last case: design and characterization of a device to create bubbles. Indeed, in the last years, the use of two-phase flow in space applications has been developed. Phenomena taking place at the interface between both phases is very interesting for energy transfers management. Another interest of two-phase flows lies in their weight, lower than one-phase flows that are already used.

Many processes, particularly the bubble generation, show very different behavior than on ground if they are performed in a microgravity environment. A device to generate bubbles under microgravity conditions has been characterized at the Microgravity Lab. The work carried out during this training period consisted in the characterization of an alternative configuration of the bubble injector.
1.3. The microgravity environment

There are many platforms to obtain microgravity condition. They differ in the microgravity time, quality and in their cost. Figure 1 resums these different facilities:

![Figure 1 – The Available facilities to obtain microgravity](image)

The most used platforms are drop towers and parabolic flights because of their simplicity and low cost. However the duration of experimentation is very short (10s for the drop towers and 20s for the parabolic flights). Sounding rockets and experimentation on ISS are used where longer duration is needed, but their setup is more complicated and expensive.

In theory, our experiment is gravity insensitive; in practice this hypothesis has been verified in parabolic flights by the group at the Microgravity Lab for the first configuration (see §2.3 below). All the studies presented here on the second configuration have been done only on ground laboratory.
Figure 2 shows the different two-phase flow regimes that can be obtained in a cylindrical tube:

As it has been observed until now, our injector only allows the three possible microgravity regimes: bubbly, slug and annular flow (figure 2, b). We have never obtained the other usual flow regimes under normal gravity which validates the hypothesis of gravity insensitivity.

Among all the flows, the slug one is one of the most interesting because its regularity, easiness to quantify and good properties for thermal exchange.
1.4. Bubble generation

Many physical results obtained under normal gravity are no more valid under microgravity conditions. For example, generating bubble in space is completely different than on ground because of the absence of buoyancy.

To generate bubbles in microgravity, two configurations are commonly used: the co-flow and the cross-flow.

In the co-flow configuration (see Figure 3 left), liquid and gas flow in the same direction and bubbles are detached from the pipe by water flow force. The size and quantity of bubbles are controlled by the water flow rate.

In the cross-flow configuration, liquid and gas flow perpendicularly. The injector used in this work corresponds to the cross-flow type of configuration (see Figure 3 right). Figure 4 shows a picture of the injector:

In this work, we have used small enough capillary tubes in order to make the effect of gravity irrelevant in front of capillary and inertial forces. To verify it, we calculate the Bond number, which compares the effects of gravity and surface tension.

\[ Bo = \frac{\rho gr^2}{\sigma} \]

*Where \( \rho \) is density, \( r \) is the radius of the bubble, \( g \) the gravity and \( \sigma \) a surface tension.*
The value of the Bond number in our experiments is 0.13, small enough to consider them gravity independent.

2. The experimental system

2.1. Previous results

The researchers at the Microgravity Lab have already worked on the characterization of the configuration shown in Figure 5 (configuration A). In this configuration, water is injected in the same axis as the mixture and air flow is perpendicularly. All pictures presented here are extracted from a paper in preparation [2].

![Figure 5 - Configuration A](image)

Several liquid (Ql) and gas flow rate (Qg) to obtain the different regimes. Bubble frequency was measured for all flow rates in slug-flow (the only regime where bubble frequency makes sense). For fixed liquid flow rates the air flow rate was changed from 1 to 100ml/min (with a precision of 0.5ml/min). Figure 6 shows the bubble frequency at different Qg.

![Figure 6 - Bubble frequency vs. air volumetric flow rate Qg for different liquid volumetric flow rates Ql. Symbols experimental results, lines fit](image)
Two regimes were identified: a linear regime for low air flow rate and a saturated regime. The saturation frequency $f_{sat}$, the crossover $x_0$ and the initial slope $a$, have been identified as characteristic parameters of these regimes.

The experimental data were fitted to (see Figure 6):

$$f(Q_g) = f_{sat} - a \log \left(1 + e^{-\left(Q_g - x_0\right)}\right)$$

With $f_{sat} = a x_0$

The fitting of the experimental data of $f_{sat}(Q_l)$ shows the saturation frequency:

$$f_{sat}(Q_l) = 15.27 Q_l - 14.37$$

Figure 7 shows both experimental data, fitting and theoretical prediction of $f_{sat}(Q_l)$.

*Figure 7 - Saturation frequency vs. liquid volumetric flow rate. Symbols experimental results, line linear fit, dot line theoretical prediction of $f_{sat}$*
The crossover point between the linear and saturation regimes is shown in Figure 8 as a function of $Q_l$:

![Figure 8 - Crossover vs. liquid volumetric flow rate. Symbols experimental results, line fit](image)

Experimental data are fitted with the following function:

$$x_0(Q_l) = d \left( b + \frac{Q_l - b}{e^{c(Q_l - b)}} \right)$$  \hspace{1cm} (3)

$$d = 3.25024, \ b = 0.513015, \ c = 0.122011$$

The initial slope can be obtained from:

$$a(Q_l) = \frac{f_{sat}(Q_l)}{x_0(Q_l)}$$  \hspace{1cm} (4)

The behavior of $a(Q_l)$ is shown in Figure 9. It can be observed a linear asymptotic tendency given by:

$$a(Q_l) = 9.25 Q_l - 8.7$$  \hspace{1cm} (5)
The work performed during this training period consisted of the determination of the parameters studied before in an injector configuration in which bubble flow in the same direction as gas is injected and water flows perpendicularly (configuration B).

### 2.2. Experimental setup

The aim of this study is to invert air and water inlets and compare the results to the no inverted injection configuration. Figure 10 shows the configuration B used here:

![Figure 10 – Configuration B](image)

Figure 11 shows the experimental setup used. It consist of a test section, a data acquisition system and the air and water supply systems.
In the water supply system, demineralised water is pumped by an *Ismatec MCP-Z* Standard pump (Figure 12 left). The flow rate is controlled directly by the interface on the pump with a precision of 0.01ml/min. At the beginning of the experiments, the pump has been calibrated using a liquid flow meter (Figure 12 right), (the supplier advises one calibration every two months).
In the air supply system, air flow is provided by a bottle (Figure 13 left) containing five liters of air at 200 bar. This brings a constant flow of synthetic air without vibration. Pressure is controlled by a computer interface (with the software flow DDE) using an air flow meter to read the gas flow rate with a precision of 0.1ml/min (Figure 13 center and right).

Water and air are driven to the injector where bubbles are created. The mixture is collected in a tank, in order to use water again.

The data acquisition system consists of a Redlake MotionXtra HG-SE high velocity camera (Figure 14 left). The parameters used are:
- Resolution: 128*640
- Frame per second: 4000fps
- Shutter time: 90µs
- Pre-trigger time: 0s

The required illumination is given by a grid of 126 LEDs with a plastic diffuser to have an homogene luminosity (Figure 14 right).
Electrical power is provided by two 30V stabilized alimentations.

*Figure 15* shows a picture of the experimental setup used in the lab:

![Figure 15 – Experimental setup](image)

### 2.3. Image treatment

The software *Image Pro Plus 5.1* © was used for the image treatment. This consists of several steps:

1. **Subtraction of the background from the video:**

![Figure 16 – Subtraction of the background from the video.](image)

*Top, original video, bottom, background, right, operation window*
We obtain a video containing only the bubbles:

2. Conversion into grey scale to have only one color dimension:

3. Equalization to increase the contrast:

4. Filtering with the background to mask the center of the bubbles to erase the white part in the centers of the bubbles:
5. Segmentation to convert the image in binary:

*Figure 21 – Video after segmentation*

6. Counting of the number of bubbles passing across the red line:

*Figure 22 – Counting the bubbles*
The only difficulty lays in the segmentation step, which needs a manual setting and a human evaluation.

A compromise has to be made. With a high tolerance for the segmentation (3rd image), smaller bubbles can be detected than with a lower tolerance (2nd image), but bubbles are not separated. They are counted only as one bubble for a high tolerance, and in the other case small bubbles are ignored. In both cases, the final result underestimates the real number of bubbles.
3. Results

3.1. Flow regimes

*Figure 24* shows the flows obtained in both configurations at the same $Q_l$ and $Q_g$.

**Configuration A:**

*Bubbles parallel to water injection*

- $Q_l=10.00\text{ml/min}, Q_g=44\text{ml/min}$
- $Q_l=25.00\text{ml/min}, Q_g=44\text{ml/min}$
- $Q_l=50.00\text{ml/min}, Q_g=44\text{ml/min}$
- $Q_l=70.00\text{ml/min}, Q_g=44\text{ml/min}$

**Configuration B:**

*Bubbles parallel to gas injection*

- $Q_l=10.00\text{ml/min}, Q_g=44\text{ml/min}$
- $Q_l=25.00\text{ml/min}, Q_g=44\text{ml/min}$
- $Q_l=50.00\text{ml/min}, Q_g=44\text{ml/min}$
- $Q_l=70.00\text{ml/min}, Q_g=44\text{ml/min}$

*Figure 24 – Comparison between the two configurations*

As we can see on *figure 24*, only the slug flow occurs in the configuration A. In configuration B, we observed a slug flow only for low liquid flow rates. For water flow rates larger than 25ml/min, an irregular transitory flow between slug and bubbly was obtained. A flow regime map for configuration B is presented in *Figure 25.*
Considering that bubbles have very different sizes and their separation varies considerably, the notion of bubble frequency previously used does not have any meaning for several cases of configuration B. Consequently the study has been restricted to water flow rates equal or lower than 25ml/min in order to be able to consider the bubble generation frequency.
3.2. Bubble generation frequency

Bubble generation frequency has been studied for different values of $Q_l$ and $Q_g$. Figure 26 shows the dependence of the bubble frequency measured at the T-junction of the injector with $Q_g$. It can be observed a linear and a saturation regime as in configuration A.

![Figure 26 – Bubble frequency vs. air volumetric flow rate $Q_g$ for different liquid volumetric flow rates $Q_l$ near the T-junction. Symbols experimental results, lines fit](image)

Experimental data in Figure 26 where fitted to $f(Q_g) = f_{\text{sat}} - a \log \left(1 + e^{-\left(Q_g - x_0\right)}\right)$. It can be observed that the bubble frequency is generally larger than in configuration A. What does not appear in these graphics, is the irregularity of the bubble scrolling shown in Figure 24. Bubble frequency has also been measured at approximately 30 diameters far from the T-junction. Results are shown in Figure 27, in which the same fitting as in Figure 26 is also represented.
Fitting of data are less accurate than in the position close to the T-junction. One would expect than some coalescence phenomena could have taken place between both positions, which would give rise to a lower frequency far from the T-junction. However this is not the case, as can be observed in Figure 28 in which the frequency for both positions is represented at a fixed Ql=15 ml/min.
The unexpected behavior could be explained by the fact that measurement at both positions were carried out at different setup runs because only one camera was available. The experimental conditions were probably different enough at each moment to produce the observed behavior.
In order to compare configuration B with the behavior of the injector in configuration A, we study $f_{sat}$, $x_0$ and $a$ for different $Q_I$. We took data of configuration B close to the T-junction.

**Figure 29** - Saturation frequency vs. liquid volumetric flow rate. Symbols experimental results, line linear fit

Figure 29 shows the behavior of $f_{sat}(Q_I)$ with the corresponding fitting curve: $f_{sat}(Q_I) = 74.64 Q_I - 12.3$. The slope in $f_{sat}(Q_I)$ is significantly large for configuration B.

The crossover point between linear and saturation regimes for configuration B as a function of $Q_I$ is shown in Figure 30.
It can be observed a similar behavior as for configuration A (Figure 8) with two differences. The maximum value of $x_0$ is larger in configuration B, and for the value of $Q_l$ considered, almost no information about the decreasing of $x_0$ can be derived.

The initial slope is represented in Figure 32.
In general it can be concluded that the characteristic parameters have only similar behavior for both configurations. The parameter values are quite different and the fitting curves do not coincide at all.

The difference between both configurations could be explained reasoning in terms of the kinetic energy. When air is injected perpendicular to the bubbles direction, there is only a small kinetic energy to be dispersed because air is very light. When water is injected perpendicular to the bubbles direction, the energy to disperse is higher, and may generate turbulence in the output tube, which could explain the irregularities observed.
3.3. Bubble bridge

The second part of the configuration B characterization consisted in an initial study on how bubbles are formed in the T-junction. Therefore we call bubble bridge to the connection between a bubble already created and the following one. We expect that a good understanding of how this formation process takes place may allow to predetermine the type of flow which is generated. However in this study it is only presented results on the slug flow.

*Figure 32* shows the bubble bridge at increasing values of QI.

![Figure 32 - Bubble bridge for increasing values of QI (smaller at the bottom)](image)

A first clear observation is that the height of the bridge increases up to the diameter value and later decreases when increasing QI.
We took the surface below the bubble bridge as the characteristic parameter of it.

In order to determine the surface, we consider the following parameters, which are indicated in Figure 33 and 34.

- **Xt** is the abscise of the higher point of the bubble bridge from the beginning of the junction
- **X** is the half of the length of the bubble bridge to the lower part of the bubble
- **Y** is the height of the bubble bridge from the back side of the tube

We define two surfaces associated to the bubble bridge: \( S = X \cdot Y \) and \( S_t = X_t \cdot Y \). We expect that \( S \) and/or \( S_t \) can show a different behavior for values of \( Q_g \) and \( Q_l \) close to the bubbly regime.
Figure 35 shows the behavior of the defined parameters as functions of $Q_g$ and $Q_l$.

**Plot in function of the gas flow rate $Q_g$**

![Graph showing $X(Q_g)$, $Y(Q_g)$, and $X_t(Q_g)$ as functions of $Q_g$.]

**Plot in function of the water flow rate $Q_l$**

![Graph showing $X(Q_l)$, $Y(Q_l)$, and $X_t(Q_l)$ as functions of $Q_l$.]

Figure 35 – $X$, $Y$ and $X_t$ for different $Q_g$ and $Q_l$
The larger values of \( Q_l \) correspond to a regime close to bubbly flow. It can be observed that for this values, the parameters \( Y \) and \( X_t \) tend to remain constant. This has an effect on \( S_t \) which also keeps constant for \( Q_l \geq 20 \text{ml/min} \) (see Figure 36). Therefore we could conclude that \( S_t \) may be an appropriate parameter to identify the flow regime. However this should be confirmed with further measurements in the bubbly flow regime.

**Figure 36 – \( S \) and \( S_t \) for different \( Q_g \) and \( Q_l \)**
4. Conclusions

4.1. Scientific conclusion

The use of the configuration B is interesting because it generates higher bubble frequencies than the configuration A for the same flow rates. This means, better conditions for thermal exchanges. However, configuration B creates very irregular flows which are difficult to control.

We have performed a characterization of a bubble injector in an alternative configuration to the one used to now. The types of working regimes obtained are independent of the configuration, although the behavior of the parameters characterizing may differ. We have also proposed a new geometrical parameter, St, to predict the flow regime.

4.2. Conclusion about the training period

This training period was a first step in the world of research. It was very interesting for my orientation project, especially as I want to make a thesis. I have liked the atmosphere, the few constraints, the autonomy, and the field of research. But I was a bit baffled because I have to observe phenomena that I had never studied before (bubble and two-phase flow), so I sometimes lost the aim of my experiments and I couldn’t be critic on my results. Also, I was left unsatisfied of scientific explanations of the phenomena. Moreover, for me, the work is too abstract, too far from the application, so I wonder if I am fated to “pure research”. But as I know I don’t want to work in the industry, I think intermediate institute like the CNES or ONERA could be the ideal destination. I don’t know yet if I prefer experimentation or numerical science. Experimentation is fun, applied, but sometime boring when we spend lot of time in treatment or repetitive tasks far away from science. I have never tried numerical simulation, it will be for my next training period.
Bibliography

