REPORT

Bubble and droplet injection for microgravity applications

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I would like to thank the team who works in this microgravity laboratory. Ricard González-Cinca, my supervisor, who has helped me to understand the behaviour of two-phase flows and who has guided me during my training period.

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Abstract

Previous studies carried out in the Microgravity laboratory at the Castedelldefels School of Technology (EPSC) allowed to characterize the behaviour of bubbles during their generation in a T-junction and previous to injection in a cavity. However, researches have only studied a configuration of the injection, in which the gas is in the top of the injector and the liquid in the horizontal (main flow). Furthermore, even if numerous studies consider the generation and dispersion of bubbles, few notify the behaviour of droplets. Thus we will study the behaviour of both bubbles and droplets formed at a T-junction in a new configuration and how they are injected to a cavity.

My work has consisted on analyzing the dynamics of bubbles and droplets during my training period in the Microgravity Laboratory at the EPSC which is a Higher Education School of the Polytechnical University of Catalonia (UPC). In order to study how bubbles and droplets are generated, we focus on their detachment at the T-junction, their shape, their size and their frequency. Regarding the injection of droplet in a cavity, the objective is to determine the best configuration to created jet and to establish optimal parameters. A T-junction with capillaries of one millimeter in diameter in which we injected both fluids was used to reproduce microgravity conditions. A camera with high resolution recorded movies which were analysed with the corresponding software.

Conclusions enable to characterize bubbles and droplets behaviour from their generation to the injection in a cavity. The way of bubble detachment in the T-junction characterizes its behaviour in the pipe and during the injection in a cavity. We have defined the best configuration to obtain a regular jet. With this configuration, we know optimal values to regulate the distance where droplets are detached from the jet during their injection.
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1. Introduction
Introduction

1.1/ Fluid dynamics

In order to study two-phase fluids in microgravity we should understand concepts and notions of fluid dynamics.

- **1.1.1 Compressible and incompressible fluid**

  Fluids are compressible if changes in pressure or temperature will result in changes in density. However, in many situations the changes in pressure and temperature are sufficiently small that the changes in density are negligible [1]. In this case the flow can be modeled as an incompressible flow.

  A fluid is considered compressible if the Mach number is larger than 0.3. The compressibility factor establishes the relation between volume and pressure:

  \[
  \chi \equiv -\frac{1}{V} \frac{dV}{dP}
  \]

  Where \( \chi \) is the compressibility factor, \( V \) is the volume and \( P \) the pressure in Pa\(^{-1}\).

- **1.1.2 Newtonian flow**

  Sir Isaac Newton showed how stress and the rate of strain are related for many common fluids, such as water and air. The so-called Newtonian fluids are described by a coefficient called viscosity, which depends on the specific fluid. Newtonian fluid behavior is described in:

  \[
  \tau = \mu \frac{du}{dx}
  \]

  Where \( \tau \) is the shear stress exerted by the fluid in Pa, \( \mu \) is the fluid viscosity in Pa.s, \( du/dx \) is the velocity gradient in s\(^{-1}\).

- **1.1.3 Viscosity**

  Viscosity describes fluids resistance to flow and may be thought as a measure of fluid friction. In viscous problems fluid friction has significant effects on the fluid
Introduction

motion. Real fluids are fluids which have a resistance to shear stress. Fluids which do not have any resistance are called ideal fluid.

Viscosity is divided in two types: dynamic (or absolute) and kinematic viscosity. Dynamic viscosity is the ratio between the pressure exerted on the surface of a fluid and the velocity gradient. The SI physical unit of dynamic viscosity is Pa.s. In many situations, we are concerned with the ratio of the viscous force to the inertial force, the latter characterized by the fluid density \( \rho \). This ratio is characterized by the kinematic viscosity, defined as follows:

\[
\nu = \frac{\mu}{\rho}.
\]

Where \( \nu \) is the kinematic viscosity in m\(^2\)/s, \( \rho \) is the density and \( \mu \) is the dynamic (or absolute) viscosity.

- 1.1.4 Laminar and turbulent flow

Turbulent flow is dominated by recirculation and apparent randomness. If the streamlines for a flow do not change with time, so that the flow is in a steady state, we say that the flow is laminar. The Reynolds number can be used to evaluate if the flow is laminar or turbulent. Flows with a high viscosity are normally laminar and Reynolds is low.

- 1.1.5 Dimensionless numbers

1.1.5.1 Reynolds number

The Reynolds number [1] is a measure of the ratio of inertial to viscous forces and quantifies the importance of these two types of forces for given flow conditions. It is the most important dimensionless number in fluid dynamics and it is commonly used to provide a criterion for determining dynamic similitude. Reynolds number is defined as follows:

\[
Re = \frac{VL}{\nu}.
\]
Introduction

Where $V$ is the velocity in $\text{ms}^{-1}$, $L$ is the characteristic length in m, $\nu$ is the kinematic fluid viscosity in $\text{m}^2\text{s}^{-1}$.

- **Re < 2000**: For weak values of Reynolds, viscosity is the dominating factor. This laminar regime is reversible and it is called Stokes flow.
- **2000 < Re < 3000**: In the intermediate values of the Reynolds, inertia is dominating, but the flow remains laminar. However the flow is not reversible.
- **Re > 3000**: For large values of Reynolds, the drainage becomes turbulent. Between the laminar and turbulent regimes, we speak about transitory regime.

### 1.1.5.2 Weber number

The Weber number is used to analyze fluid flows where there is an interface between two different fluids, especially for multiphase flows with strongly curved surfaces. It can be thought of as a measure of the relative importance of the fluid inertia compared to its surface tension. Weber number is useful in analyzing thin film flows and the formation of droplets and bubbles[2].

$$We = \frac{\rho \nu^2 L}{\gamma}$$

Where $\gamma$ is the surface tension.

### 1.1.5.3 Bond number:

The Bond number $Bo$ is a dimensionless number expressing the ratio of body forces (often gravitational) to surface tension forces:

$$Bo = \frac{\rho a L^2}{\gamma}$$

Where $a$ the acceleration associated with the body force, $L$ the length of a capillary tube, $\gamma$ is the surface tension of the interface.
Introduction

1.2/ Two-phase flows

• 1.2.1 Two-phase flows on ground

The gas-liquid flow patterns depend on the mass flow rate of phases, the capillary size, the phase properties, and the gravity vector. Considerable efforts have been made to study the flow patterns and their transitions under normal and microgravity conditions. We can distinguish four flow patterns in gravity conditions[3].

_The bubble flow_, in the figure I.1, in which the gas-phase is distributed as discrete bubbles in an axially continuous liquid-phase. The gas bubble tends to flow near the top of the tube, but as the liquid flow rates increases, the bubbles are dispersed.

![Fig I.1: Bubble flow](image)

_The intermittent flow_, in which the small gas bubbles have coalesced to produce large gas bubbles. The intermittent pattern, showed in the figure I.2, is sometimes divided into slug and elongated bubbles patterns.

![Fig I.2: Intermittent Flow](image)

_In the stratified flow_ (figure I.3) liquid flows are in the bottom section and the gas flow near the top of the pipe. Both phases are continuous in the axial direction. The interface may be smooth or wavy.

![Fig I.3: Stratified flow](image)
Introduction

In the annular flow a part of liquid are in the perimeter, the other part is in the center of the tube with small drops, as we can see in the figure I.4.

Fig I.4 : Annular flow

• 1.2.2 Two-phase flows in microgravity

Basically four flow patterns are observed to exist under microgravity (Fig I.5) conditions. The flow patterns can be categorized as follows [4]:

Bubble flow, in which the gas bubble, distributed in a liquid continuum, are of a size less than or equal to the tube diameter.

Slug flow, in which the length of the gas bubble is greater than the tube diameter. The liquid slugs that separate the large bubble can contain small gas bubble.

Transitional or frothy slug-annular flow, in which case the liquid is flowing in the form of a film at the tube wall. The gas phase is in the center and frothy slugs can appear.

In Annular flow the gas-phase is at the center of the tube.

Fig I.5 Microgravity two-phases flow regime
Introduction

The way to generate bubbles in microgravity is not the same than on ground. In microgravity, gas and liquid can be assembled in two different configurations: coflow and crossflow.

Coflow

Liquid flow is in the perimeter and gas flow is in the middle. Both flows are in the same direction, as we can see in Figure I.6. The force generated by the water detaches bubbles from the pipe. The size of bubbles and the separation between gas and liquid are controlled by the water velocity.

Crossflow

In this configuration the liquid flow is perpendicular to the gas flow (Figure I.7). The gas flow is inside a tube and the two flows are mixed in a cavity. This configuration is better than coflow to control bubble size.

Bubgen

This configuration is a particular case of crossflow (see Figure I.8). In Bubgen both flows are injected in perpendicular capillaries and meet at their junction [5]. With a small diameter of the pipe (around 1 or 1.5 mm), the behaviour of the two-phase flow is
Introduction

the same in gravity and in microgravity. So we can test the T-junction in the laboratory and foresee the behaviour of the system. Moreover, this configuration is better to controlled size and frequency of bubble.

![Diagram of T-junction](Image)

Fig I.8 Bubgen

1.3/The microgravity environment

- **1.3.1 What is microgravity**

  Gravity is a force that governs motion throughout the Universe. It holds us to the ground, keeps the Moon in orbit around the Earth, and the Earth in orbit around the Sun. The nature of gravity was first described more than 300 years ago. Gravity is the attraction between two masses. Bigger the mass, most apparent the attraction is. The acceleration of an object caused only by gravity, near the surface of the Earth, is called normal gravity, or 1g.

  The condition of microgravity comes about whenever an object is in "free fall": that is, it falls faster and faster, accelerating with exactly the acceleration due to gravity (1g). Objects in a state of free-fall or orbit are said to be "weightless."

- **1.3.2 Fall in parabolic flight**

  1.3.2.1 Planes:
Introduction

The European Space Agency (ESA) is currently running 2 to 3 professional parabolic flight campaigns every year, in addition to an annual student flight campaign. These are performed with a modified Airbus A300, as we can see it in Figure I.9, operating from Bordeaux Airport. Each flight consists of 30 parabolas of approximately 22 seconds of weightlessness[6]. NASA’s Johnson Space Center, operates a C-9 Low-G Flight Research aircraft also known as the "Vomit Comet." Its predecessor used to create weightless to, was a KC-135 aircraft. Russia is performing similar flights from an airport near Moscow. The primary factor that limits the duration of the microgravity period is the maximum speed dictated by turbulence at the wings together with the maximum tolerable forces exerted on the wings of the aircraft during the 1.8g injection and pull out phases. Fall in parabolic flight with planes is composed on four phases, represented in Figure I.10.

Fig I.9: Airbus A 300

Fig I.10: Phases of a parabola
The horizontal flight: The aircraft starts with a normal horizontal flight at 1800 ft (6000 meters) at around 800 km/h.

The pull-up phase: The aircraft takes a 1.8 g load factor, nosing up to 45°, which lets the aircraft climb to 23 000 ft during about twenty seconds. The velocity is reducing at around 650 km/h. This is the entry pull-up phase.

The free-fall: The engine thrust is considerably reduced. This transitory phase of "injection" separating the 1.8 g pull-up from the zero g parabolas lasts fewer than five seconds. The aircraft is then in microgravity phase for around twenty-five seconds.

The pull-out phase: A symmetrical 1.8g pullout phase is then executed on the down side of the parabola to bring the aircraft back to its steady horizontal flight in about 20 seconds.

1.3.2.2 Sounding Rocket:

Small sounding rockets have also been used to create weightlessness periods of 5 to 15 minutes. Sounding rockets are advantageous for some research due to their low cost, the quality of the flight and their ability to conduct research in areas inaccessible to either balloons or satellites. For instance the microgravity level of a parabolic flight heavily depends on the skills of the pilots, while the quality on board the ISS depends on astronaut activities, and mechanical noise from engines and fans.

Rockets are commonly used to take data or carry instruments from 50 to 1,500 kilometers above the surface of the Earth, the altitude generally between weather balloons and satellites. Several agencies develop sounding rockets for research.

a) The Swedish Space Corporation:

REXUS is an annual research programme for Rocket Experiments for University Students. Rockets are launched from the Esrange Space Center, as we can see in Figure I.11.
Introduction

The TEXUS project is a sounding rocket program for professionals with the primary aim to investigate the properties and behaviour of materials, chemicals and biological substances in a microgravity environment. The TEXUS programme started in 1980 and it gives around six minutes of microgravity.

b) NASA

The Sounding Rocket Program Office (SRPO), provides suborbital launch vehicles, payload development, and field operations support to NASA and other government agencies. SRPO works to provide launch opportunities facilitating a broad spectrum of science applications[7]. It conducts approximately 20 flights annually from launch sites around the world. Operations are conducted from fixed sites in Virginia, Alaska, New Mexico, Norway and Sweden or from mobile sites. We can see this rocket in Figure I.12.

![Rocket of SSC](image1)
![Rocket of SRPO](image2)

1.3.3 Simple free-fall: Drop tower

Microgravity experiments can also be carried out in drop towers.

1.3.3.1 Composition

A drop tower has a unit of deceleration, represented in Figure I.13, to stop the fall of the capsule. The experiment is isolated from aerodynamic drag because it is not attached to the drag shield. The experiment itself falls seven and one half inches (19 cm) within the drag shield while the entire package is falling [8]. The drop ends when
**Introduction**

the drag shield and experiment are stopped by an airbag, located at the bottom of the tower.

![Diagram of Upper end and Deceleration unit](image)

There are five drop towers in the world (Bremen, Madrid, Cleveland, Tokyo City, Beijing) which have different capacity, height, and times of microgravity. The quality of the microgravity is similar between these drop towers.

1.3.3.2 Bremen Drop Tower

The Bremen Drop Tower, see in Figure I.14, is a large facility, exclusive in Europe. The installation delivers 4.74 seconds of near weightlessness up to three times a day. In order to double the microgravity time to 9.3 seconds, a catapult system has been implemented into the drop tower. With the drop tower catapult, the capsule is thrown upwards instead of being dropped.
The microgravity laboratory system is a cylindrical capsule with a diameter of 800 mm and a length between 1.6 and 2.4 meter depending on the space required for experimental studies. The capsule is closed pressure tight with an aluminium cover after the integration of the experiment. The drop capsule is pulled up by a winch to a height of 120 meters.

Drop towers have some advantages compared to parabolic flight. Experiments can be carried out at a lower cost and quality of microgravity is better.

1.3.4 Foton capsule

The first Foton capsule (see Figure I.15) was launched in 1985 providing researchers with gravity levels are less than 10⁻⁵ g. Foton capsule provides between 12 and 18 days of weightlessness. It reduces safety constraints for the experiments with respect to manned space missions. However, access facility is limited because the payload usually flies approximately 2 years after experiments approval. The main Foton capsule has build by ESA, we can see its plan in Figure I.16. Since the first launch, fifteen Foton capsules have been built.
Introduction

Foton provides ideal conditions for scientists requiring excellent and unperturbed microgravity conditions. The Foton environment gives users the opportunity to test their hardware under longer microgravity conditions, so that any necessary modifications can be made to future experiments. Foton is around 6.2 meter long with a weight of 6.500 kilograms. It can sustain 650 kilograms of equipment. Foton capsules are made up of three modules: the service module, the battery module and the re-entry module, the latter module being the only one retrieved after landing.

- **1.3.5 International Space Station (ISS)**

  The on-orbit assembly of ISS, shows in Figure I.17, began in 1998. The space station is at an altitude of approximately 350 km (217 mi) above the surface of the Earth, and travels at an average speed of 27,700 km (17,210 statute miles) per hour. It turns around the Earth in 90 minutes. The ISS is a joint project among the space agencies of the NASA, Russia (RKA), Japan (JAXA), Canada (CSA) and eleven European countries (ESA). The ISS provides a continuous microgravity environment.

Fig I.17: International Space Station
2. Objectives
Objectives

2.1/ Bubbles and droplet generation

• 2.1.1 Characterization of a minibubble injector

A previous experience carried out in the laboratory has been able to characterize a new injector of minibubbles based on the Bubgen configuration. The small diameter of the capillaries (1 mm) makes the performance of the injector independent of the gravity level. With this new injector small gas bubbles were formed with a liquid cross-flow, generating a slug flow.

For a given water flowrate, different gas flowrates are used. The purpose is to have the higher number and the smallest and round bubbles in order to maximize the area between both phases. Two working regimes are distinguished, as we can see in the figure II.1, and an optimal performance can be determined. At the beginning, a linear regime can be obtained in which the frequency of bubbles increases. Then the frequency of bubbles becomes constant and the size of the bubbles increases. We are then in the saturation regime and bubbles become oval.

![Figure II.1: Influence of gas and liquid flow rates on the frequency](image-url)
Objectives

- **2.1.2 Injection configurations**

We have called Configuration A, the configuration used in last experiment. For the configuration A (see in Figure II.2), injection of gas was realized by the height of the injector whereas the injection of liquid was horizontal. The new configuration: B (Figure II.3) is the inverted injection, liquid was injected by the height of the injector and the gas was injected in the horizontal tube. The optimal parameters can be determined according the use. We could determine the ideal injection configuration for every kind of application.

In the case of the inverted injection, we will study the frequency and the size of bubbles obtained and results will be compared with the results of the first injection. We use the same injector in order to compare the results.

![Fig II.2: Configuration A: Injection of the previous experiments](image)

![Fig II.3: Configuration B: New type of injection:](image)

For given $Q_g$ and $Q_L$, we expect to find a different behaviour in the inverse injection compared to what was obtained in the previous works (Fig II.4), in which bubbles of different sizes forming an slug flow were obtained when liquid and gas flowrates were changed.
Objectives

With the new configuration, other types of flows other than slug flow are expected (for example: bubbly flow – see Fig II.5).

2.2/ Injection in a cavity

- **2.2.1 Dispersion of bubbles**

A previous experiment was carried out to study the dispersion of bubbles inside a cavity full of water [5]. When the experiment is performed on ground, buoyancy brings bubbles to the surface and it allows bubbles to be far from each other. In microgravity, bubbles are located in a reduced zone closed to the output of the injection.
Objectives

- **2.2.2 Study of the jet**

Droplet injection is an issue of relevant importance for combustion processes in microgravity [9]. Another objective of this project is the study on ground of the droplet injection into a cavity. We will compare how droplets formed in both configurations are injected. The types of jets obtained will be compared with the type of flow in the capillary. Regularity of the jet or existence of satellite droplets are issues to be considered.
3. Experimental setup
Experimental setup

3.1/ Setup

The experimental setup is composed of the test cell (the injector) and the subsystems for air and water supply and for image acquisition and processing (see Figure III.1).

![Fig III.1 Experimental setup](image-url)

3.2/ Air supply system

- **3.2.1 Air Bottle and manometer**

  The supply pressure required by the majority of applications is considerably lower than the available pressure in a bottle. To reduce and regulate the pressure of the gas to the required value, a regulator is used as primary control system. The air liquid bottle contains gas around 200 atm and we can obtain an outlet pressure around 1.5 bar. The pressure indicator has graduation every 0.2 bars but this indicator is not enough and we need to use a regulator.

  In order to use the air bottle we must close the vacuum gauge of the manometer before opening the bottle gauge around 150-200 bar. Next, we can open the vacuum gauge and choose the pressure we need. To stop injection of gas, we must close bottle gauge and expulse air of the manometer. When the pressure in manometer is 0 bars, we can close its gauge.
Experimental setup

- **3.2.2 Air mass regulator**

  Pressure provided to the tubes is fixed by the manometer. But this is not the pressure that arrives into the T-junction. Pressure inside T-junction depends on the rate of filling of the reservoir and the length of pipe. A regulator system is used to regulate the pressure in the circuit and to keep it constant.

  This regulator system is composed of a pressure controller, a gas flow meter and software. The software used - FlowDDE - is composed of two interfaces to connect the pressure controller and the gas flow meter, an screen to choose the desired gas flowrate, and a plot to see the actual values. Gas flow meter allows only to know the air flow rate, but it can not regulate the flow.

- **3.3/ Liquid supply system**

  - **3.3.1 Water tank**

    Distilled water is employed to protect the pump from undesired particules. The tube connecting the reservoir to the pump must be immersed in the tank to avoid air passing into the pump.

  - **3.3.2 Pump**

    In order to keep a constant flow of water between the tank and the injector a Ismatec MCP-Z Standard pump is used in the circuit. Tubes must contain only water in order to protect the pump. For this reason, we suck up water into the tubes before connecting them to in the pump.

    Water flow rate can be directly read from the pump, but the value is not exact. In order to have more precise values, the pump must be calibrated before using it. To calibrate the pump, we read the flowrate in rounds per minute and convert it to mililiters per minute.
Experimental setup

• 3.3.3 Water mass flow meter

The measurement of the water flowrate is obtained with a liquid flow meter. This device can not regulate the flow rate. The pump is used to choose the values and the water mass flow meter checks if the value is correct. The liquid flow meter is connected to the computer, and we can follow the evolution of the flow on a graphic and read numerical values.

3.4/Data processing

• 3.4.1 Camera

The used camera is a MotionXtra HG-SE from Redlake. We can record images at high speed around 500 and 32,000 frames per second. Movies allow to see the injector with high quality because of the zoom. The maximum resolution is 1280x1024, but we can not use it because the frame rate is too high. Movies can be analyzed with the Redlake software but an other software, Image Pro Plus, has more advantages.

• 3.4.2 Light and diffuser

Movies can be recorded with natural light or with a stronger luminosity. If we do not use an illumination system, movies will be very dark. In order to obtain clear movies where we can see more contrast, we have added an additional light which is made up with 308 LEDs and need a power supply of 30 V with 1,2 A intensity.

• 3.4.3 Image Pro Plus

Image Pro Plus is the software that has been used to analyze images obtained in the experiments.
Experimental setup

The background correction tool:

The background correction tool, represented in Figure III.2, enables to obtain movies without environment. We extract the background and change the contrast in order to only visualise the bubble.

![Background Correction Tool](image)

Fig III.2: Background Correction Tool

Segmentation

The segmentation tool binarizes the movie. In Figure III.3, we can see the movies during the segmentation. This tool enables to obtain movies in black and white (in Figure III.4), which is easier to analyse.

![Segmentation Tool](image)

Fig III.3: Movies during segmentation
Experimental setup

Fig III.4 Movies after the segmentation

Frequency / velocity determination

Once the movie in black and white is obtained, we can calculate with the software the frequency of bubbles we have in the movie. First we must define the object with the ellipse tool, as we can see in Figure III.5, and the kind of tracking (Figure III.6). We obtain a movie where we see the ellipse tool. Number of bubbles which enter the ellipse are counted, as we see in Figure III.7.

Fig III.5: Ellipse Tool

Fig III.7: Entrance in the ellipse tool

Fig III.6: Kind of tracking
Experimental setup

The results give the number of bubbles in every movie. Bubbles are called track in Figure III.8, and we can count the number of tracks we have in the movies. If we know the number of frames in the movies (generally 852) we can obtain the number of bubbles for one second – corresponding to 2500 frames. The number of tracks in one second is the frequency. Moreover, we can calculate the velocity of bubbles with the graph (Figure III.9). Indeed the velocity is the distance in meter during one second and the number of frames gives the times.

![Tracking Data Table]

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![Fig III.9 Graph: Number of bubbles during 900 frames]
4. Results
Results

4.1/ Generation of bubbles

The results presented in this report consist of two parts. We have first studied the generation of bubbles by means of configuration B and compare it to existing results with configuration A. Second part consists of the injection of droplets in a cavity.

• **4.1.1 Bubbles in the capillary tube**

Appearance of bubbles

In configuration B, when we increase the water flowrate $Q_l$, for a constant flow of gas $Q_g$, we observe bubbles disappear. It is thus necessary to determine the appearance of bubbles according to the gas and liquid flowrate. The limit of appearance of bubbles was defined by the minimum liquid flowrate for a fixed gas flowrate for which bubble appear (see Figure IV.1).

\[ y = 1,614 + 4,651 \]

Data of Figure IV.1 can be fitted by a linear regression, with $a = 1,614$ and $b = 4.651$. 
Results

Shape of bubbles

If we make vary liquid and gas flow rates we obtain diverse shape of bubbles. For \( Q_L = 20 \text{ ml/min} \) and \( Q_g \) between 20 and 30 ml/min, bubbles were little lengthened. When the gas flow rate increases between this values the shape of bubbles are similar but the number of bubbles increase, as we can see in Figure IV.2.

\[
\begin{align*}
\text{Qg} &= 20 \text{ ml/min} \\
\text{Qg} &= 30 \text{ ml/min}
\end{align*}
\]

Fig IV.2: Constant liquid flow rate: 20 ml/min - Bubbles’ shape are similar

If we increase further \( Q_g \), bubbles lengthen. The weaker water flow rate is, the faster bubbles lengthen. For gas flow rate around 45 ml/min, influence of the flow of water on the shape of bubbles is visible in Figure IV.3.

\[
\begin{align*}
\text{QL} &= 10 \text{ ml/min} \\
\text{QL} &= 20 \text{ ml/min}
\end{align*}
\]

Fig IV.3: Constant gas flow rate: 45 ml/min - Bubbles are smaller at higher Q_L
Results

At the range of values considered, for constant $Q_L$, when $Q_g$ increases, bubbles become more numerous and conserve a similar shape. From a certain value of $Q_g$, the number of bubbles is constant but the width of bubbles increases. We have studied the variation of the number of bubbles for several flowrate.

Generation frequency

We have chosen several gas flow rate values:

- 3 ml/min
- 7 ml/min
- 10 ml/min
- 15 ml/min
- 20 ml/min

For each flow of gas we have varied water flow rate between 10 ml/min and 40 ml/min. We have calculated frequency for each movies recorded. We obtain the graph shown in Figure IV.4.
Results

Fig IV.4: Bubble frequency as a function of gas flowrate obtained with configuration B

Fig IV.5: Bubble frequency as a function of gas flowrate obtained with configuration A
Results

It can be observed from figure IV.4 that bubble generation frequency has a linear dependence on \( Q_g \) for a water flowrate \( Q_L \) between 3 and 10 ml/min. For larger liquid flow rate the bubble generation frequency has an apparently linear dependence on \( Q_g \). This result can be compared to the behaviour of the bubble frequency for different \( Q_g \) and \( Q_L \) in the case of configuration A on Figure IV.5 [2].

There are two conclusions that can be derived from the comparison of both configurations:

- For given \( Q_g \) and \( Q_L \), generation frequency appears to be larger in configuration B.

- **4.1.2 Bubble detachment at the T-junction**

Bubbles at detachment

We have studied the bubbles behaviour in the capillary tube. But their behaviour is linked to the way bubbles get disconnected. We have to determine how bubbles are created to predict their specificity (size and shape) during the injection. We have recorded images for three liquid flow rates: 10 ml/min, 15 ml/min and 20 ml/min. For each \( Q_L \) we have varied \( Q_g \) from 20 to 30 ml/min.

First we have observed the instant when the bubble is cut (last image before the bubble is already created). We have determined the influence of the liquid and gas flow rates on this cut. For a constant liquid flow rate, the length of the bubble bridge decrease (see figure IV.6) when the gas flow rate increases.

![Fig IV.6: Liquid flowrate: 20 ml/min: the length of the bubble bridge decrease](image)

Then we have varied the flow of liquid and kept the same gas flow rate. We have observed that when liquid flow rate is increased, the length of bubble bridge increases too (see Figure IV.7).
Results

Fig IV.7 Gas flowrate: 20 ml/min: the length of the bubble bridge increases for larger $Q_L$

Bubbles after detachment

Once observed that liquid and gas flow rate influence the length of the bubble bridge, we have analysed what happens after the detachment of bubbles. We have compared bubble bridge during ten frames for a constant flow of liquid and two gas flowrate: 20 ml/min and 40 ml/min. We can see the results in Figure IV.8.

<table>
<thead>
<tr>
<th>Frame 1: Bubble detachment</th>
<th>$Q_g = 20$ ml/min</th>
<th>$Q_g = 40$ ml/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame 6: (3ms)</td>
<td>There is liquid under the bubble of gas</td>
<td>There is almost no liquid under the bubble of gas.</td>
</tr>
<tr>
<td>Frame 10: (5 ms)</td>
<td>There is still some liquid under the bubble of gas</td>
<td>The bubble of gas is stabilized.</td>
</tr>
</tbody>
</table>

Fig IV.8: Comparison of bubble bridge evolution after detachment for $Q_L = 20$ ml/min and different gas flowrates
Results

When we use smaller gas flowrate ($Q_g = 20\, \text{ml/min}$), the liquid under the bubble takes more time to disappear. In other words, a faster stabilization is produced at larger $Q_g$. Indeed, if the gas flow rate increases, velocity increases, and the gas travels a longer distance during the same time interval.

To conclude, the liquid part will disappear faster when the bridge will be shorter. This observation is important, because if we want to generate bubbles, the liquid part has to have totally disappeared.

4.2/ Injection in a cavity

• 4.2.1 Formation of the jet

We have worked with both configurations (A and B) of the injector. We have studied the formation of the jet when it is injected into the air with a liquid flow rate of $45\, \text{ml/min}$.

The jet was not obtained for the same values of $Q_g$ in each configuration. In configuration A, we have obtained a jet only when the gas flow rate was larger than $38\, \text{ml/min}$ (Figure IV.9), whereas the jet is formed with configuration B if the gas flow rate is larger than $45\, \text{ml/min}$ (figure IV.10).

![Fig IV.9 Configuration A: $Q_g = 38\, \text{ml/min}$, $Q_L = 45\, \text{ml/min}$](image)
Results

Fig IV.10 Configuration B: $Q_L = 45$ ml/min

4.2.2 Jet regularity

We wanted to obtain a regular jet, and try to relate its regularity to see how bubbles are formed. For a constant liquid flow rate of 45ml/min we have recorded movies and have compared both configurations (see in Figure IV.11).

Fig IV.11: Difference of regularity between both configurations : $Q_L = 45$ ml/min, $Q_g = 45$ ml/min
Results

Configuration A seems to provide a more regular jet with droplets of a smaller size. In order to understand the difference in regularity between both jets, we have observed what took place in the generation of bubble for both configuration (fig IV.12).

![Configuration A and Configuration B](image)

Fig IV.12: Bubble generation in both configurations, $Q_l = 45$ ml/min $Q_g = 40$ ml/min

Due to the high speed, quality of movies obtained was poor. Nevertheless we can observe that for configuration A, bubbles seem more regular (similar sizes, close frequencies), while for configuration B, bubbles have very different sizes and are irregular (some are grouped and others very remote). Configuration A contains a slug flow while configuration B shows a bubbly flow.

We can conclude that for the range of parameters considered the best configuration to obtain a regular jet is configuration A. In the next section we will only work with this configuration in order to study the jet.

- **4.2.3 Detachment of droplets**

A main goal of our study was to inject bubbles (or droplets) in a cavity. For this reason, it was essential to foresee the distance in which the droplets will be clearly detach from the jet. We have measured the distance in which droplets were detach for three different gas flow rates: 38, 40, 42 ml/min with a constant flow of water of 45 ml/min.
Results

Figure IV.13 establishes the number of droplets detached at several distances. For a $Q_g = 38$ ml/min, we observe that droplets are all detached at a similar distance, from 38 to 50 mm, most of them between 44 and 48 mm.

When gas flow rate increases (40 ml/min) the distance where droplets are detached varies considerably, between 45 and 65 mm. For $Q_g = 42$ ml/min, droplets are detached at distance between 100 and 150 mm and they are created much faster.

These results could be related to the fact that flow in the injector at $Q_g = 38$ ml/min is more regular that at $Q_g = 42$ ml/min.
QL = 40 ml/min

Fig IV.14  Droplets at the distance where they are created during the time for QL = 40 ml/min

QL = 43 ml/min

Fig IV.15  Droplets at the distance where they are created during the time for QL = 43 ml/min
These three graphs show that the distance where bubbles are detached is unpredictable. Indeed, data recorded cannot be fitted by a regression. We need to have more data to determine a period or a regression for the distance where bubbles are detached.
Conclusions

Results presented in this study enable to characterize bubbles and droplets behaviour from the detachment to the injection in a cavity. Similar behaviour has been obtained for the considered two configurations of the injector. When gas flow rate increases, bubbles become more numerous and conserve a similar shape up to a certain value of Qg. Then, if gas flow rate continues to increase, the number of bubbles is constant but the width of bubbles increases.

The way how bubbles detach characterizes its behaviour in the pipe and during the injection in a cavity. We have selected the best configuration to obtain proper and regular jet. This is when the gas is injected from the height of the injector and the water in the horizontal capillary. With this configuration, we know optimal values to regulate the distance where droplets are created during their injection. These results must be compared with future results in microgravity in order to obtain more information on the described effects.
Bibliography


[8] www.zarm.uni-bremen.de/6zarm_fab/download/pdf/General_Information.pdf