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Study of the dynamic behaviour in a multiphase flow system when bubbles of CO2 or Air passes through the interface of two immiscible liquids.

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Abstract

The behavior of bubbles at the interface between oil/water is studied. The test are done with Silicon Oil 10 cS as the overlaying liquid and aqueous solutions underneath. Polyanionic Cellulose (PAC) were implemented and dissolved in distilled water with the purpose of having a shear thinning fluid behavior. Air or CO2 bubbles are injected from the bottom of the container. In this project the dynamics and behavior of the bubble at the is evaluated. When the buoyancy force of a single bubble is high enough to overcome the capillary forces at the interface the bubble that is moving upwards drift a column of water that is dragged into the lighter liquid.

A total of 18 different tests were performed. Fluid dynamics of the bubbles and interface of the fluids were examined, explained, and compared between the multiple test performed. With the utilization of high-speed camera, the effect of any asymmetry in the bubble shape and the rising pathway is analyzed. Physical data as the viscosity was obtain using a viscosimeter, were it provided the shear rate and shear stress of the fluids that were used. A tensimeter was used to obtained data of the interfacial and superficial tension of each fluid used on the tests. Based of equations obtained on previous studies three different sizes of the bubble were chosen and used for the experiment 0.014, 0.065 and 0.11 cm^3 respectively.

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ANDRÉS FELIPE FONSECA TORRES

Introduction

The study of a bubble passing through a two immiscible liquids interface is a dynamic process with different outcomes and is a relevant matter in many technological applications and industrial processes. On the oil and gas industry, mixtures of oil, water, and gas, nowadays, CO_2 are important for oil recovery or Carbon Capture, utilization, and storage. When there are two non-miscible fluids of different densities in stratified layers, the lighter fluid is above of the heavier fluid. If a bubble is introduced in the bottom of the system this one will rise up at constant velocity until the growing drag force balances with the buoyancy force and reaches the interface of those immiscible fluids. If the upward forces are strong enough, the bubble drags a water column until film of the interface of the fluids breaks, the rising behavior will continue until the bubble reaches the surface of the lighter fluid.

At the moment when the rising bubble reaches the horizontal interface, a resistance from the interfacial tension is found, and a film is formed between the interface and the bubble leading to a drift and a reflux across the flow volume. (Bush & Eames, 1998). For bubble passage through a liquid−liquid interface, the kinetic to free surface energy transfer would stem from bubble deformation and increased interfacial area between the liquids (Emery, Raghupathi, & Kandlikar, 2018). Once the film of the fluids is broke, if the buoyancy forces are large enough, there will be a formation of microdroplets depending on the liquid-liquid interfacial tension. (Rabenjafimanantsoa & Time, 2013).

In this project, previous experiments for the passage of a bubble passing through the interface of two immiscible liquids are reviewed, from the study of each specific phenomena such as the passing or bouncing of a bubble at the interface of the two immiscible fluids (Bonhomme, Magnaudet, Duval, & Piar, 2012), (Natsui, Takai, Kumagai, Kikuchi, & Susuki, 2014), and the generation of the microdroplets due to the break of the film formed on the rising bubble (Rabenjafimanantsoa & Time, 2013). With the support of previous experiments of a rising bubble through/at the interface of two immiscible fluids are reviewed. A controlled size of the bubble is implemented. All the possible phenomena is observed, giving the proper analysis to the behavior of the fluid dynamics of the bubbles and the liquid phases.

Chapter 2

2. Theory

2.1 Fluids

2.1.1 Immiscible Fluids

The immiscible liquids are all those liquids that because the difference of densities they will not mix, making a heterogeneous mixture, this can be related to the entropy. If the fluids have a higher entropy, the miscibility, or the capability to mixed between them is higher; for this reason, when two fluids with different densities are in the same system, both fluids will separate from each other, where the lightest one will go to the top, while the heavier one will be located at the bottom of the system.

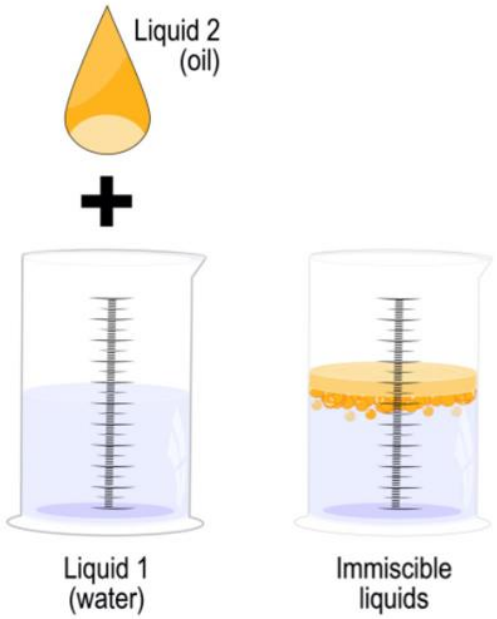


Figure 2.1: *Illustration of immiscible fluids*

2.1.2 Newtonian Fluids

When there is a linear relation between the applied shear stress τ and the shear rate γ, it will be considered as a Newtonian fluid, and the relation can be found as:

$$\tau = \frac{F}{A} = \mu\gamma \tag{1}$$

Where the factor μ is the viscosity of the fluid and it is only affected by pressure and temperature, one representation of a Newtonian fluid is the water, which was used in one part of this project.

2.1.3 Non-Newtonian Fluids

In a non-Newtonian fluid, there is a non-linear relation between the shear rate γ and the shear stress τ, and this relation can also change regarding the time, on this fluids, the viscosity of the fluid as the Newtonian fluid, is dependent on the temperature and pressure, in addition to shear stress and shear rate, consequently a constant coefficient of viscosity cannot be defined. (Sletteng, 2014)

There are different types of non-Newtonian fluids can be found:

- Pseudoplastic Fluid: For this kind of fluids, the apparent viscosity reduces when the stress is increased, shear thinning fluids.
- Dilatant Fluids: When the shear strain increases the apparent viscosity also increases.
- Bingham Plastic Fluid: this fluids have a linear stress-strain relationship, but there is a resistance to initial flow, so it is necessary an initial stress in order to flow.

- Viscoplastic: this fluids have the same behavior as the pseudoplastic fluids, where when there is an increase of stress, the viscosity reduces, the difference is that it is necessary a finite stress before they start to flow.

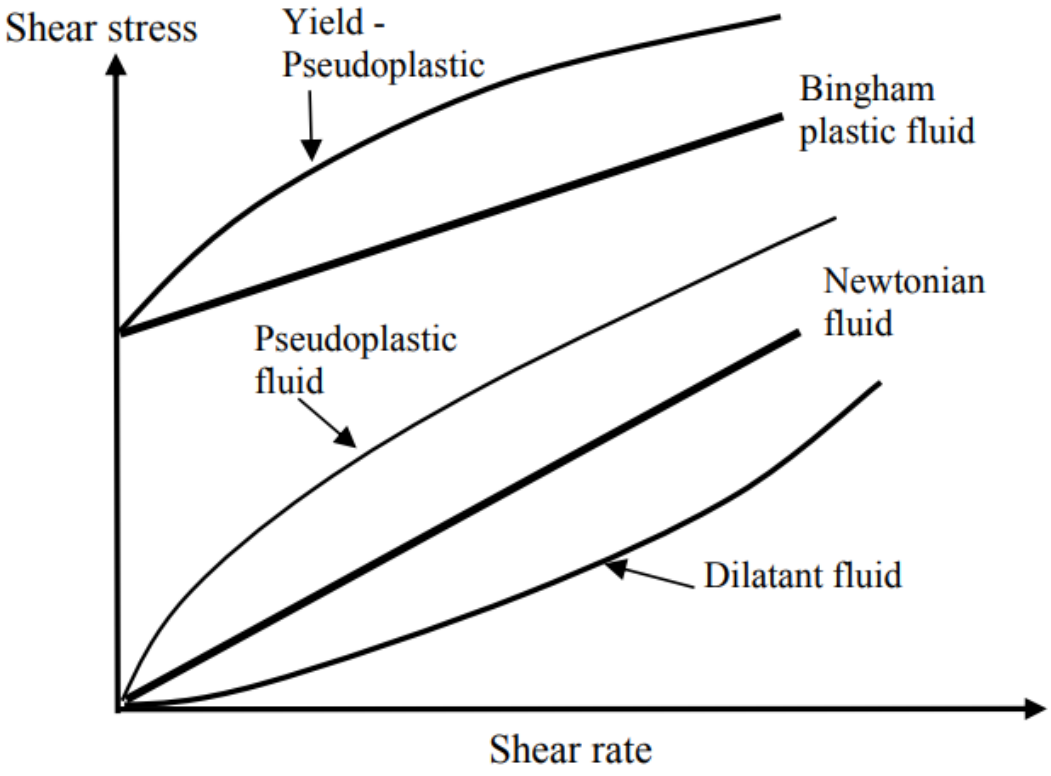


***Figure 2.2**: Comparation of Newtonian and non-Newtonian Fluids.*

2.2Bubble Behavior

2.2.1 Bubble behavior in static condition

If a bubble is located in the interface of two immiscible fluids, a three-phase contact line will be found (TPCL), depending on the magnitude of the interfacial and surface tension, the behavior of the bubble will change, as is shown in the Figure 3. This behavior in the liquid-

liquid-gas system can be predicted with the parameter S, as it was presented by (Pannacci, et al., 2008).

$$S_b = \sigma_{12} - (\sigma_{b1} + \sigma_{b2}) \quad (2)$$

Where σ is the interfacial tension, while the indices b, 1 and 2 represents gas, light liquid, and heavy liquid phases, respectively, while Sb represents the surface energy. Depending on the value of S the shape of the bubble will change.

Under static conditions, when the buoyancy force acting on the bubble overcomes the interfacial tension of two liquids, the bubble is able to pass though the interface of two immiscible liquids.

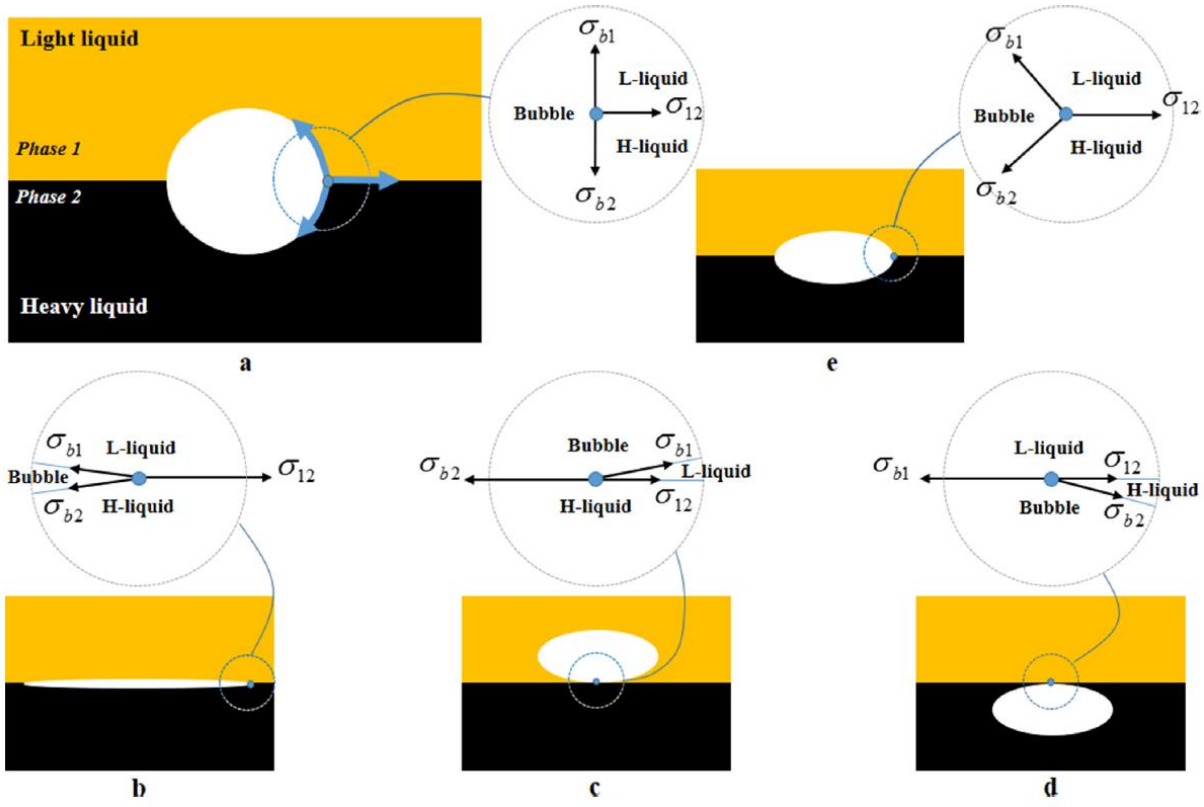


***Figure 2.3**: **a-** Situation of three-phase contact line (TPCL) of a spherical bubble initially located at inactive liquid–liquid interface can be changed depending on the magnitude of interfacial and surface tensions: **b-** Sb is positive **c-** S1 is positive **d-** S2 is*

*positive **e**- None of the single components of interfacial or surface tensions are dominant. (Edrisi, Dadvar, & Dabir, 2021)*

When the tangent line to the surface of the bubble is exactly in the same direction of the gravity, the maximum tensile force against the bubble occurs, as is shown in the **Figure 2.4.**

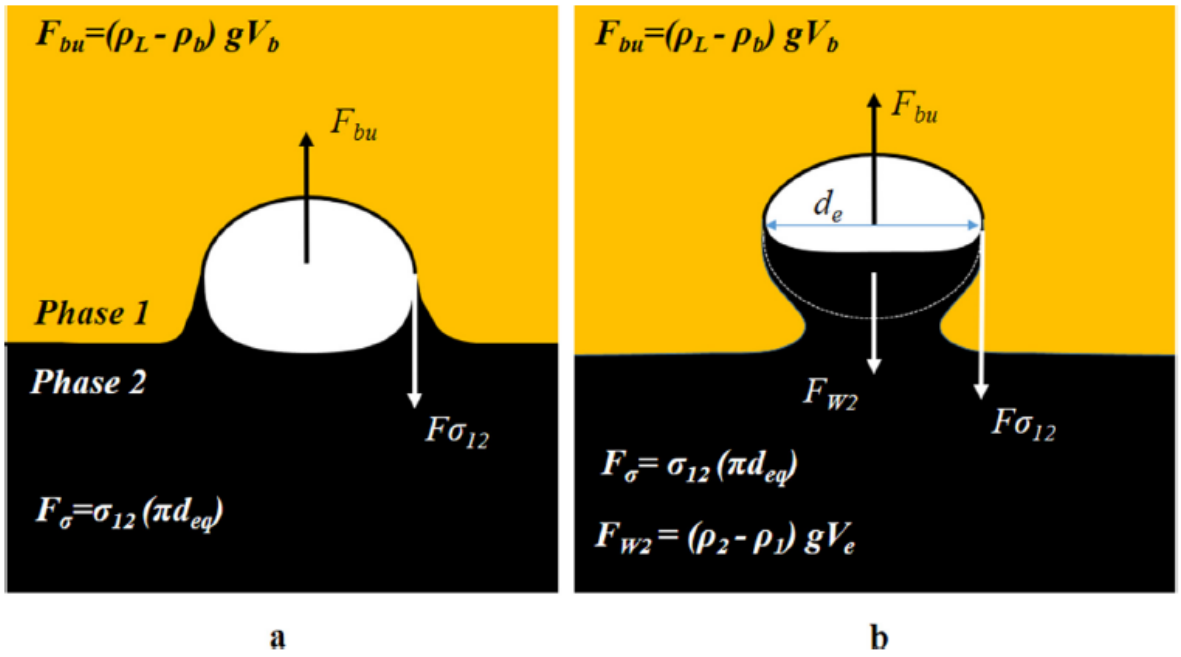


***Figure 2.4:** Forces acting on a rising bubble depend on interfacial phenomena **a**- bubble passing interface without entrainment **b**- bubble entrain some heavy liquid (Edrisi, Dadvar, & Dabir, 2021)*

According to the **Figure 2.4,** the maximum tensile force happens when the gravity and the tangent line of the bubble surface are in the exact same direction. Based on the presented forces on the bubble, as are the Interfacial tension F_σ, and the buoyancy forces, F_{bu}, (Greene, Chen, & Conlin, 1988), proposed the following equation:

$$V^* > \left(\frac{3.9\sigma_{12}}{(\rho_1 - \rho_b)g)}\right)^{\frac{3}{2}} \quad (3)$$

Where V^* is the minimum volume of the bubble necessary to pass through the interphase of the liquids, g is the gravity, ρb is the density of the bubble and ρ1 is the density of the light liquid and σ_{12} is the interfacial tension between the liquids.

If the rising bubble is carrying some heavy liquid into the light liquid, as is presented in the **Figure 2.4b,** the entrained weight needs to be considered, so in order to calculate the minimum volume necessary for the bubble to drag some liquid was proposed by (Greene, Chen, & Conlin, 1988) and is the follow equation:

$$V^* > \left(\frac{2\ x\ 3.9\sigma_{12}}{(3\rho_1 - 2\rho_b - \rho_2)g)}\right)^{\frac{3}{2}} \quad (4)$$

According to (Edrisi, Dadvar, & Dabir, 2021), a new model to calculate the minimum volume of the penetrating bubble was made, giving a more accurate compared with the experiments the made and it was represented by the following equation:

$$V^* > \left(\frac{2\ x\ 3.9\sigma_{12}}{(3\rho_1 - 2\rho_b)g)}\right)^{\frac{3}{2}} \quad (5)$$

Where:

- V^* is the minimum volume of the bubble that pass through the liquid-liquid interface
- g is the gravity
- ρ1 is the density of the light liquid

- ρb is the density of the bubble
- σ_{12} is the interfacial tension between the liquids.

2.2.2 Bubble behavior in dynamic condition

Under dynamic conditions, in a system with two phases, liquid and gas, the passage of rising bubbles through the liquid-air interface can be predicted by the inertia of viscous forces whit the Reynolds number and the surface tension with the dimensionless number of Weber. (Sanada, Watanabe, & Fukano, 2005).

$$We = \frac{\rho_l \cdot u^2 \cdot d}{2\sigma} \tag{6}$$

Where:

- We: Number of weber
- ρ_l: Density of the liquid
- u: Velocity of the rising bubble
- d: Diameter of the bubble

➢ Interface Rupture

If there is the presence of a lighter fluid over the fluid previous mentioned, there will be a thin film due to the difference of densities, if the rising bubble passes through this interface, the amplitude of the bubble oscillations will decrease (Feng, Muradoglu, Kim, Ault, & Stone, 2016). One important phenomenon in the dynamics of fluids in a multiphase system involves the changes in the interface of the immiscible fluids. When the bubble passes thought the interface, due to buoyancy forces, a filament of water will cover the bubble and many droplets

will be generated because of the instable filament on the bubble. (Rabenjafimanantsoa & Time, 2013), (Emery, Raghupathi, & Kandlikar, Flow Regimes and Transition Criteria during Passage of Bubbles through a Liquid–Liquid Interface, 2018). On the **Figure 2.5** is presented the behavior of a bubble of air passing through the interface of water and silicon oil.

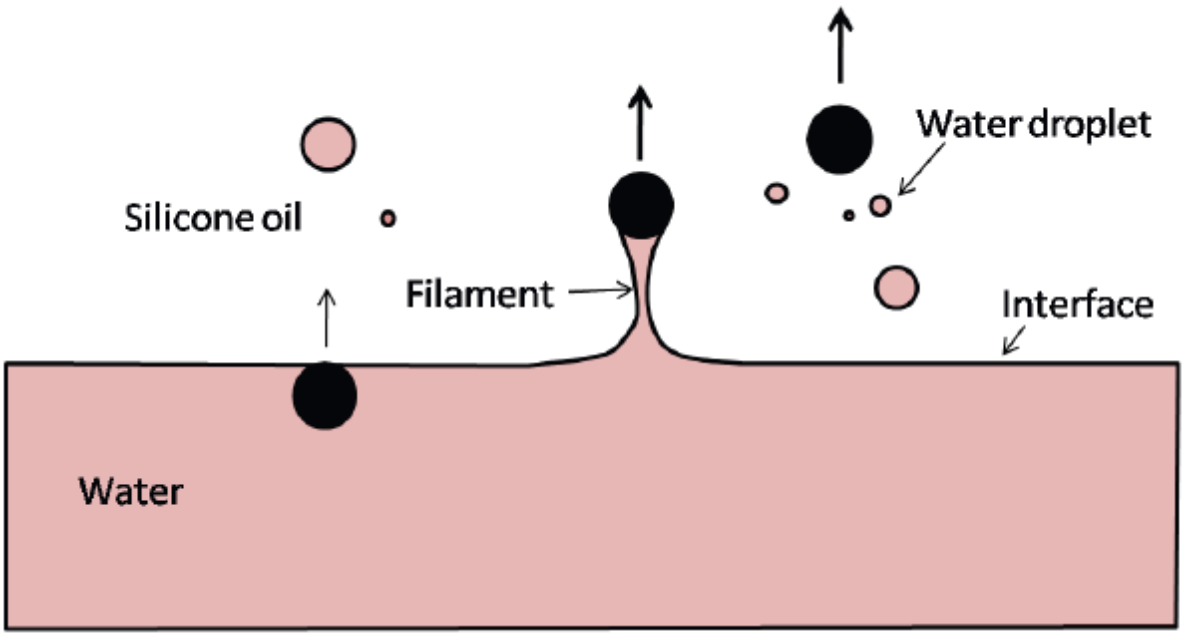


Figure 2.5*: Illustration of traveling bubble thought the interface between water and silicone oil (Rabenjafimanantsoa & Time, 2013)*

As is presented on the **Figure 6** a dimensionless graph indicates the threshold values for specific surface phenomena. The dimensionless volume of bubble and the heavy/light liquid density ratio determine the possibility of bubble passage through the interface or/and entrainment of heavy liquid. (Rozario, Viswanathan, & Basu, 2019).

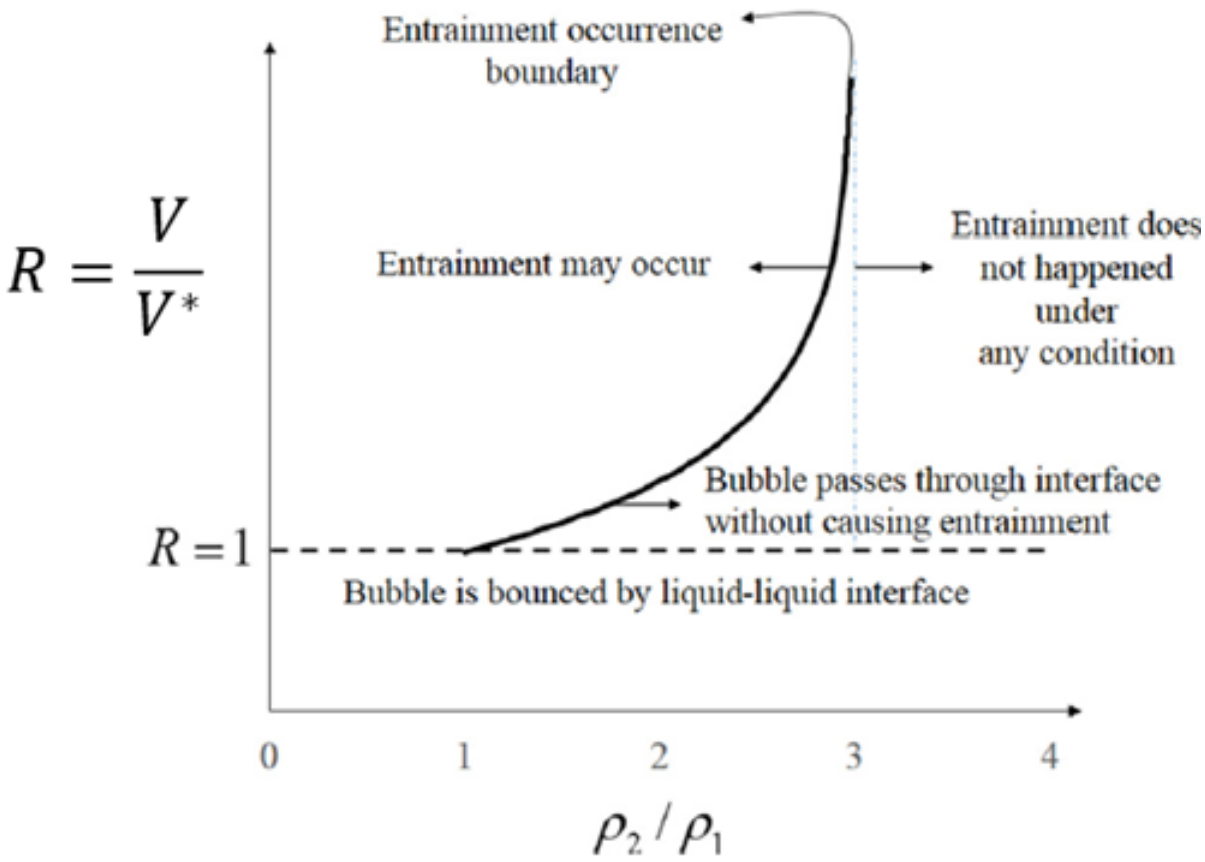


Figure 2.6: *Dimensionless graph of possible surface phenomena (Greene, Chen, & Conlin, 1988)*

On the **Figure 2.6** is presented the dimensionless volume of the bubble R=V/V*, which is the ratio of bubble volume on its minimum required value in order to pass the liquid-liquid interface.

When the bubble is raising due to buoyancy forces, trough the interface of the liquids, it will react to a downward force, the surface tension, for the entrainment process to be successfully, the buoyancy force needs to be larger than the surface tension, in this way, we can get the next equation (Greene, Chen, & Conlin, 1988):

$$V_g(\rho_1 - \rho_g) - V_2(\rho_2 - \rho_1) > \frac{2\pi R_2 \sigma_{12}}{g} sin\beta \quad (7)$$

$$R_2 = \left(\frac{3}{4\pi} Vg\right)^{\frac{1}{3}} \quad (8)$$

Where:

- Vg: volume of the bubble
- ρ1: density of the light liquid
- ρ2: density heavy liquid
- ρg: density of the bubble
- V_2: volume of the denser fluid pulled above the liquid interface
- R_2: Column radius
- β: interfacial contact angle
- g: gravity

➢ Interface Bouncing

When a bubble is raising in the direction of the interface, there is a deformation of that interface, and the formation of a liquid film will appear between the interface and the bubble. The pressure on that film will start to increase leading to a force that will repel the bubble from the interface, because of the buoyancy force, the bubble will continue its path and will have some deformation on the curvature of the top of the bubble while the thickness of the fill keeps getting thinner and the velocity of the raising bubble is slower. This thinning goes on until a film thickness of 10–100 nm is reached (Kosior, Zawala, Todorov, Ecerowa, &

Malysa, 2014). If the repelling forces from the interface are strong enough, the bubble will be pushed away before the film on bubble reaches a critical thickness and the coalescence with the interface will not happen, leading the bubble bouncing at the interface of the liquids.

2.3 Interfacial Tension

It can be defined as the force of attraction between the molecules at the interface of two fluids, if the interface is between air and liquid, it is referred as surface tension. The interfacial tension occurs because a molecule near an interface has different molecular interactions than an equivalent molecule within the standard fluid. Surfactant molecules preferentially locate at the interface and thus lower interfacial tension. (Speight, 2016). To make this measurement quantitative it can be defined as the force exerted at the interface per unit length (mN/m).

Chapter 3

3. Experimental Set up

In this work, the project was developed for the utilization of a small-scale experimental set up to investigate the behavior of interface behavior of two immiscible fluids when a bubble of different sizes is passing through it. From the experimental set up and conditions the following can be observed:

- Temperature of the system is fixed, i.e., room temperature. 15°C
- Newtonian and Non-Newtonian Fluids will be considered (Water, Silicone Oil, Water + Polymer)
- Single bubbles of three different sizes will be considered for the experiment (0.014, 0.065, 0.11 cc).
- Two different gases were injected in order to compare their behavior (Air and CO_2)

In the following section of the experimental model, the laboratory set up will be described, the processes, equipment installation for the experiment, fluids analysis and measurement. The experiment includes visual observation of the different bubble sizes on the different fluid systems and at the liquid-liquid interface.

3.1 Set up

The set up was previously made and adjusted for the current experiment also, the nozzle diameter was changed in order to change the size of the injected bubbles, on the **Figure 3.1** is presented a scheme of the set up.

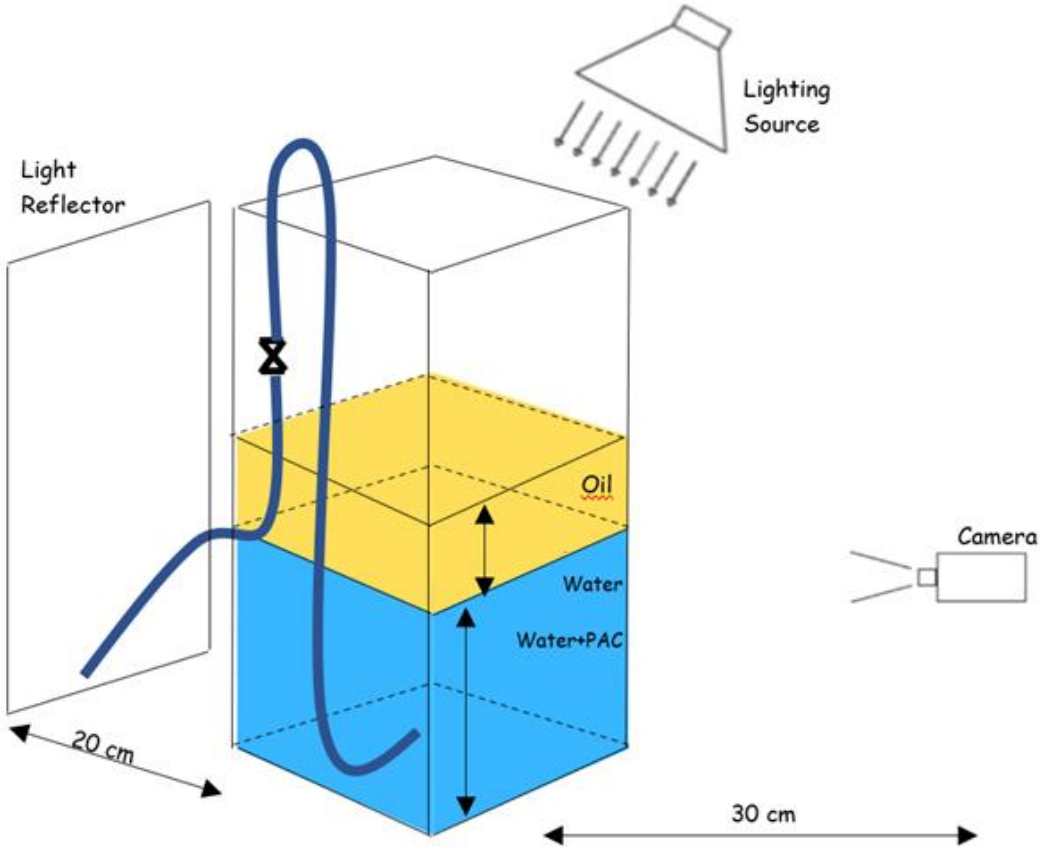


***Figure 3.1**: Experiment Set Up*

The system consist of a quadrangular acrylic container of 15x15 m^2 of area and 60 cm of, this container was used in order to prevent any unwanted force on the bubbles with its surroundings. With the pressure control valve and the three different sizes of nozzles, 1, 3 and 5mm the volume of gas (air or CO_2) injected into the container was controlled and presided on each experiment. The container was filled with 15 cm of water or water + polymer at its bottom and 7 cm of silicon at the top of it. The volume of the bubble on the experiment varies from 0.014 to 0.11 cm^3. With a light source located at the top of the system and a light reflector behind the system, located 20 cm gives great lighting to record a slow-motion video of 960 fps with camera of 720x1280p resolution located 30 cm away from the system. The supply of CO_2 was provided by a tank, while for the air was used a supply

connected to the wall system of the lab. The recorder video is analyzed by the software **Tracker** frame by frame to determine the exact position and velocity of the bubble in time. The fluctuation of the interface of the fluids is eliminated by giving sufficient time to it to stabilize before each test.

On the **Figure 3.2** is presented the real set up of the experiment.

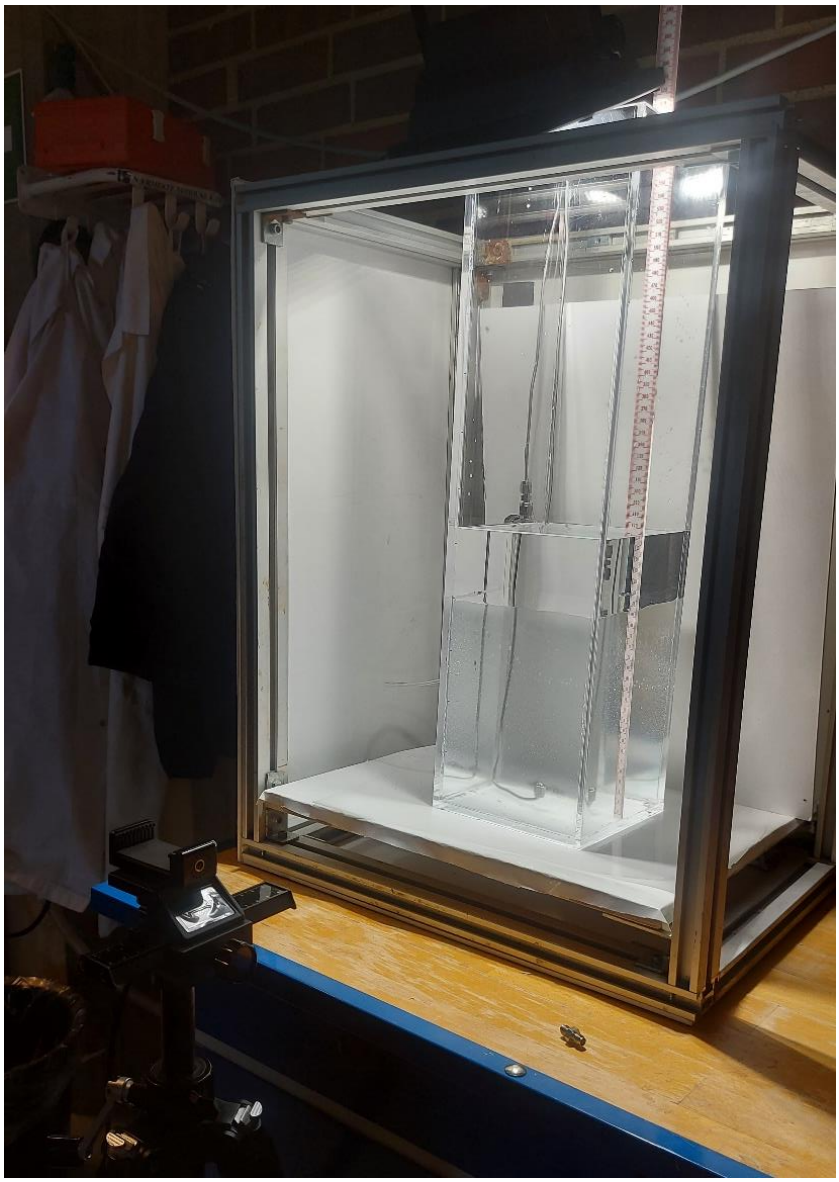


***Figure 3.2**: Live Experiment Set Up*

3.2 Preparation of fluids

With the objective to have different data and new results from previous experiments it was decided to work with non-Newtonian fluids; owing to this, it was necessary to determinate which concentration was going to be analyzed, being decide two different concentrations, 1 gr/l and 2 gr/l specifically.

The Polyanionic Cellulose (PAC) was mixed in a Silverson L2R laboratory mixer emulsifier with a Square Hole High Shear Screen worked, as shown in **Figure 3.3**. The volume used for each experiment was 3.3375 l. So, for the first experiment 3.375 grams PAC were dissolved in 3.375 l of water; the PAC was added slowly to the water with the purpose of avoid any kind of flocculation. At the moment of the mixture there was not any RPM specified on the mixer, so the mixture started with 20% of the maximum power and were increased every 90 seconds in a 20% for a total of 7.5 minutes. PAC 2 gr/l concentration, the procedure was almost the same, where 6.75 gr were dissolved. However, the mixture had a higher viscosity, because of this it was decided to increase the mixture time of each speed to 120 seconds, for a total of 10 minutes of mixing.

After the mixing was done, in order to have a proper interaction between the polymer and the water, each mixture was left to rest for a period of five hours before the measurements of the properties and utilization on the tests, the reason for this was to have a better interaction between the fluids and more exact criteria at the moment of the measurements.

Figure 3.3: *Silverson L2R laboratory mixer*

To prepare the experiments and with the intention of getting some quantitative data to be compared with the theory and to analyze the behaviors of the different fluids, previous measurements were made, including the surface tension, interfacial tension, density, and viscosity of each fluid, on the next part each procedure will be explained.

3.2.1 Viscosity

For the measurement of the viscosity, the utilization of a Viscometer Model 800 from OFITE was used, **Figure 3.4**. This viscometer was used because of its Motor RPM that is continuously monitored and automatically adjusted by the pulse power electronic speed regulator to maintain a constant shear rate under varying input power and fluid shear. To determine the rheology of the fluid, the shear rate was set to decrease from 600 s^{-1} to 1 s^{-1} and then increase back to 600 s^{-1}, with a time gap of 1 minute at each shear rate (8 in total), this was done to check if there was any deviation or hysteresis because of any influence of the viscometer. The measurement of the rheology was done at 20°C.

***Figure 3.4**: Viscometer OFITE Model 800*

3.2.2 Interfacial and Superficial Tension

The main focus of the experiment is the interfacial tension and its behavior, so, with the purpose of having a physical data to compare and have to reference, the utilization of a Kruss K6 Tensiometer, that is a robust and reliable manual instrument for measuring surface and interfacial tension using the ring tear-off method that mainly consist of the measurement of the surface or interfacial tension using the tensile force of a lamella which is stretched until it disrupts as is presented on the **Figure 3.5** where is shown the behavior of the ring and the fluids, right before the interface breaks, and that how the measurement is made. The ring that was used for the measurement was the K 810 **Figure 3.6**.

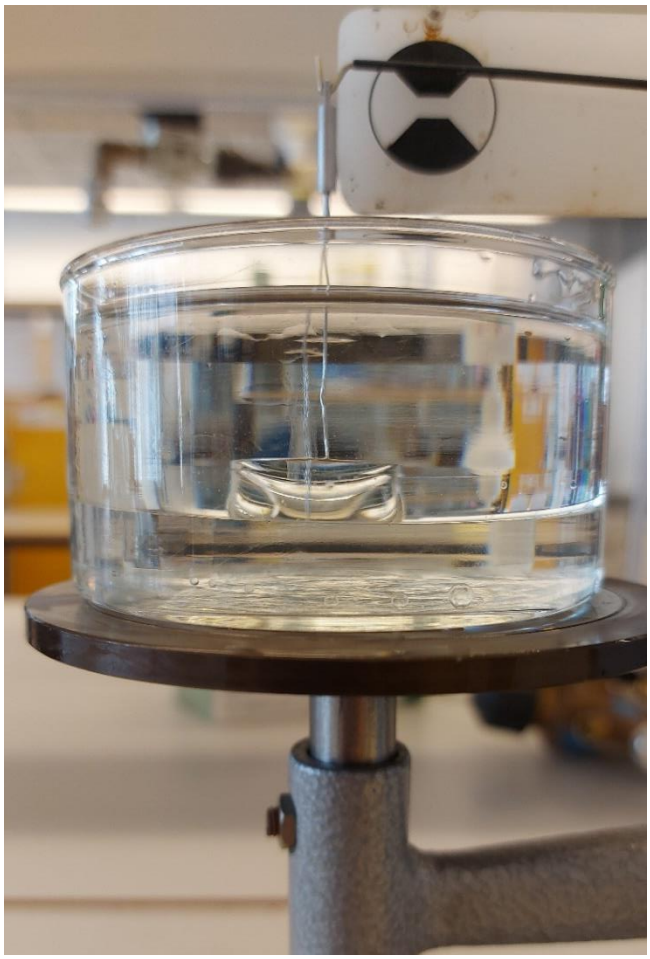


Figure 3.5: *Measurement of interface tension using Kruss Tensiometer and Ring K810*

Figure 3.6: *Ring K 810 Used for the measurement of Interfacial and Surface tension*

The measurement of the surface tension was made for each liquid i.e., Silicone Oil, Distillated water, Distilled water + PAC 1 g/l and, Distilled water + Polymer 2 g/l., and the interfacial tension was made between, Silicone Oil and Distilled water, Silicone Oil and Distilled water + PAC 1 g/l and Distilled water + PAC 2 g/l. On the **Figure 3.7** is presented the Kruss K6 Tensiometer.

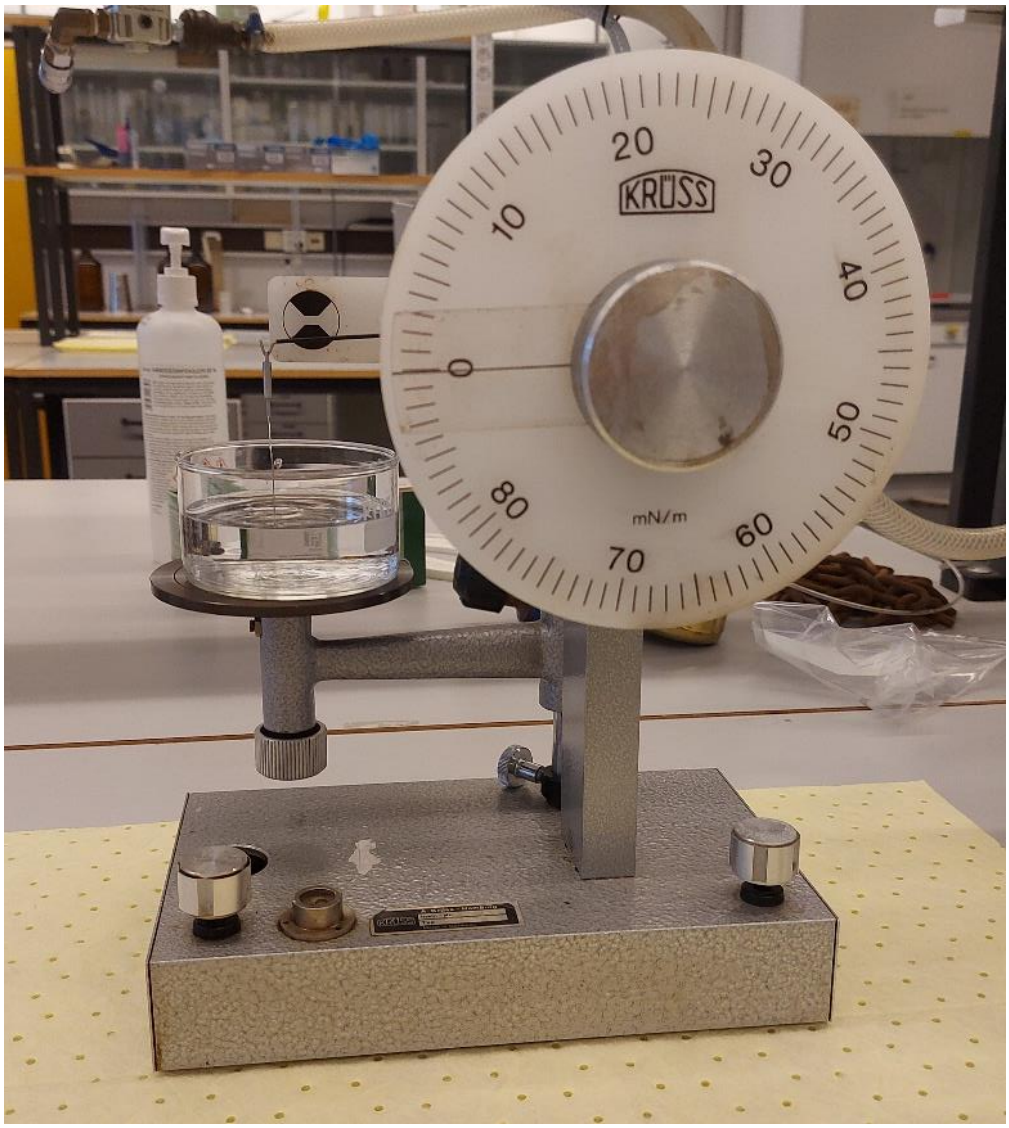


***Figure 3.7**: Kruss K6 Tensiometer*

3.2.3 Density

The measurement of the density of the fluids were made with the utilization of a densimeter DMA 4500 M. that consist of a U-shaped borosilicate glass tube, that when the sample is injected on the side of the equipment, the U-tube stars

to generate vibrations, and the density will alter the frequency of those vibrations providing an accurate value of the fluid that is being measured.

3.3Data Processing

To process the captured videos, and determinate the bubble track and behavior through the whole system the software **Tracker Video Analysis and Modeling Tool** was used, this software is a modeling tool built on the Open Source Physics (OSP) Java framework that gives the tool to manual and automated object tracking with position, velocity and acceleration overlays and data of a desire object, also with the Model Builder creates kinematic and dynamic models of point mass particles and two-body systems. This software is used mainly for physic analysis and studies in all academic levels and is a free and open source that can be found online. This software was chosen because the ease of use. The version used for the analysis was the **Version 6.0.8.**

Chapter 4

4. Experiment Procedure

4.1 Visual Data Analysis

Different phenomena on the system and at the interface are observed, based on the type of fluids and size of the bubble. Multiple videos were made as the supporting material of the project where is presented the different collisions of the different bubble sizes and depending on the bubble component if it was an air or CO2 bubble in a water-oil or polymer-oil system. All the experiments were made for three different sizes of the bubble i.e., 0.014, 0.065, 0.11 cc for a total of 18 different focused at the interface of the fluids. All the videos were recorded in slow motion of ¼ of the real speed, the reason for this was to have better image of the path, motion, and speed of the bubbles; this motion and speed of the bubbles are presented on graphs that were obtained using the software **Tracker** as it was mentioned before, each test was repeated between 15-20 times in order to have the most accurate behavior.

Once the experiments were made and the videos were recorded, the next step was to repeat all of them but now with a recording distance of 5 cm away from the system, in a slow motion video of 1/8 of the real speed, the reason for this was to have a clearer image of the interface, and to analyze the different ruptures of it, formation of droplets, bouncing of the bubbles at this point and all possible motions and behaviors that could be analyzed.

Furthermore, the frames of this short distance recorded videos were split into images through a website called the same software**,** the reason of this was to compare and analyze in the

videos frame by frame and give better results to the experiment and the software gives the tool to know in which frame is located each picture.

4.1.1 Software Tracker

The reason for the utilization of the software **Tracker**, was for the features that this software gives, that can be summarized as:

Tracking:

- Manual and automated object tracking with position, velocity and acceleration overlays and data.
- Center of mass tracks.
- Interactive graphical vectors and vector sums.
- RGB line profiles at any angle, time dependent RGB regions.

Modeling:

- Model Builder creates kinematic and dynamic models of point mass particles and two-body systems.
- External models animate and overlay multi-point data from separate modeling programs such as spreadsheets and Easy Java Simulations.
- Model overlays are automatically synchronized and scaled to the video for direct visual comparison with the real world.

The procedure for the utilization of the software was the same for each experiment, a total of 18 experiments were done, divided by the 3 different systems, e.i., Water+Oil, Polymer 2 g/l+Oil and Polymer 1g/l+Oil, and each of those with injection of CO2 or Air, where each recorded video was analyzed, and the motion of the bubbles observed frame by frame from the bottom of the system to the surface of the lighter fluid, all the study was made with the

software **Tracker v 6.0.8**. The **Figure 4.1** shows the main interface without any data uploaded.

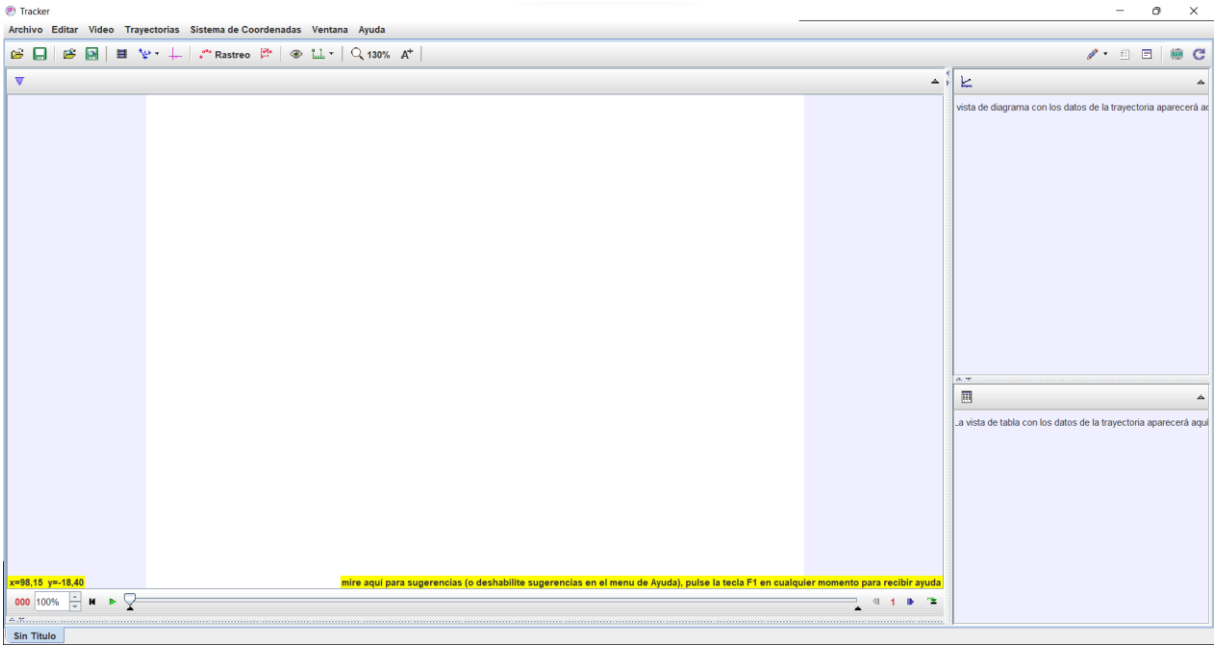


***Figure 4.1**: Interface Software Tracker without any data*

Once the interface is open, the video use for the study of the motion needs to be uploaded, and the software automatically will divide the video into the number of frames that de video contains.

When the video has been uploaded, it is necessary to give a calibration of the measurement and give the axis so the software will give the plots, as the video was uploaded horizontal, for this case, the Y axis is the horizontal and the X axis is the vertical, where the X=0 point is the interface of the fluids, and the Y=0 is the origin of the bubble, the calibration was made with the metric scale in the system with 5 cm., as is shown in the **Figure 4.2.**

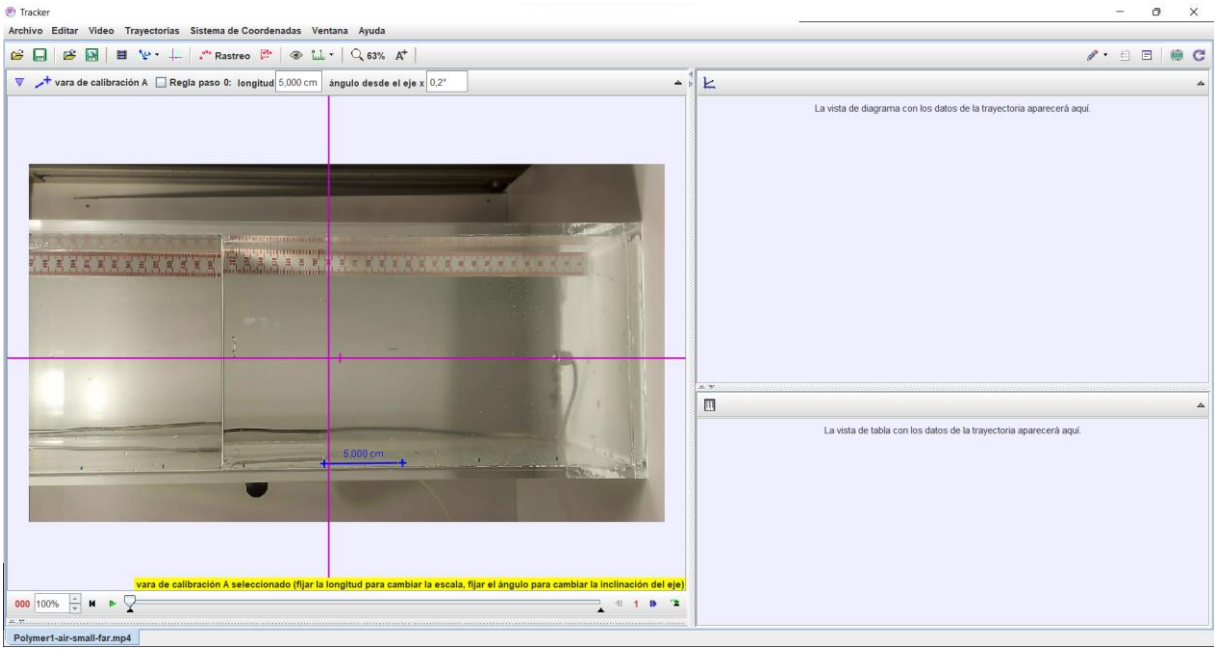


Figure 4.2: *Software Tracker, calibration of the measurements*

After the calibration has been done, it is necessary to determinate the frames that are going to be study, starting and end point, also the jump between frames, as the videos recorded were made with 240 frames per second, each video has a total of frames between 800-3000 frames, for this reason. The jump between frames was determined as 3, **Figure 4.3.** Also, the object to be follow is named as "**Mass A"**, and the software will generate two plot automatically, that usually are "x position vs time" and "y position vs time" as was mentioned before, for this cases, the vertical axis is the **X,** and the horizontal axis is the **Y.**

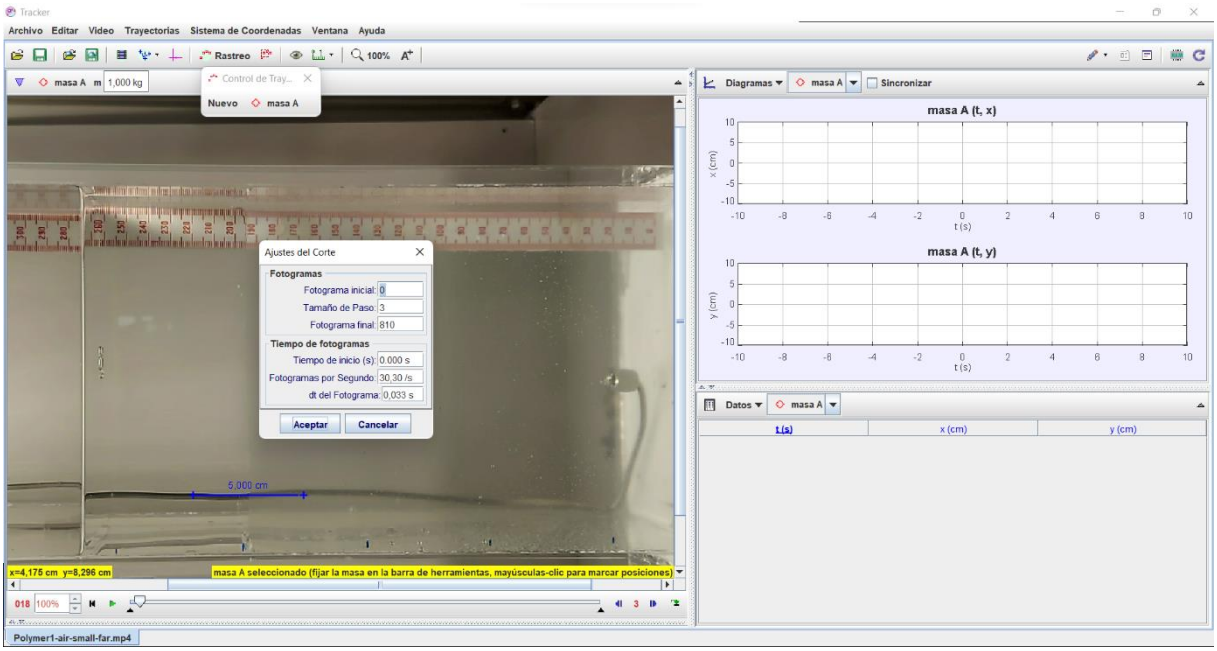


Figure 4.3: *Software Tracker, selection of frames and creation plots*

Now that all is set up, the software is ready to run, so, the position of the bubble is selected for each frame, this points selected will generate the plots on the upper right corner and on the lower right corner is all the data obtained from this points, it need to be clarified that the videos were recorded ¼ of the original speed, so the time shown on the software should be fixed afterwards. On the **Figure 4.4** is shown the behavior of the bubble of air in the water with a concentration of 1 g/l of PAC some centimeters before its collision with the interface, all the data obtained is showed, also the auto-generated plots.

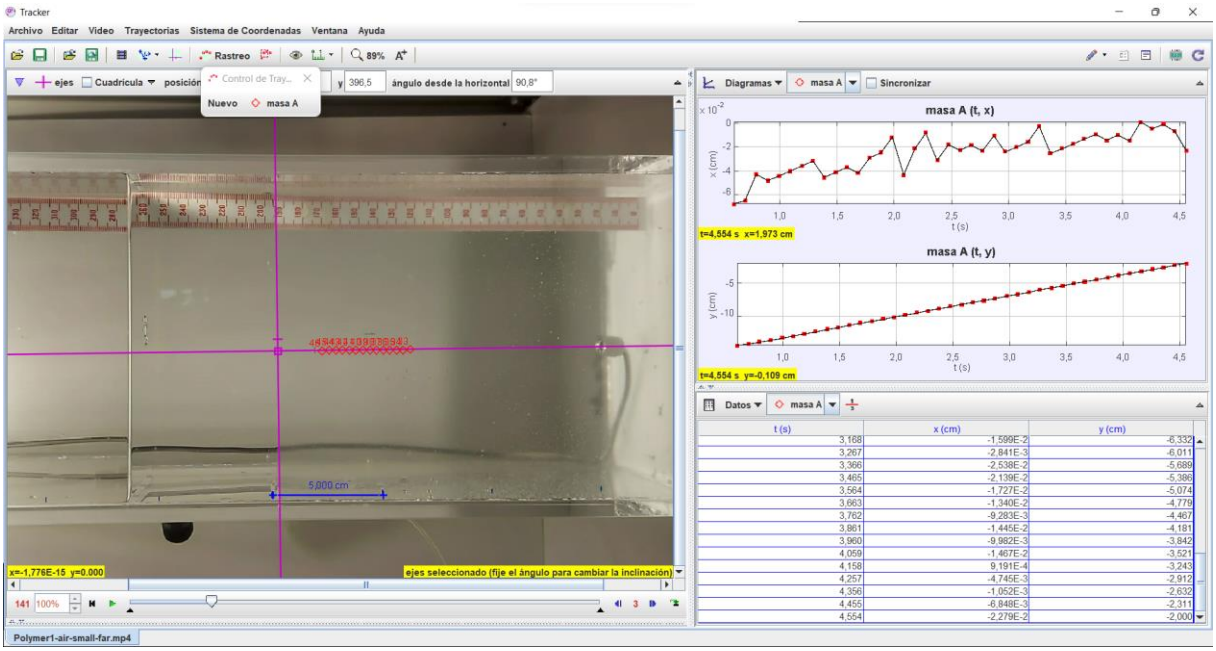


Figure 4.4: *Software Tracker tracking of the motion of the bubble*

To conclude with the software, for all the frames previously determined the position of the bubble has been chosen, and the plots has been generated, with the corresponding data, on this step, the plot of "vertical speed vs time" was added, as was mentioned before the speed of the recorded videos were ¼ of the real speed, for this reason, the table with the data of time, vertical position, horizontal potion and speed was exported to excel were the correspond data was fixed into the real time and the origin point of the bubble -15 cm was set up as the time 0. On the **Figure 4.5** is presented the software at the last step, more over on the **Figure 4.6** are the auto generated plots by the software.

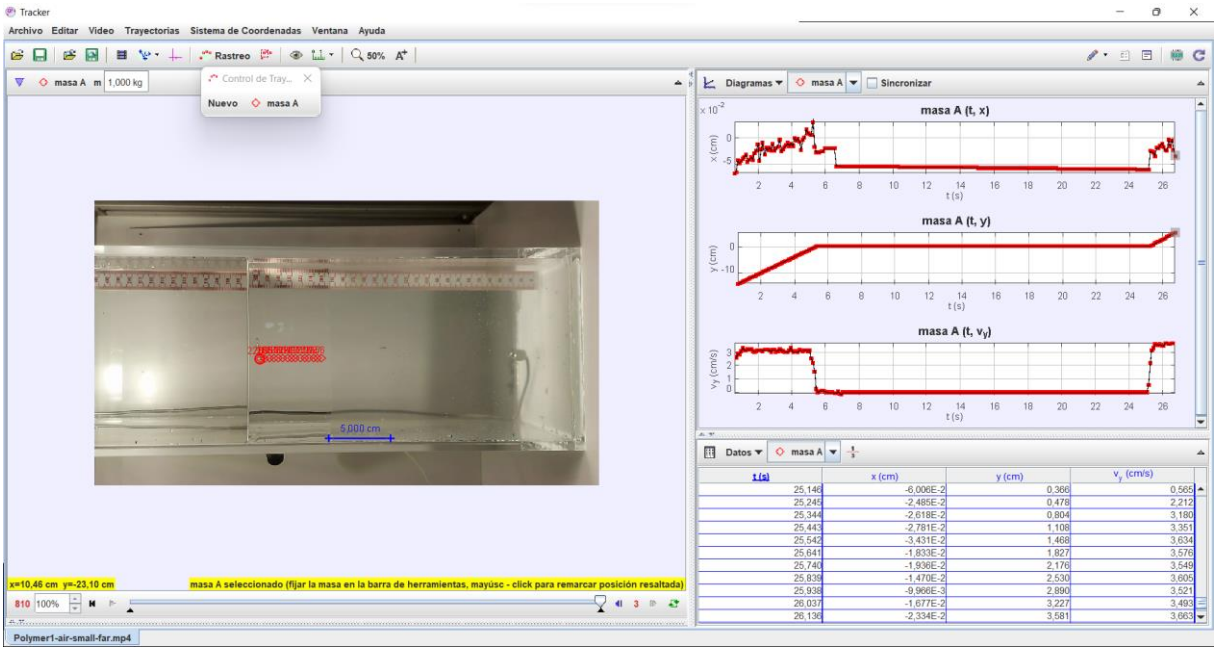


Figure 4.5: *Software Tracker. Final results*

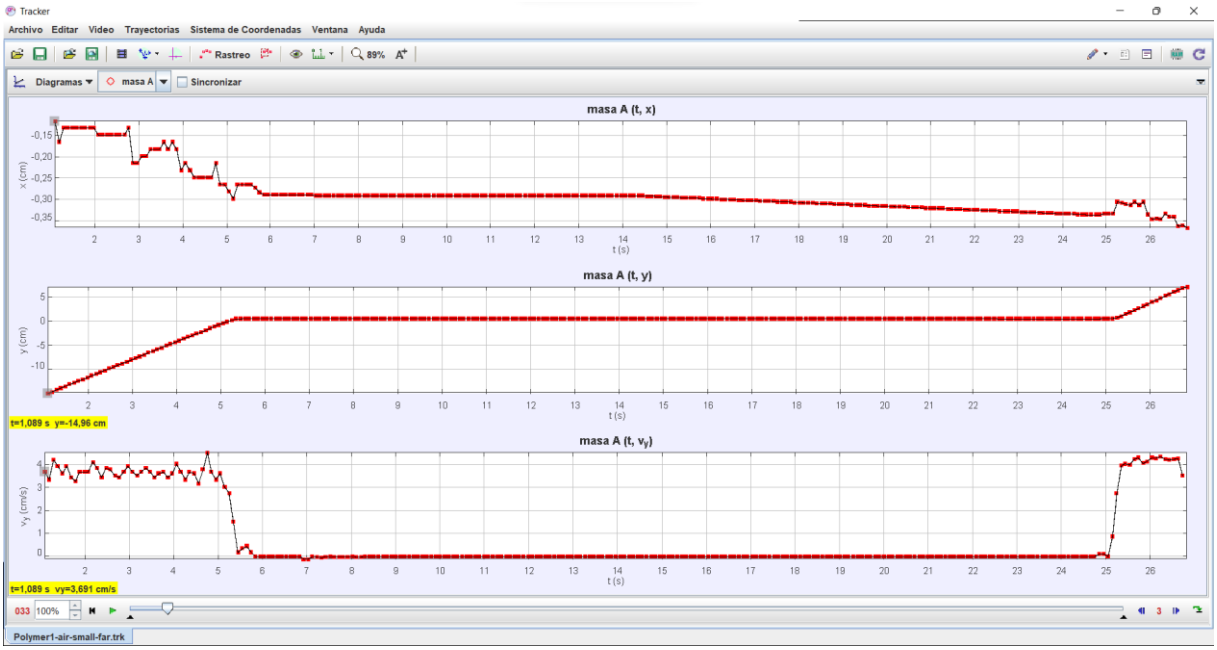


Figure 4.6: *Software Tracker. Auto-generated plots*

4.2Data Obtained from measurements at the lab

As it was presented on the chapter 3, some measurements of physical properties were made to have a reference for the experiments.

4.2.1 Viscosity

With the utilization of the Viscometer Model 800 from OFITE, the measurement of the viscosity of the water with polymers shear rate vs shear stress was made, giving the plots presented on **Figure 4.7 and 4.8.**

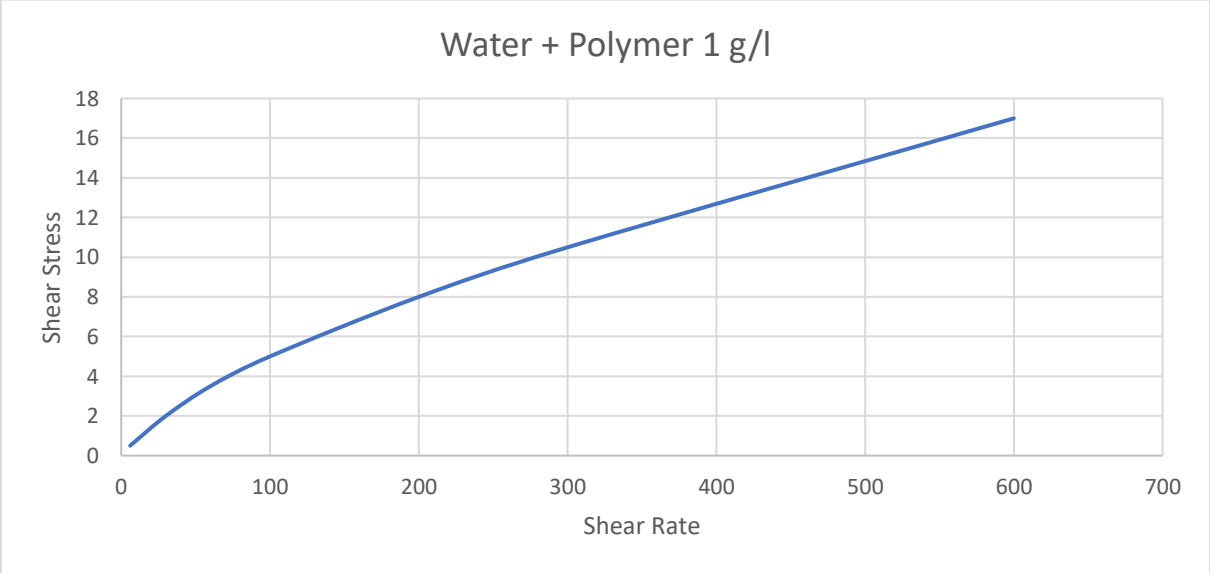


***Figure 4.7**: Shear Rate vs Shear Stress Plot. Water + Polymer 1 g/l*

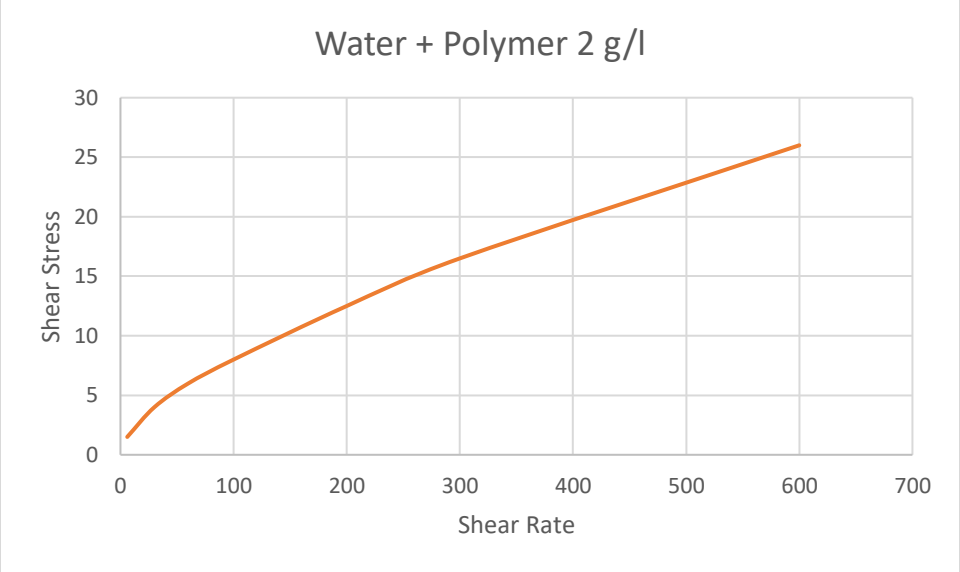


***Figure 4.8**: Shear Rate vs Shear Stress Plot. Water + Polymer 2 g/l*

With the data obtained, and with the study of the behavior of the fluids, it was determinate that both fluids present a pseudoplastic fluid behavior, that means a non-Newtonian behavior, were the shear stress increases in a nonlinear behavior until it reaches a plateau, for this cases, it is necessary the utilization of the Bluckey Hershel Equation **(Eq. 4.1)** in order to get the viscosity of the fluids. (Ferraris, 1999).

$$\tau = \tau_0 + K\gamma^n \tag{4.1}$$

Where:

- τ = Shear stress.
- τ_0 = Yield stress.
- K = Constant
- γ = Shear rate

- n = viscosity

To have a clear comparation of between the fluids on **Figure 4.9** is the behavior of both curves is presented. Here can be observed how a small concentration can change dramatically the inclination of the curve, and same way the increase on the shear stress for the fluids.

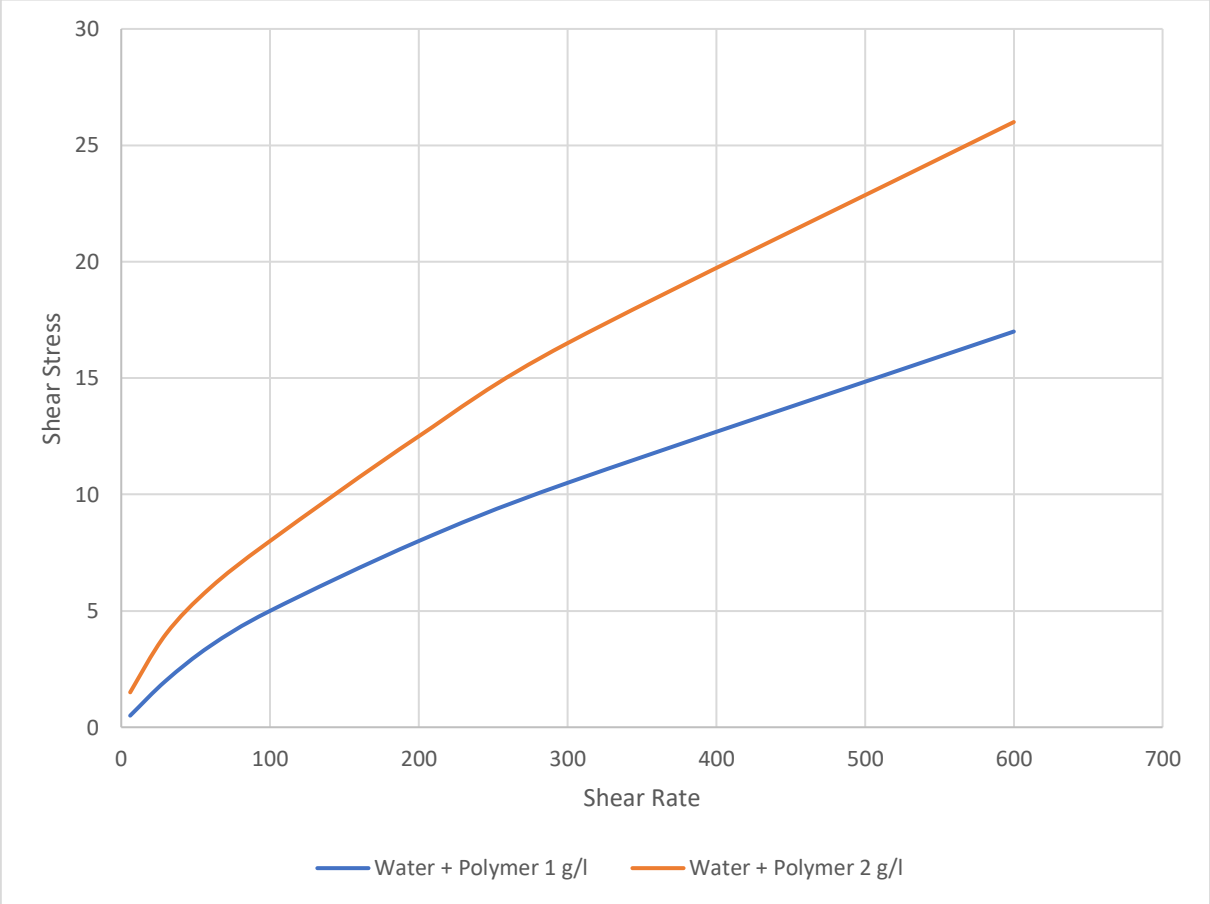


Figure 4.9: *Shear Rate vs Shear Stress Plot. Water + Polymer 1 ppm and, Water + Polymer 2 ppm*

4.2.2 Superficial and Interfacial Tension

With the utilization of the Kruss K6 Tensiometer and the ring K 810, superficial tension of all the fluids were measured, also the measurement of interfacial tension between Water and Oil, Water + Polymer 1 g/l and Oil and finally Water + Polymer 2 g/l and Oil, it was desirable to have the tension between the liquid fluids and CO_2, but the laboratory does not have the proper equipment to do this measurement. On the **Table 4.1** is presented the data obtained for this measurement

Table 4.1*: Interfacial and Superficial Tension of the Fluids used on the experiment*

Fluid	*Surface Tension mN/m*	*Interfacial Tension mN/m*
Silicone Oil 10K	20.5	
Water	72	32
Water + Polymer 1ppm	73.5	42
Water + Polymer 2ppm	75	48

As is presented on the table a higher concentration of the polymer in the water, will lead to a linear increase on the interfacial and surface tension between the fluids, all the data obtained has a measurement accuracy of ±1 mN/m.

4.2.3 Density

The density obtained by the utilization of the densimeter DMA 4500 M is presented on the **Table 4.2**

***Table 4.2**: Density of the Fluids used on the experiment*

FLUID	***DENSITY***
DETILATED WATER	*998 kg/m^3*
WATER + POLYMER 1 PPM	*999 kg/m^3*
WATER + POLYMER 2 PPM	*1000 kg/m^3*
SILICONE OIL	*930 kg/m^3*

Chapter 5

5. Experiment Results

On this section will be described all the results obtained on each experiment, furthermore comparation between the different fluids, bubble path of the different sizes will be explained, interface behavior, bouncing of the bubbles at the interface, film rupture, shape of the bubble, formation of droplets and others. Based on the **Equation 5** the sized of the bubbles decided to run the experiment with three different bubble sizes that were 0.014, 0.065 and 0.11 cc respectively, furthermore, for each experiment bubbles of Air and CO_2 were injected at the in the system for a total of 18 experiments. Each plot will present three zones (3) the heavier fluid zone, the interface zone and the last one will be the lighter fluid zone, where three different plots will be presented, the vertical position, horizontal position, and vertical speed of the bubble. Each test was repeated for 20 times and the difference of time was ±0.5 seconds for the 0.014 cc bubble ±0.3 seconds for the 0.065 cc bubble and 0.1 seconds for the 0.11 cc bubble.

5.1 Water - Oil System

The first experiment made, was the one that has been study on previous experiments, as is shown in (Greene, Chen, & Conlin, 1988), (Rozario, Viswanathan, & Basu, 2019), (Rabenjafimanantsoa & Time, 2013), this experiment was made mainly to have a reference and compare with the other experiments two experiments that were done between a Non-Newtonian + Oil system.

5.1.1 Small Size bubble of Air in a Water - Oil system

A small bubble of air is injected at the bottom of the system, it rises up for a time around 0.74 seconds util it reaches the interface, at this point, during the first collision, the vertical component of interfacial tension force overcomes with both buoyancy and inertia forces presenting a slight braking for around 0.16 seconds, after that the interface breaks, and the bubble continues its path to the silicon oil. On the **Figure 5.1** is shown the vertical position of the bubble of air of 0.014 cc versus time.

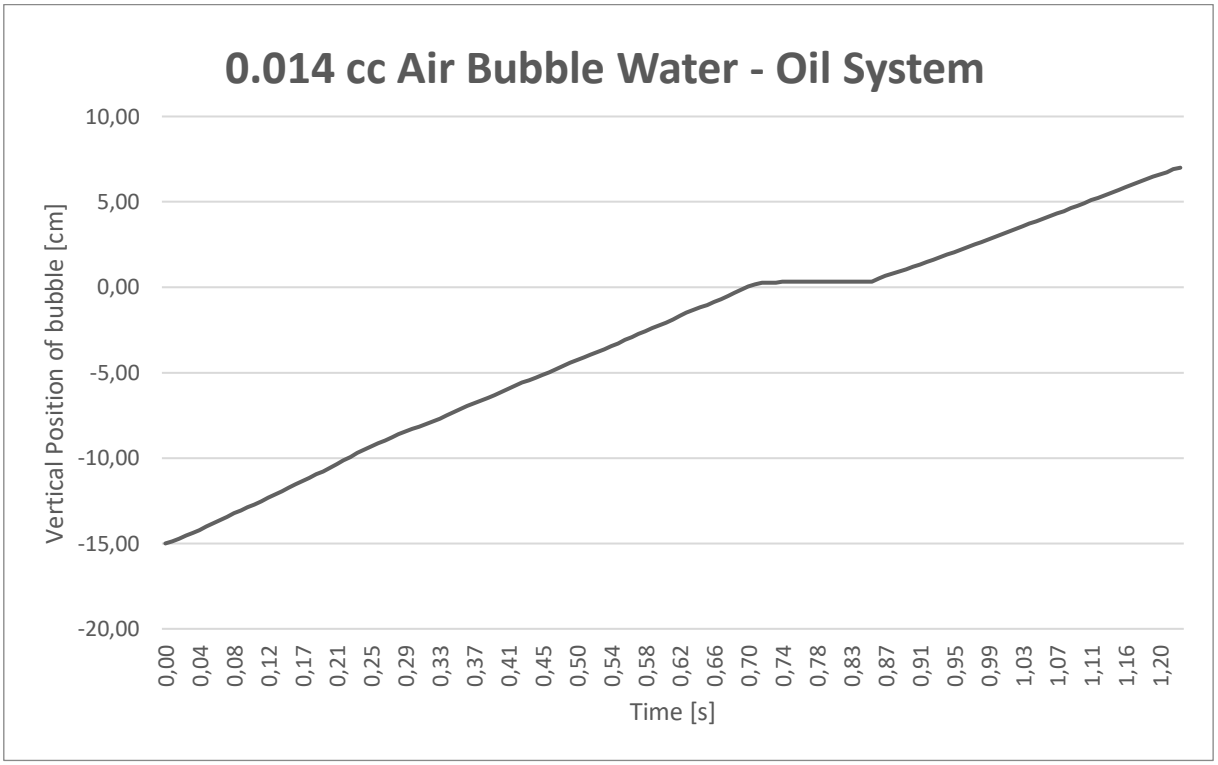


***Figure 5.1**: Vertical Position vs Time, Bubble of Air 0.014 cc in a Water - Oil system*

Along the first zone, the heavy liquid zone, the bubble presents a zig zag movement until it reaches the interface, **Figure 5.2**, after this point it will present a more linear behavior with a soft inclination to one side, while the speed on the lighter fluid is slightly slower than in the heavier one (**Figure 5.3)** even though the path of the bubble has lower fluctuations. Also, with the speed is presented clearly the behavior at the interface.

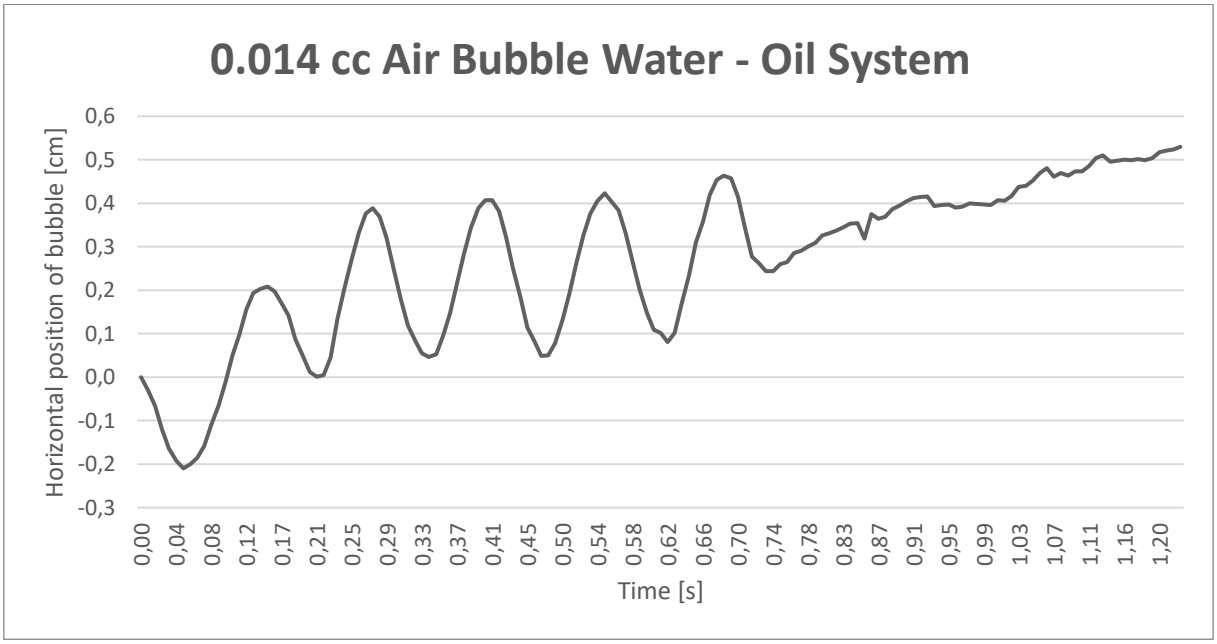


Figure 5.2: *Horizontal Position vs Time, Bubble of Air 0.014 cc in a Water - Oil system*

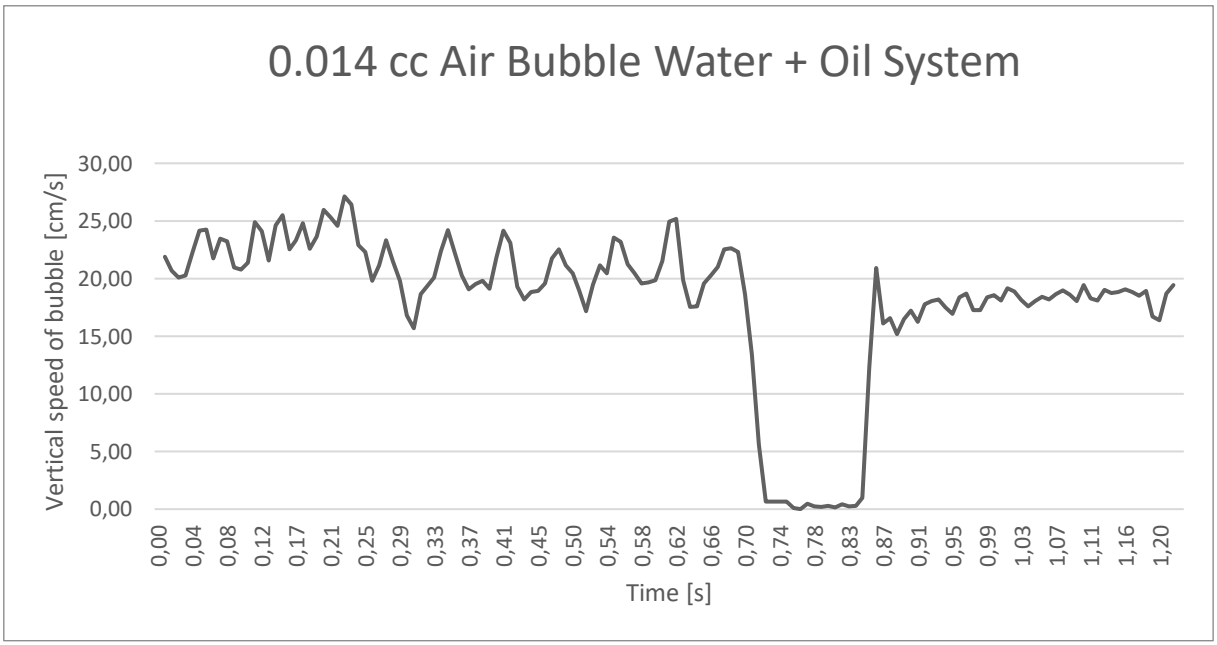


Figure 5.3: *Vertical Speed vs Time, Bubble of Air 0.014 cc in a Water - Oil system*

On the **Figure 5.4** is presented the behavior of the bubble at the interface, here as it can be seen, due to the viscosity of the oil, the shape of the bubble changes significantly, changing from an spherical shape to one more elliptical. The rupture of the interface does not present significant droplets or any drag from the heavier fluid into the lighter one and a thin film of water is formed over the bubble and rises to the surface of the oil surrounding the air bubble.

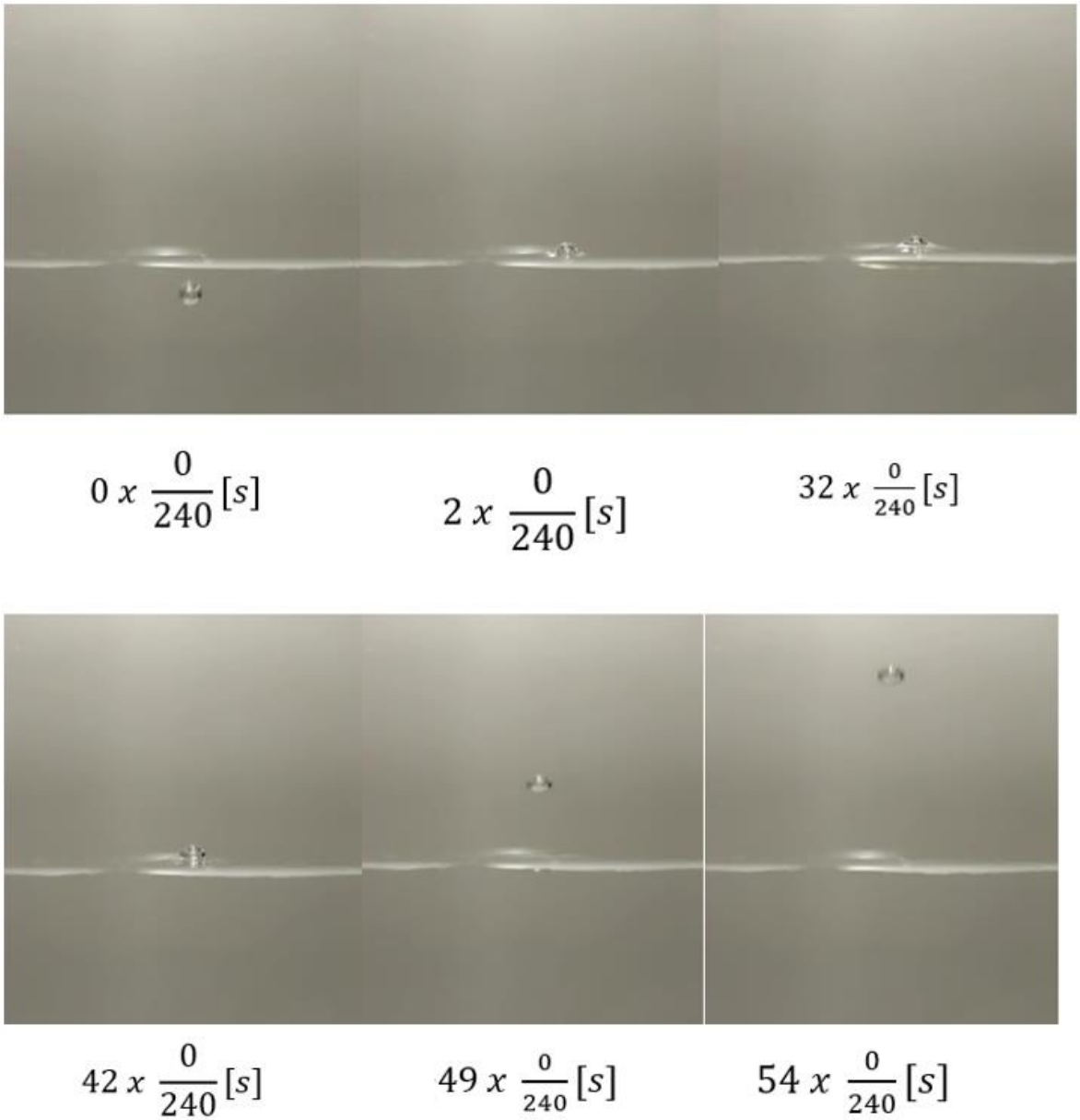


Figure 5.4: *Bubble of Air 0.014 cc at the interface in a Water - Oil system*

5.1.2 Small Size Bubble of CO2 in a Water – Oil System

The behavior of the CO2 and the air are similar to the one presented by the bubble of Air, but this one will have a faster movement along the system, where a small bubble of CO_2 is injected at the bottom of the system, it rises up for a time around 0.74 seconds util it reaches the interface, at this point, due to the vertical force of interfacial tension force is strong enough to overcome the buoyancy and inertia forces reduce the speed of the bubble considerably for approximately 0.21 seconds, a longer time that the air, subsequently the interface breaks, and the bubble continues its path to the silicon oil. The vertical position of the bubble of CO_2 of 0.014 cc versus time is presented on the **Figure 5.5**. The vertical component of the interfacial tension force.

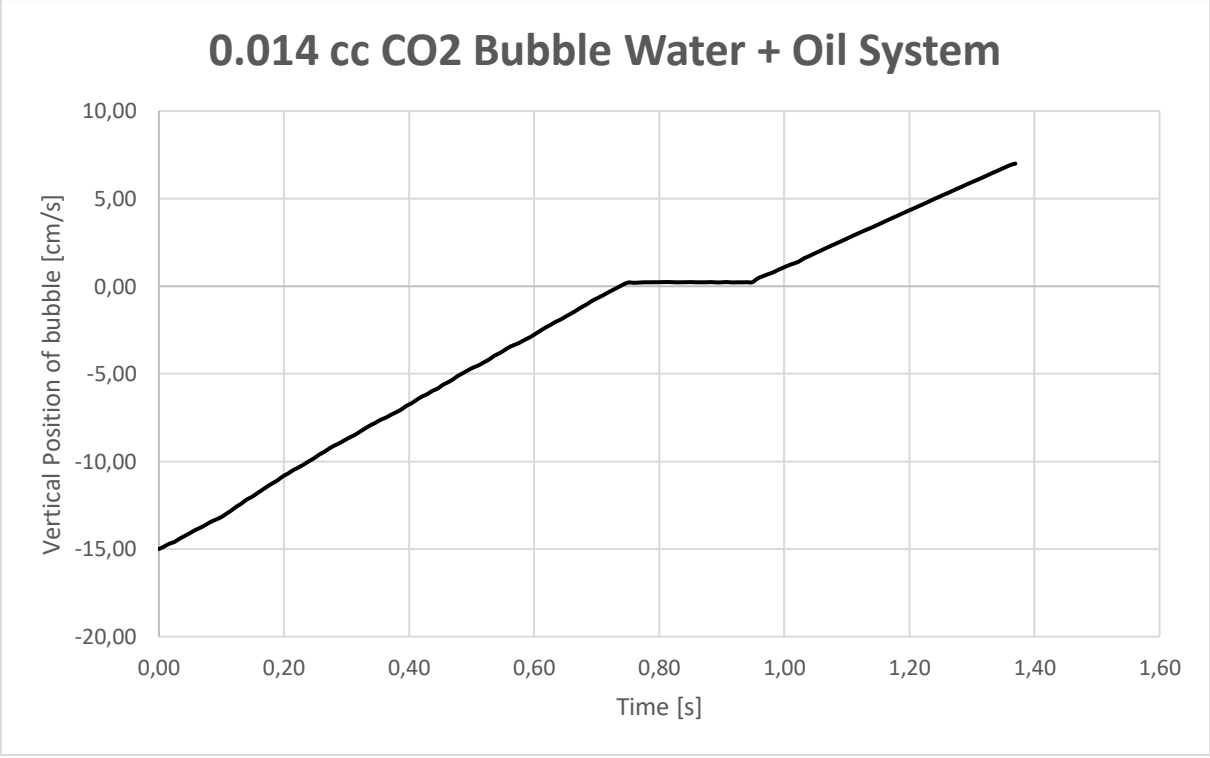


Figure 5.5: *Vertical Position vs Time, Bubble of CO2 0.014 cc in a Water - Oil system*

The behavior of the bubble in the horizontal axis present wider fluctuation that in the experiment with air, **Figure 5.6**, and the position at the interface is more constant, also, there

is no inclination on the direction of the bubble in the lighter zone, the speed of the bubble in the system is shown in the **Figure 5.7.**

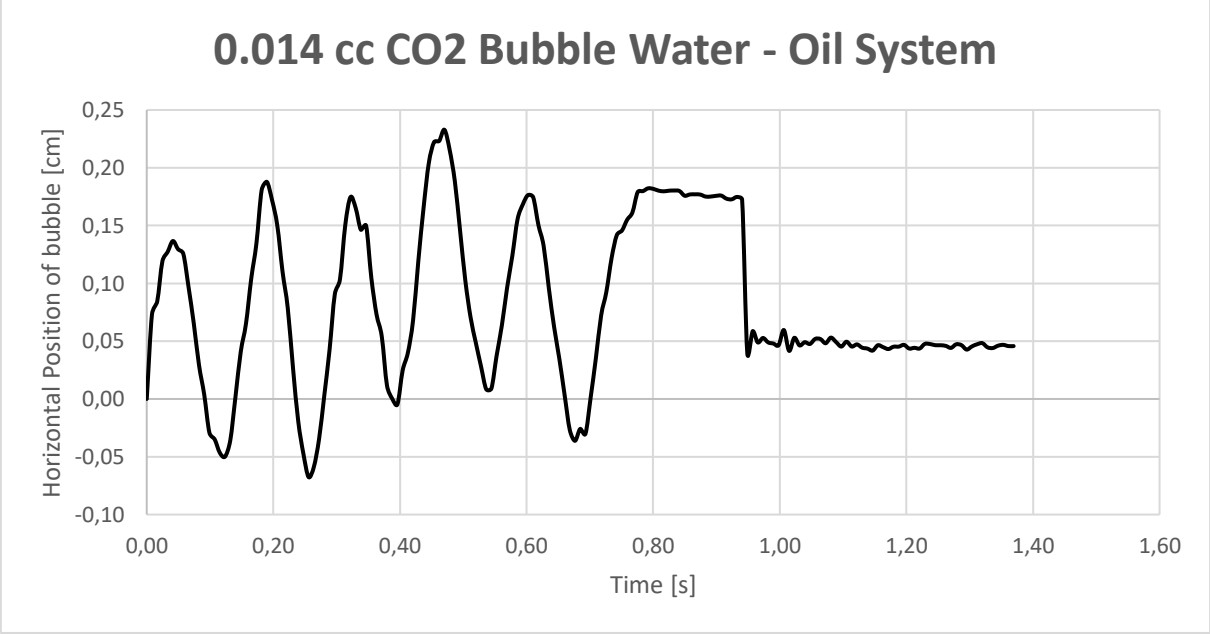


Figure 5.6: *Horizontal Position vs Time, Bubble of CO2 0.014 cc in a Water - Oil system*

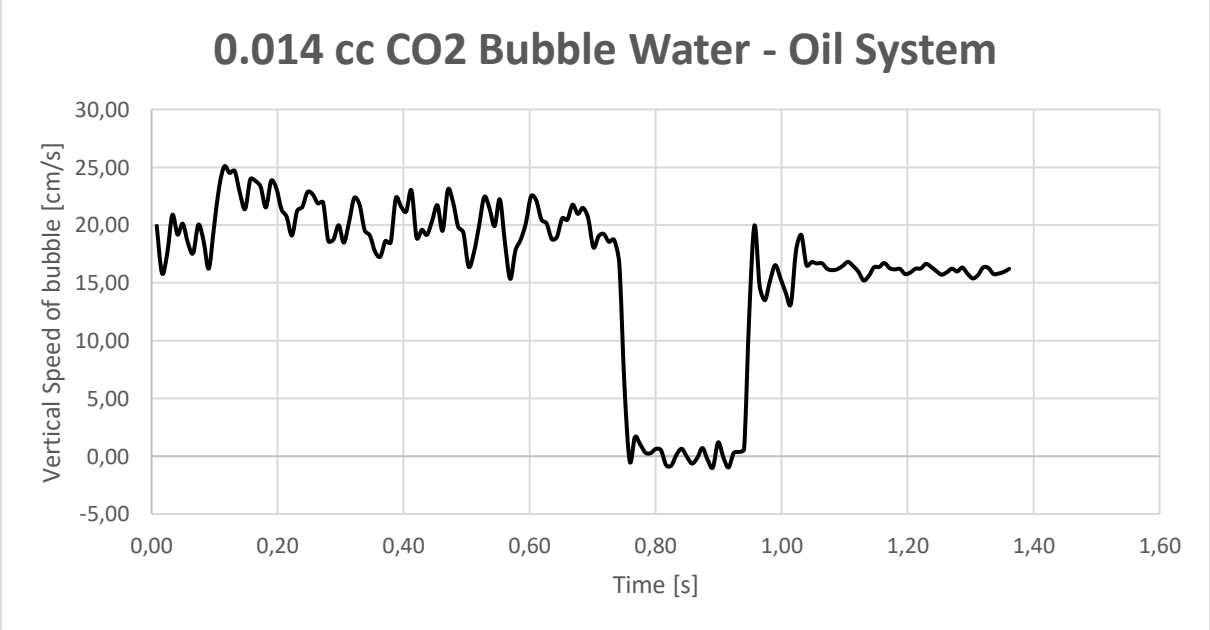


Figure 5.7*: Vertical Speed vs Time, Bubble of CO2 0.014 cc in a Water - Oil system*

The behavior of the bubble of CO2 at the interface shows less desviation of the movement at the interface and the shape of the bubble is almost constant, a thin film of water is formed over the bubble and rises to the surface of the oil, the bubble keeps an spherical shape along both fluids as is presented on the **Figure 5.8**. When the interface breaks there is not formation of any droplets or grag from the heavier fluid into the lighter one.

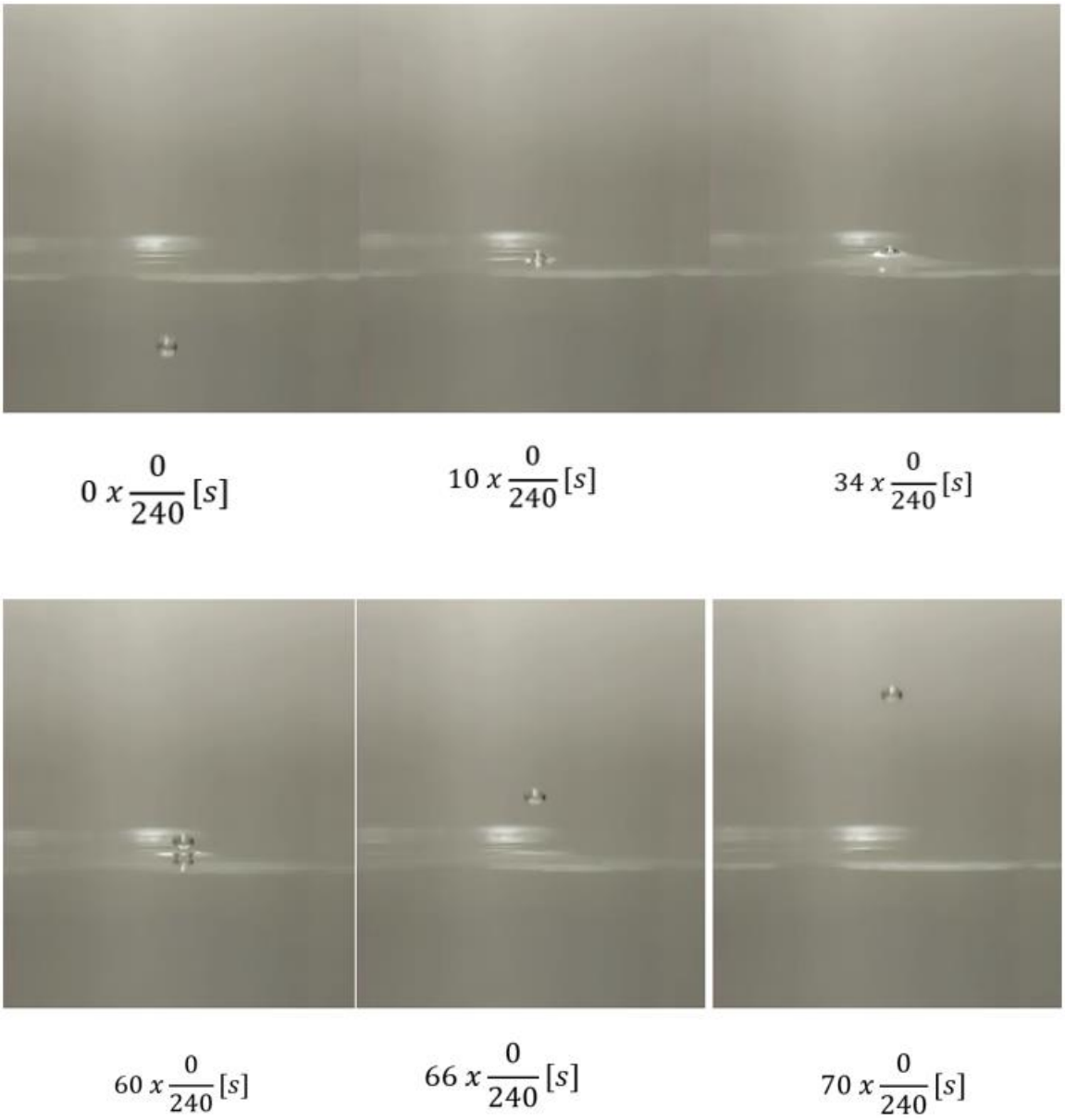


Figure 5.8: *Bubble of CO2 0.014 cc at the interface in a Water - Oil system*

5.1.3 Medium Size Bubble of Air in a Water - Oil System

The bubble of 0.065 cc (the intermediate volume used for the experiment), was injected at the bottom, where the time on the first zone, before it reaches the interface is approximately 0.70 seconds, here at the interface, the position of the bubble is slightly over the interface without breaking it, for a period of 0.13 seconds, at this point the vertical forces are not strong enough to completely stop the motion of the bubble and this one keeps rising constantly, on the **Figure 5.9** is presented the Vertical Position of the bubble vs time.

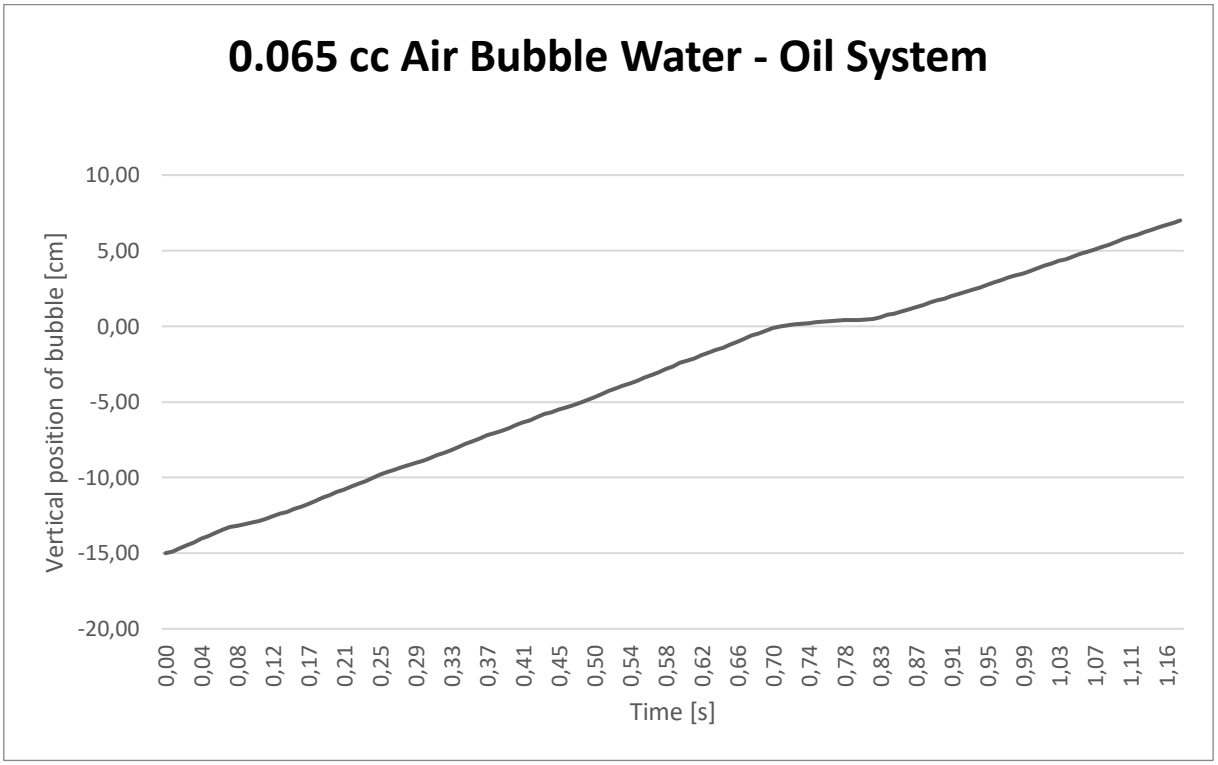


Figure 5.9: *Vertical Position vs Time, Bubble of Air 0.065 cc in a Water - Oil system*

On the heavy liquid zone, the bubble presents a zig zag movement with a slight tendency to one direction, where the amplitude of the movement increases until it reaches the interface, **Figure 5.10**, after this point it will present a more linear behavior keeping the soft inclination to the side that was having before the interface, while the speed on the lighter fluid is slightly

slower than in the heavier one (**Figure 5.11)**, here at the interface is presented a soft bouncing of the bubble.

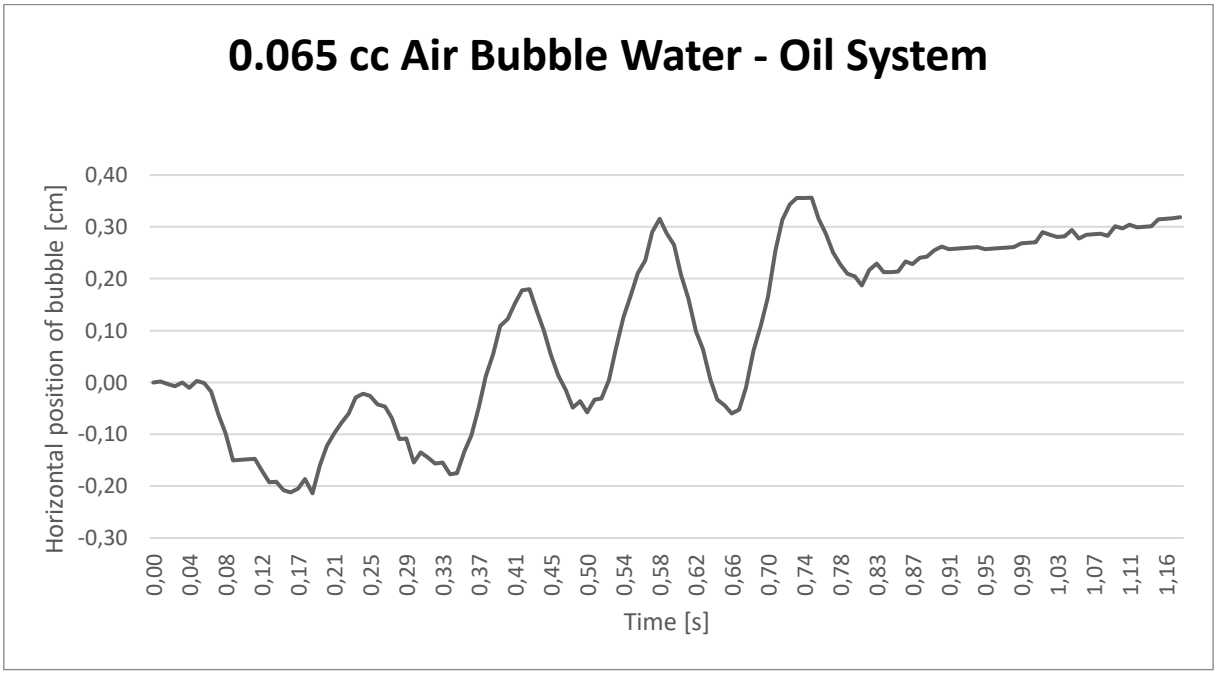


Figure 5.10: *Horizontal Position vs Time, Bubble of Air 0.065 cc in a Water - Oil system*

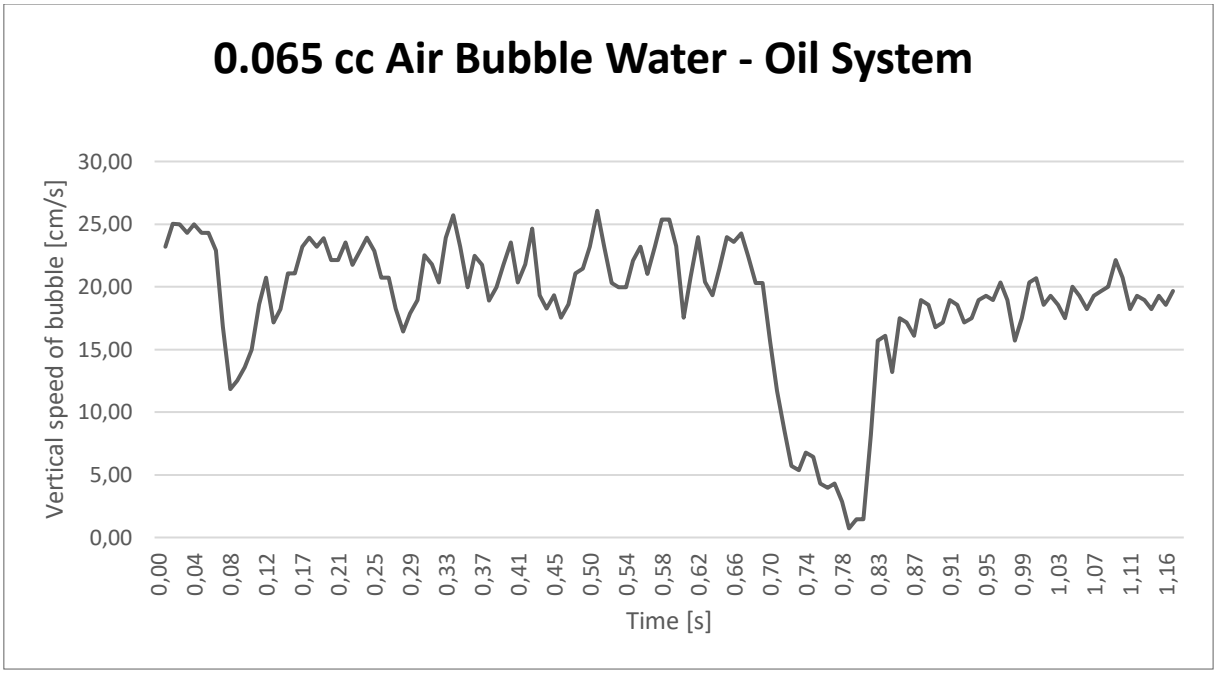


Figure 5.11: *Vertical Speed vs Time, Bubble of Air 0.065 cc in a Water - Oil system*

At the interface, the bubble will reduce its velocity but never stops, then, when it keeps raising, the formation of a thin fil over the bubble will occur, when the bubble keeps rising, there will be a lifting of a column of the heavier liquid, util the column breaks, the thin film of water will stay on the bubble and this one keep the rising motin almost at constant velocity, on this movement, because of the rupture of the column of water, there can be found formation of small satellites bellow the bubble. The shape of the bubble will change on the heavier liquid because of the viscosity presented on this one, on the **Figure 5.12** is presented the behavior just mentioned.

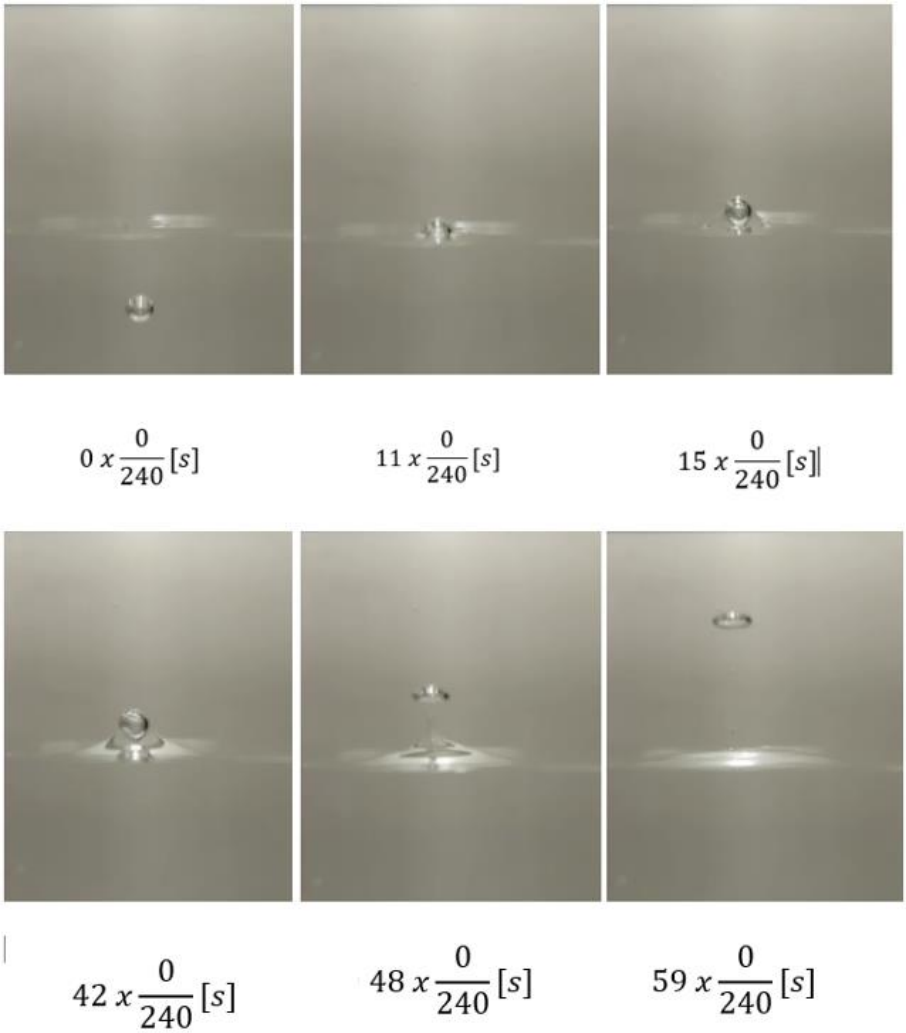


Figure 5.12: *Bubble of Air 0.065 cc at the interface. in a Water - Oil system*

5.1.4 Medium Size Bubble of CO2 in Water – Oil System

With the bubble of 0.065 cc injected at the bottom of the system, the time necessary for it to reach the interface was 0.75 seconds, here at the interface, the bubble takes a lapse of time of 0.16 seconds, the buoyancy force is strong enough after that time gap to overcome the vertical forces and, the bubble breaks the interface continuing its path to the surface through the lighter fluid, the time gap at the interface is 0.33 seconds, on the **Figure 5.13** is presented the Vertical Position of the bubble vs Time.

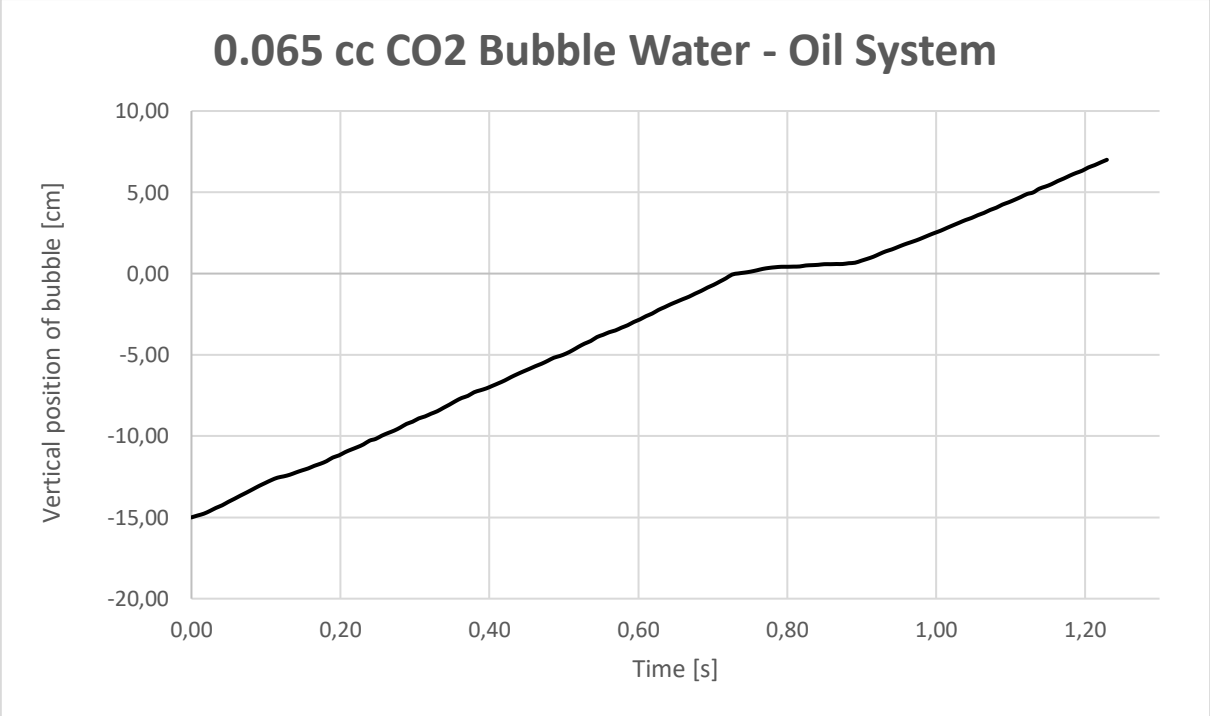


Figure 5.13: *Vertical Position vs Time, Bubble of CO2 0.065 cc in a Water - Oil system*

On the horizontal position of the bubble, it can be seen a zig zag movement that tends to keep the same path, with no inclination, that after the interface, is almost linear, as is seen on the **Figure 5.14,** on the other hand, at **Figure 5.15** is presented the vertical speed of the bubble, where can be seen a reduction of the speed on the lighter zone (zone 3).

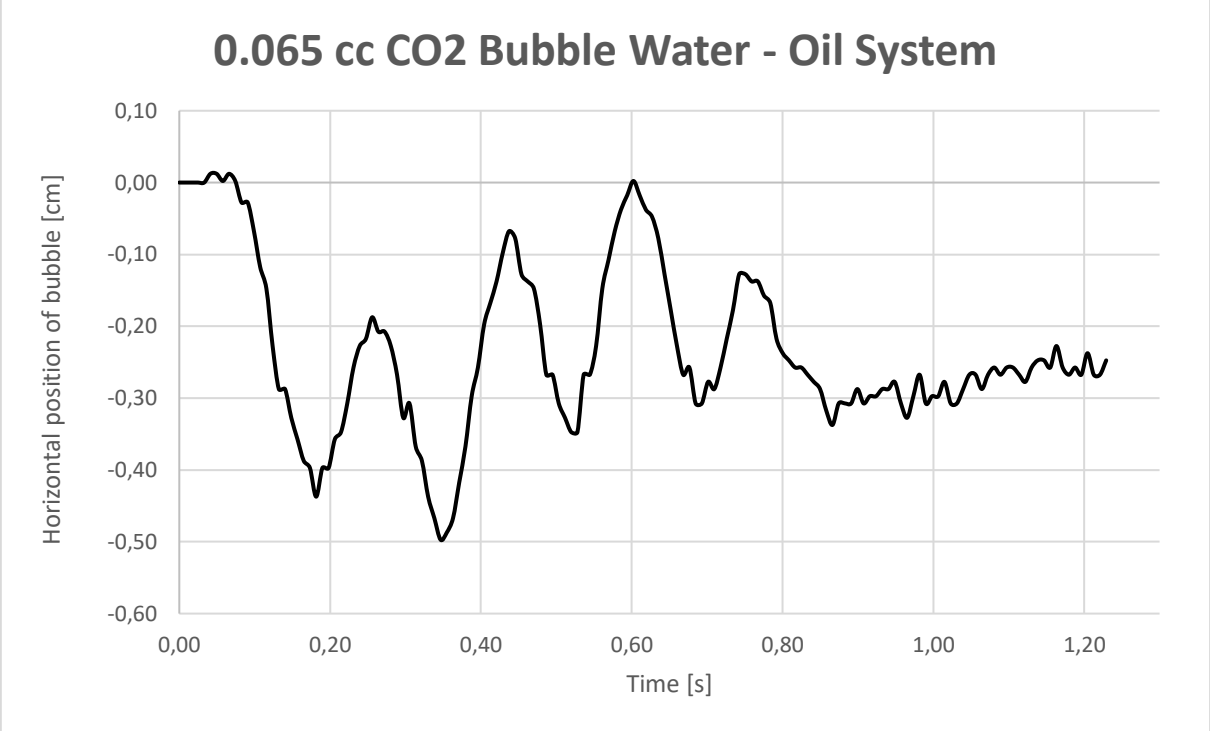


Figure 5.14: *Horizontal Position vs Time, Bubble of CO2 0.065 cc*

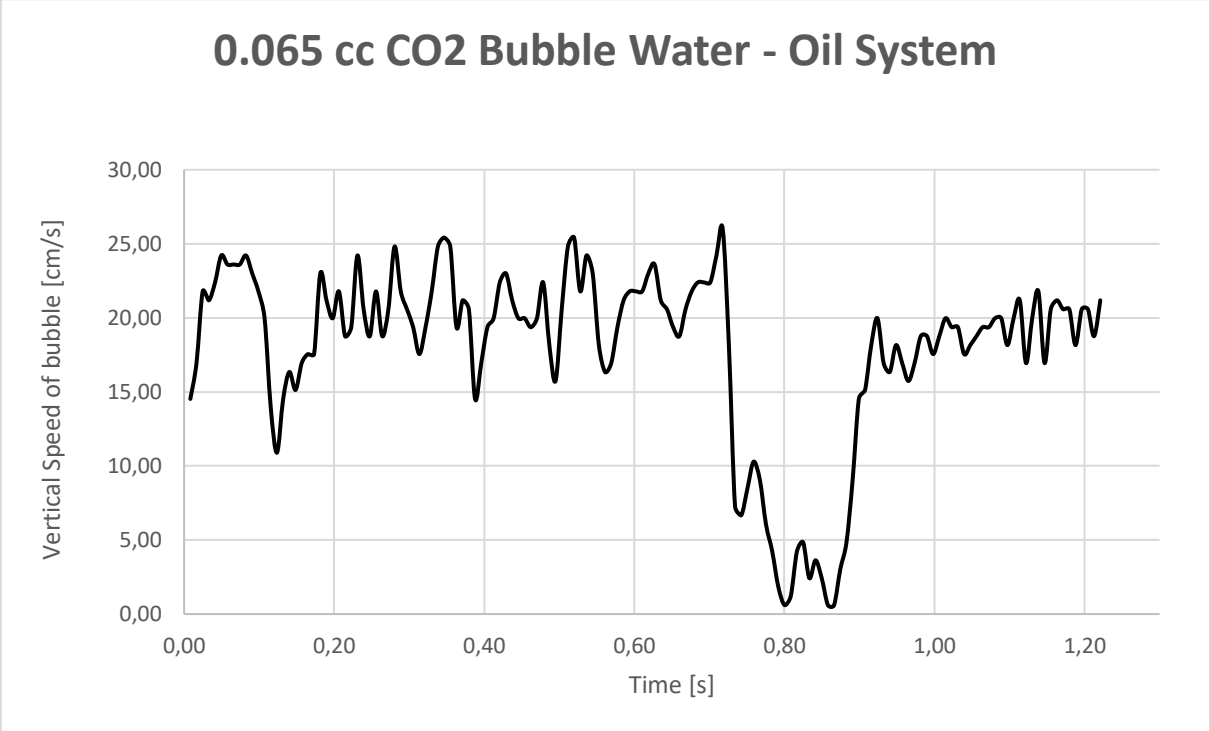


Figure 5.15: *Vertica Speed vs Time, Bubble of CO2 0.065 cc in a Water - Oil system*

On the **Figure 5.16** is presented the behavior of the bubble Medium size of CO2 at the interface, at this position, an small column of the heavier liquid is lifted to the light liquid, that will break and form small droplets, a small bubble of the column is presented because of the inertial forces presented on the water column. In adition a thin film of water will cover the bubble of CO2 the rest of the path, however, due to the viscosity of the oil, the shape of the bubble changes significantly, from an spherical shape to one more elliptical.

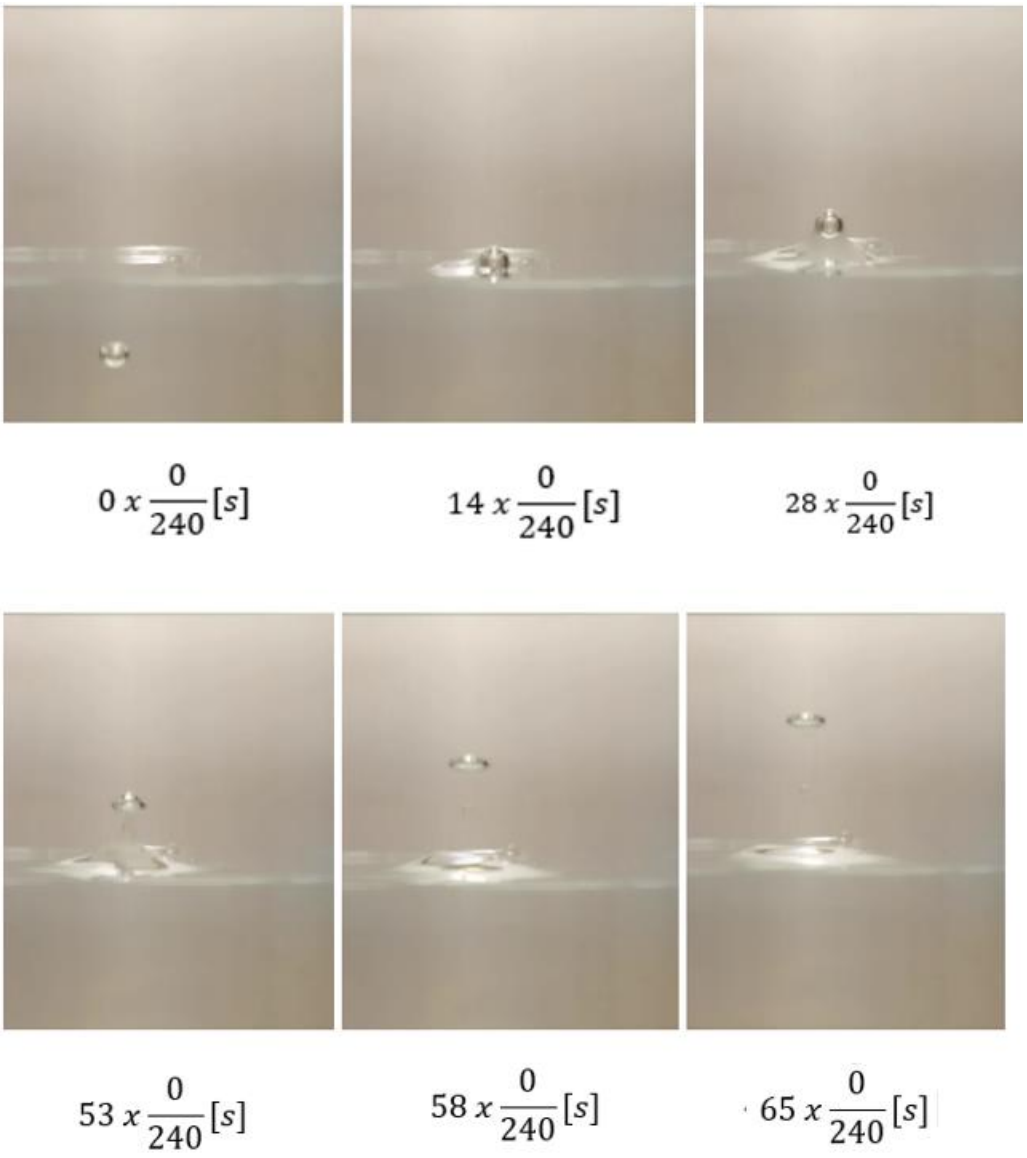


Figure 5.16: *Bubble of CO2 0.065 cc at the interface. in a Water - Oil system*

5.1.5 Big Size Bubble of Air in Water – Oil System

The biggest size of the bubble was 0.11 cc, on this experiment, the motion of the bubble is almost constant, where the bubble reaches the interface after 0.60 seconds of motion, as the size of the bubble has increase, the total upward force acting on the bubble is considerably higher than the previous two experiments, this can be observed, because the interface does not interrupt significantly the motion of the bubble and after the interface, the inclination of the plot goes softly downwards, the main reason for this behavior is the viscosity of the lighter fluid, the vertical movement of the bubble is shown on the **Figure 5.17**.

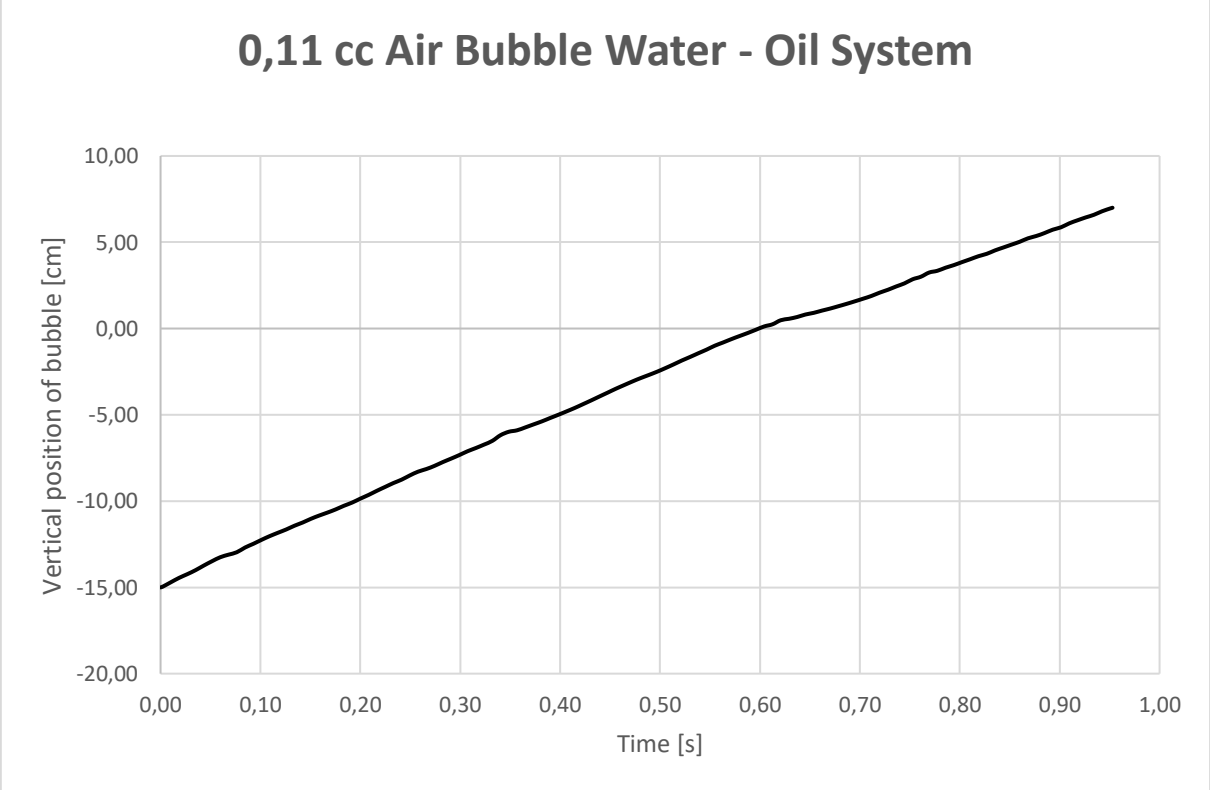


Figure 5.17: *Vertical Position vs Time, Bubble of Air 0.11 cc in a Water - Oil system*

The horizontal motion of the bubble, **Figure 5.18,** shows lower fluctuations along the system, having a more linear behavior, also, the speed is almost constant in both fluids, as can be seen on the **Figure 5.19,** meanwhile the interface does not show a significant reduction on the speed, where, for previous cases, the instant speed sometimes was zero or below, because of smalls bouncing. The total time for the bubble travel was 0.95 seconds having a maximum speed of 30 cm/s.

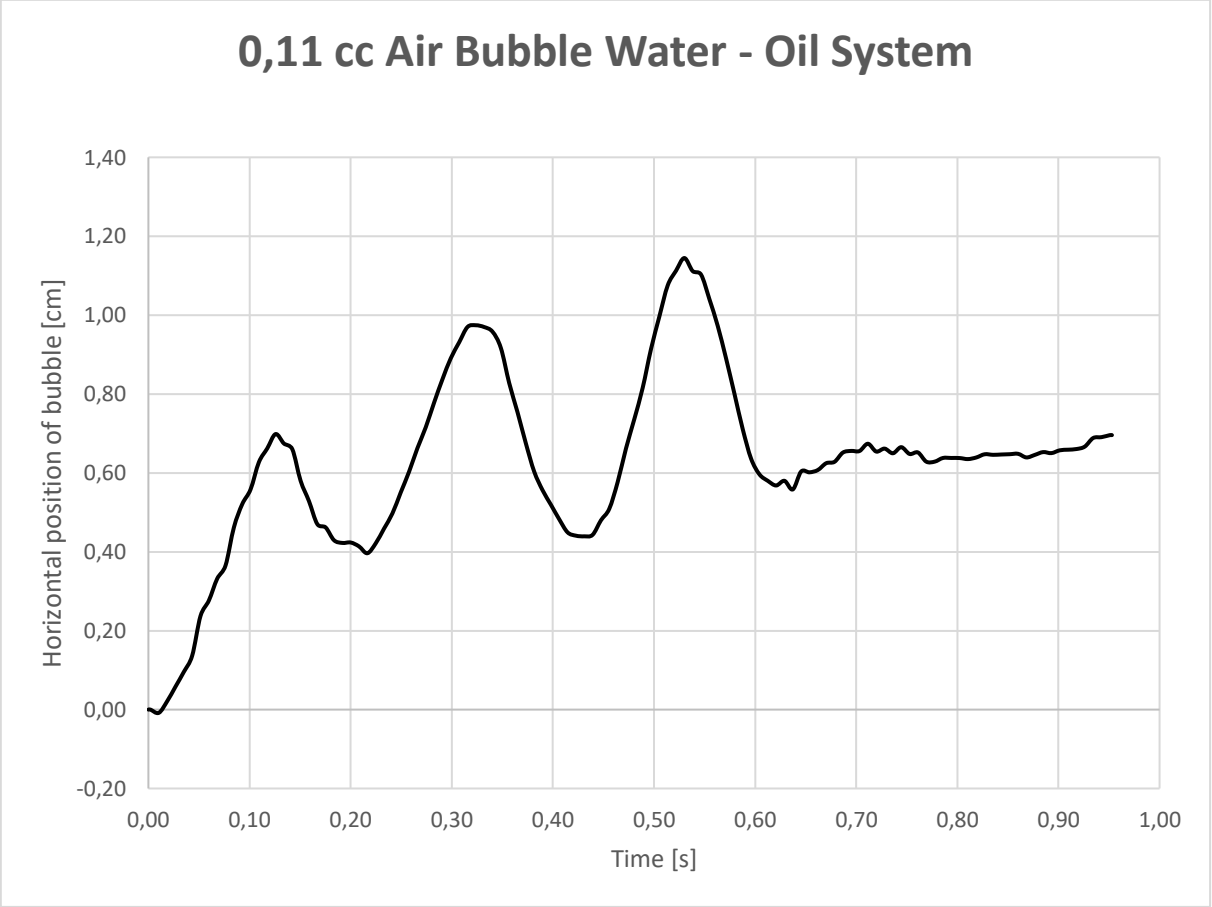


***Figure 5.18**: Horizontal Position vs Time, Bubble of Air 0.11 cc in a Water - Oil system*

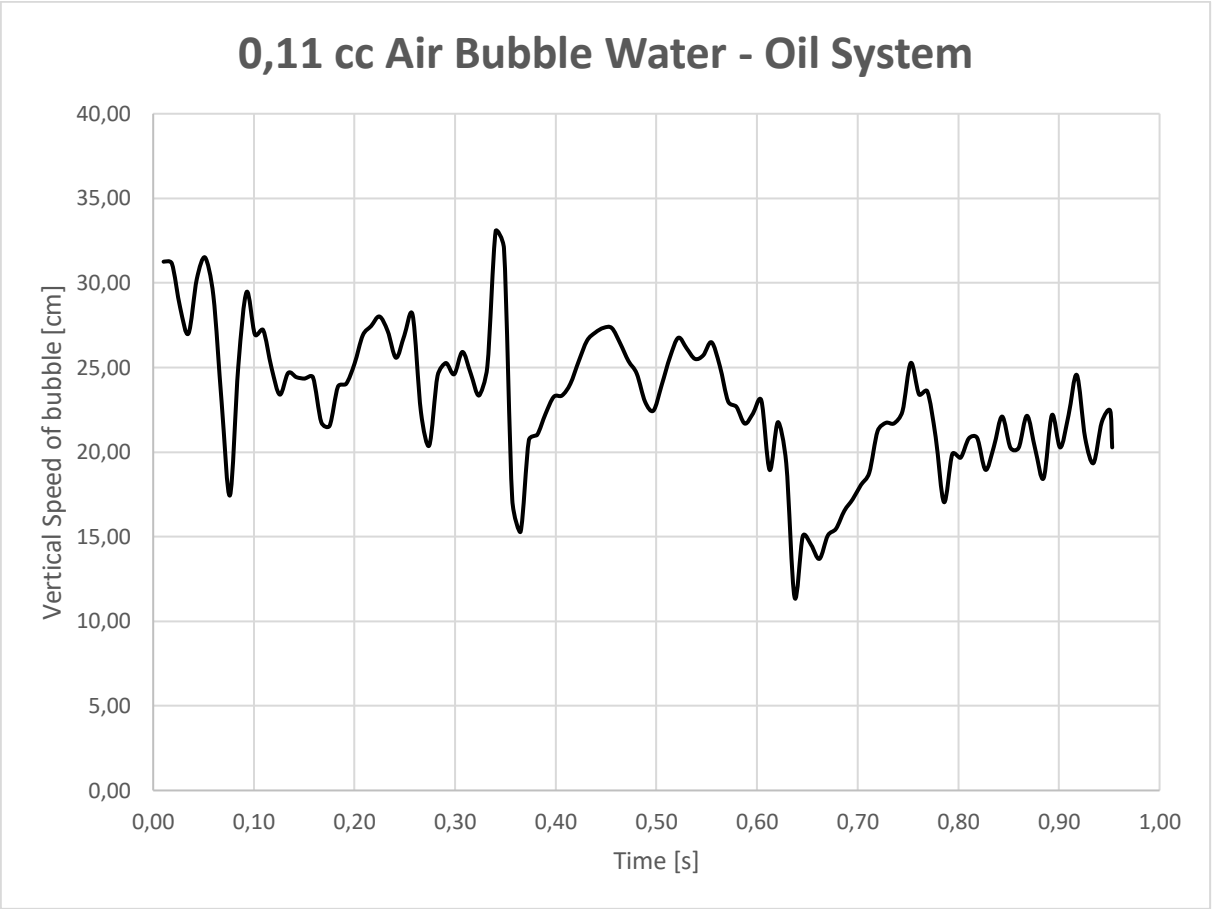
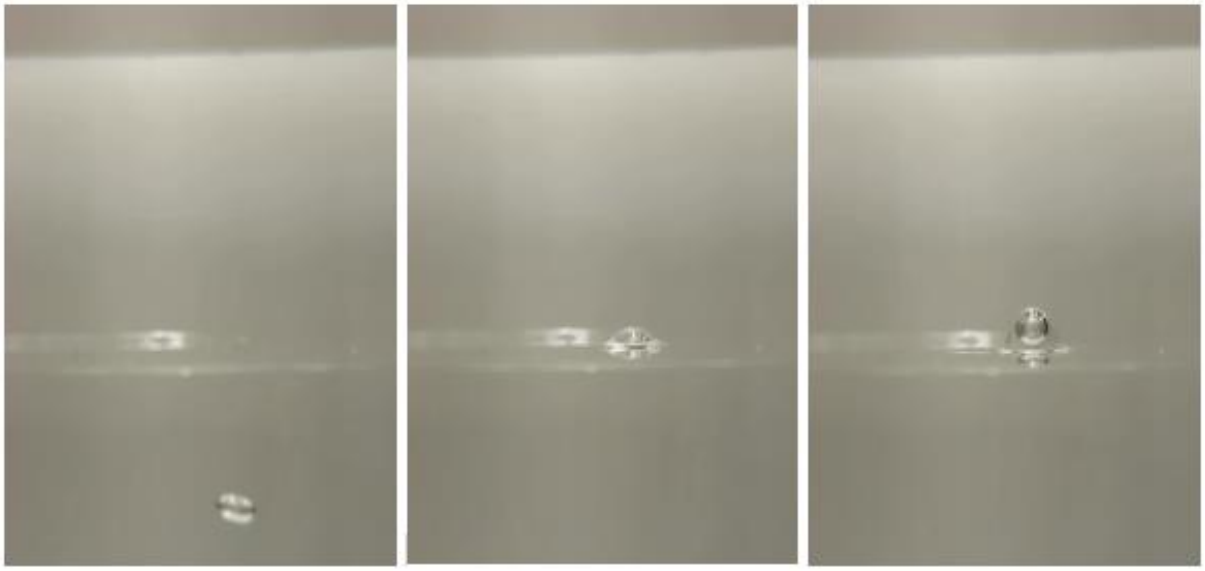
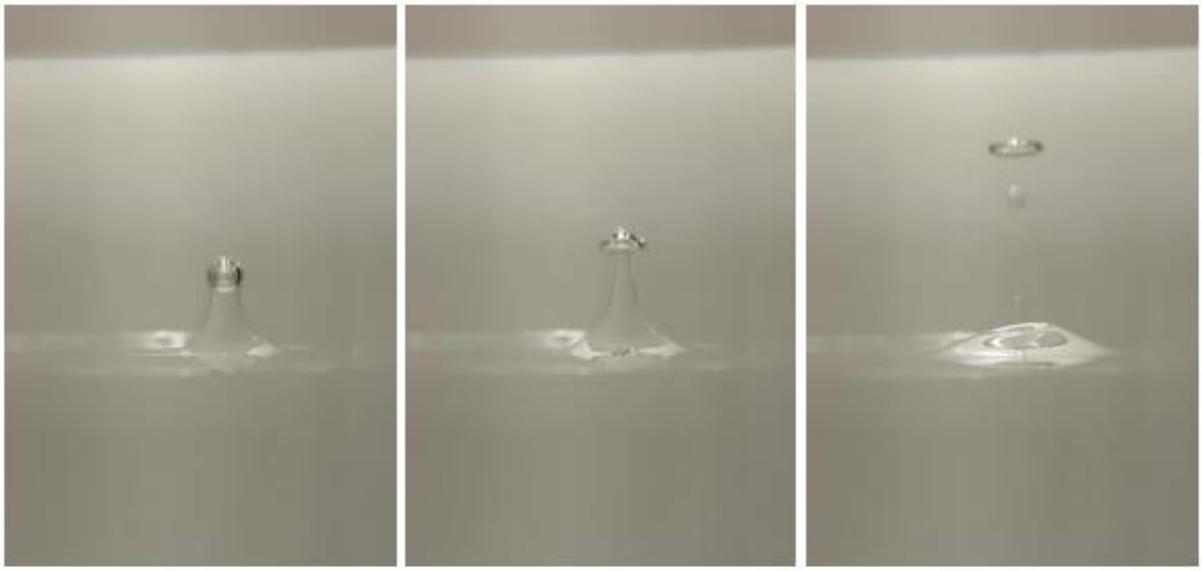


***Figure 5.19**: Vertical Speed vs Time, Bubble of Air 0.11 cc in a Water - Oil system*

Due to the high speed of the rising bubble, the time gap at the interface is really low, and there is not considerably reduction of the speed, on the **Figure 5.20** can be observed all the behavior of the bubble at this point and at the point "0 x 36/240", the rupture and the formation of the three phase contact line (TPCL) is presented, this TPCL is described on the first chapter, the reason for this TPLC, is mainly because of the buoyancy forces are strong enough not only to overcome the vertical forces at the interface, but also to break the film that forms on the bubble. Formation of a large column of the heavier fluid can be observed, also formation of big drops and small droplets are presented. The shape of the bubble after the rupture of the TPCL and the break of the bubble is elliptical.



$0\ x\ \frac{0}{240}[s]$ $19\ x\ \frac{0}{240}[s]$ $23\ x\ \frac{0}{240}[s]$



$32\ x\ \frac{0}{240}[s]$ $36\ x\ \frac{0}{240}[s]$ $49\ x\ \frac{0}{240}[s]$

Figure 5.20: *Bubble of Air 0.11 cc at the interface. in a Water - Oil system*

5.1.6 Big Size Bubble of CO2 in Water – Oil System

With the bubble of 0.11 cc of CO2 the vertical movement had an almost linear movement, where reaches the interface at 0.69 seconds of movement and the top of the lighter fluids at 1.06 seconds. With this plot, **Figure 5.21,** is clear that the effect of the buoyancy, due to the size of the bubble, overcomes every force in the opposite direction, giving a constant movement of the bubble along the system. Moreover, the interface does not have any significant effect on the vertical movement of the bubble.

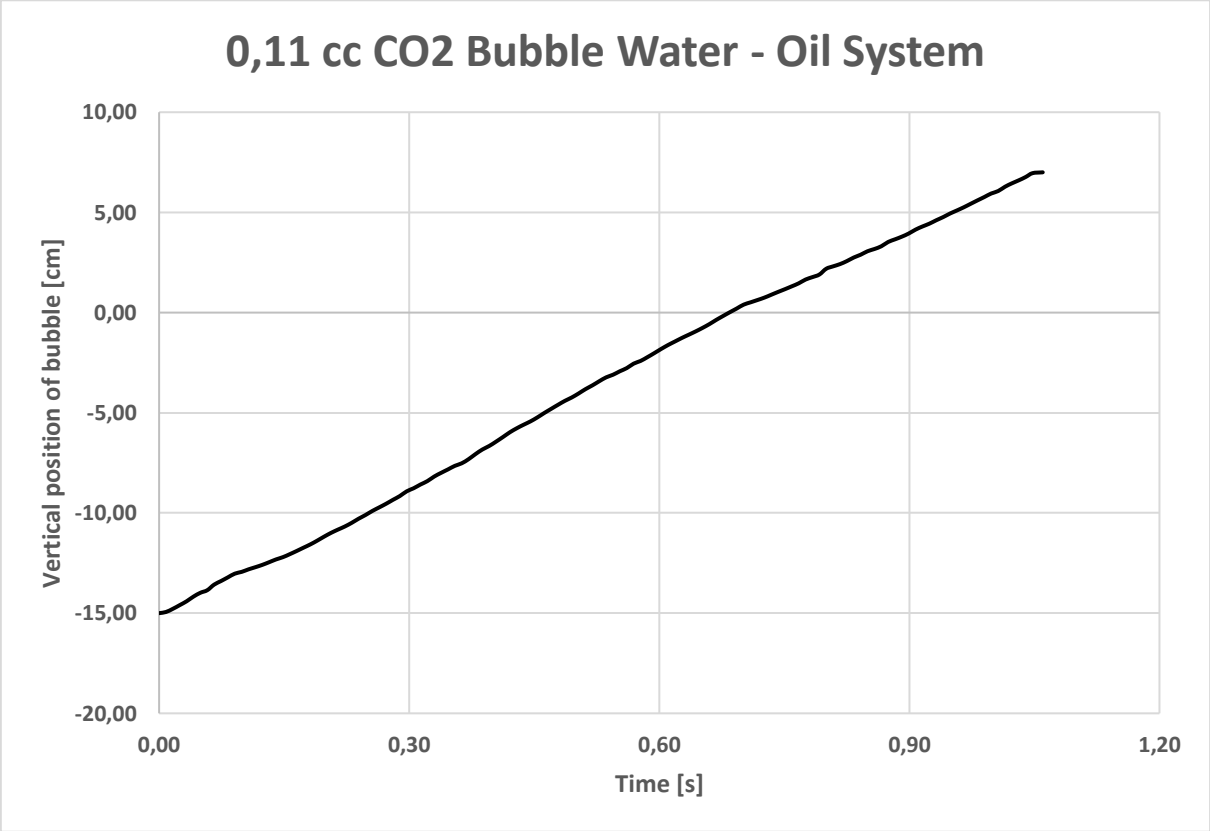


Figure 5.21: *Vertical Movement vs Time, Bubble of CO2 0.11 cc in a Water - Oil system*

The horizontal movement can be observed on the **Figure 5.22**, here, the bubble present a tendency to one side, that will tend to be constant after one period, furthermore, the zigzag movement reduces but never stops, in addition on the **Figure 5.23**, the vertical velocity vs time present that with slow fluctuations, the velocity of the bubble tends to be continuous during the whole system.

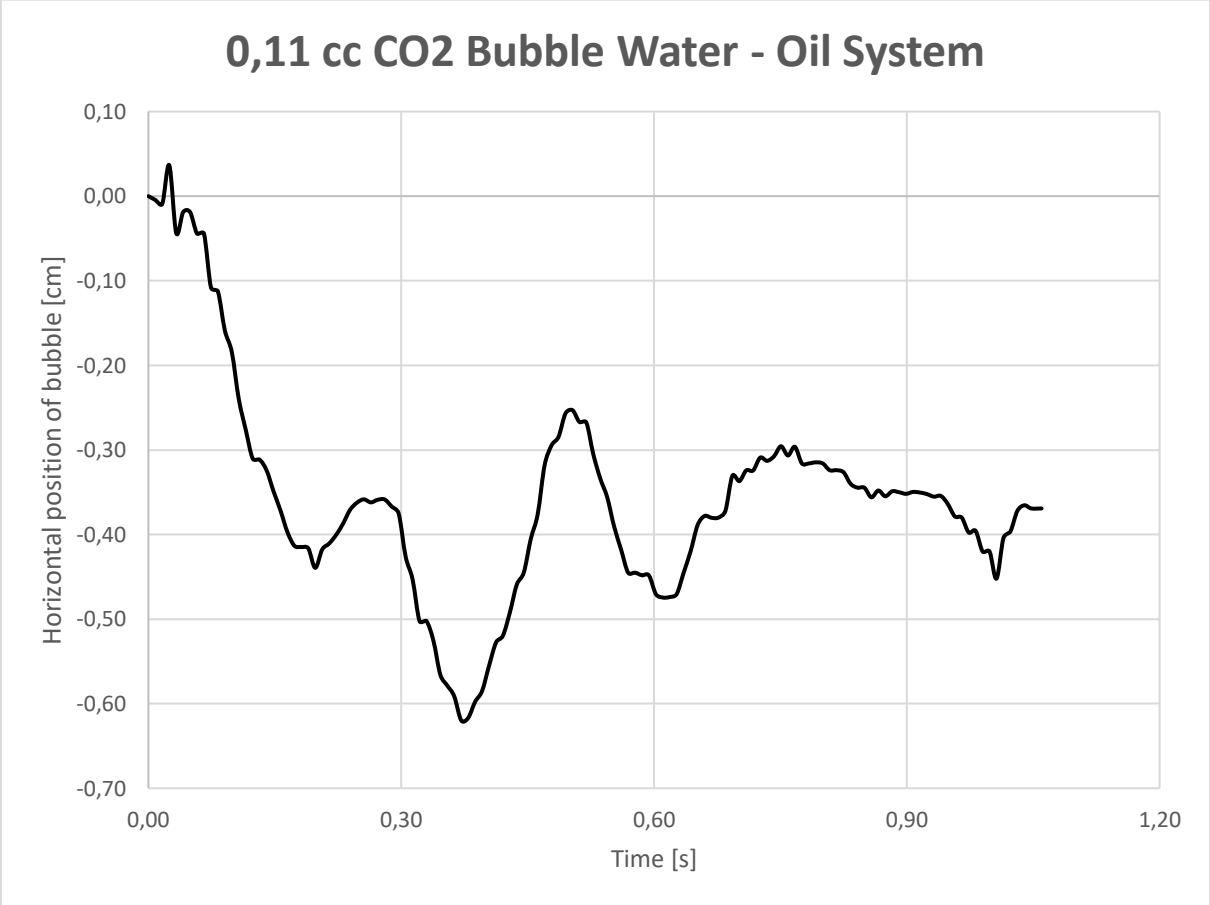


***Figure 5.22**: Horizontal Movement vs Time, Bubble of CO2 0.11 cc in a Water - Oil system*

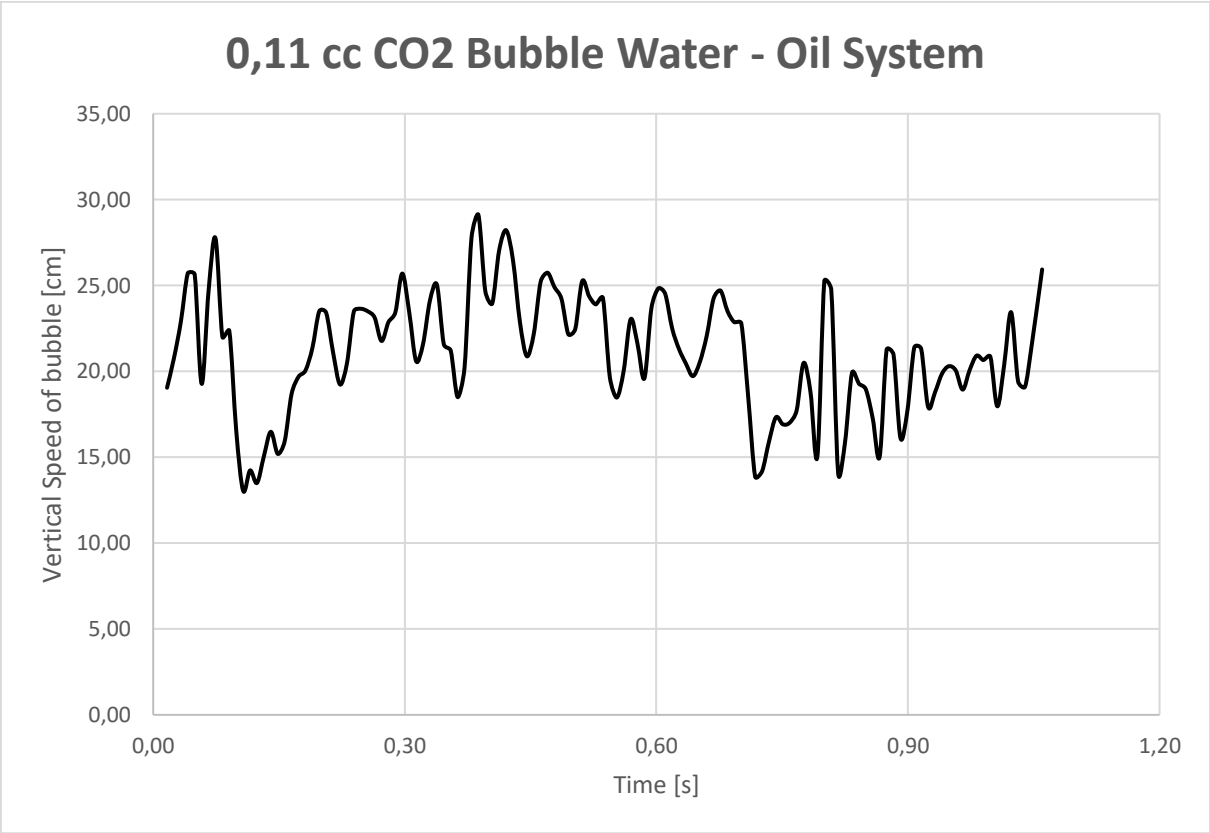
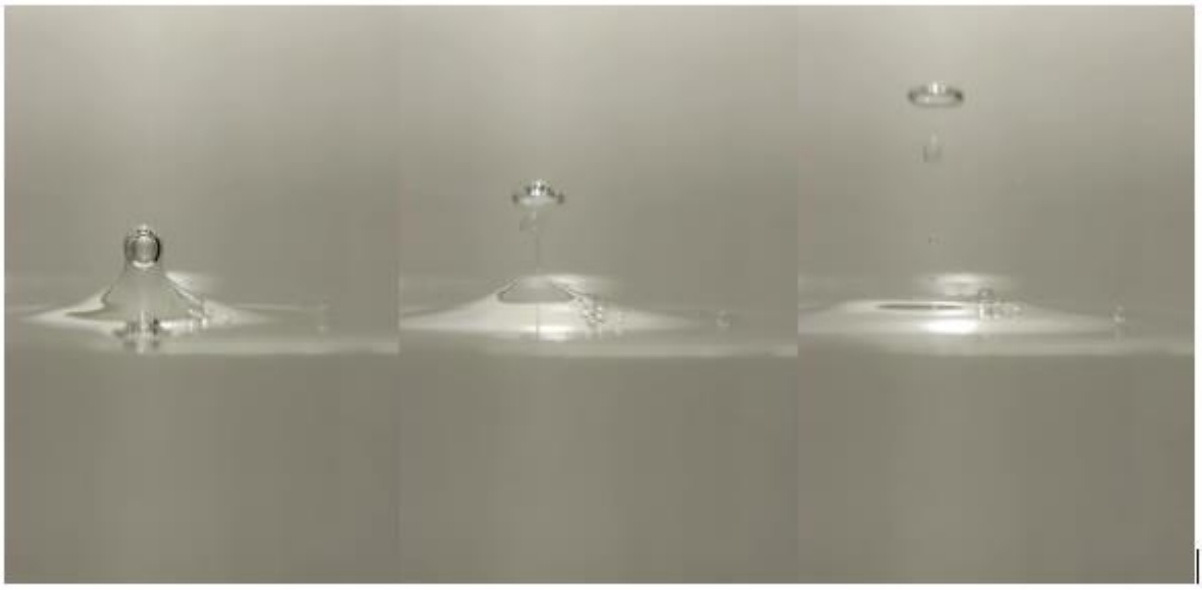


Figure 5.23: *Vertical Speed vs Time, Bubble of CO2 0.11 cc in a Water - Oil system*

The bubble of CO2 of 0.11 cc at the interface will form a long column of water, that will lead to a higher formation droplets at the moment of the rupture, as a matter of fact, there will be a higher drag of heavier liquid into the light one due to the size of the bubble, on this experiment the TPCL can be observed at the moment of the rupture "36 x 0/240". On the **Figure 5.24** can be observed the behavior of the bubble at the interface of Silicone Oil and Water. After the water column breaks, a drop of water will continue the upward motion for a short period of time. The shape of the bubble after the rupture of the TPCL and the break of the bubble is elliptical.

$0\ x\ \frac{0}{240}\ [s]$ $12\ x\ \frac{0}{240}\ [s]$ $20\ x\ \frac{0}{240}\ [s]$



$36\ x\ \frac{0}{240}\ [s]$ $45\ x\ \frac{0}{240}\ [s]$ $60\ x\ \frac{0}{240}\ [s]$

Figure 5.24: *Bubble of CO2 0.11 cc at the interface. in a Water - Oil system*

5.2PAC 2 ppm diluted in Water - Oil System

Once the experiments with water were made, it was desire to analyze the behavior of the fluids in a non-Newtonian system, based on the experiment made by (Rabenjafimanantsoa & Time, 2013), they conducted an experiment with a 1 ppm concentration of CMC, for this experiment was decide the utilization PolyAnionic Cellulose knowing as **PAC.** For the first experiment, a concentration of a 2 ppm was chosen. The procedure was mentioned on the **Chapter 3** and after 5 hours that the mixture was let to rest, the tests were run.

5.2.1 Small Size bubble of Air in a PAC 2 ppm in Water - Oil system

The first thing that can be notice on the **Figure 5.25** is the long period that the bubble stays on the interface of the fluids, that starts on the second 1.74 and ends on the second 5.77 for a total of 4.03 seconds, it is notice that the 0.014 cc bubble of air does not break the interface easily, as a matter of fact the time of the bubble at the interface is considerably high. Furthermore, it can be seen that the inclination on the first zone is a little bit lower than in the third zone.

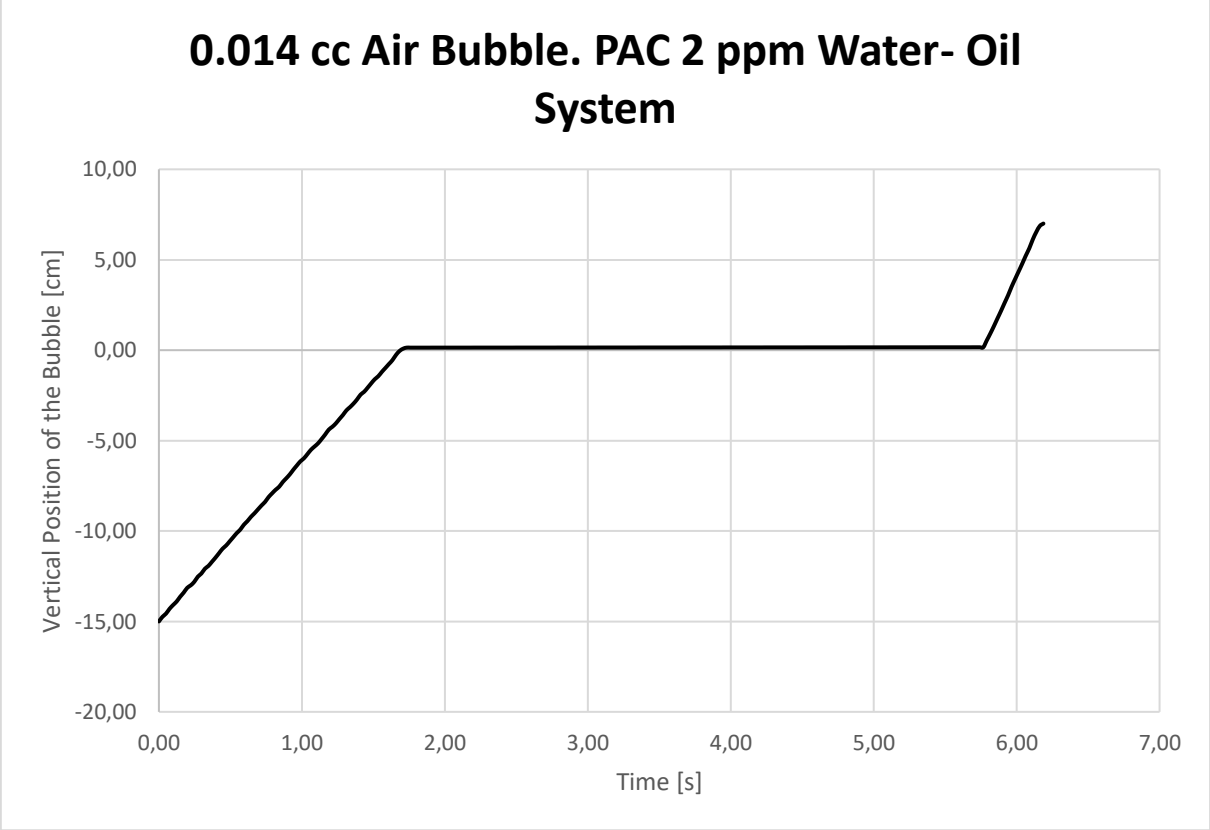


Figure 5.25: *Vertical Movement vs Time, Bubble of Air 0.014 cc in a polymer 2 ppm – Oil System*

The fluctuation of the bubble on the horizontal plane is almost linear, were in the first zone, the bubble has an amplitude of maximum 0.06 cm, on the second zone is around 0.015 cm as can be observed on the **Figure 5.26**, at the same time, on the **Figure 5.27** is observed that the speed on the heavier liquid zone is considerably lower than the speed on the lighter liquid

As it was mentioned, the time at the interface is around 4 seconds, where there is not formation of any kind of film on the bubble, and at the moment when the bubble continues rising, there is a small vertical elongation of the bubble that does not stays long, after that, the bubble continues the path to the surface with a semi elliptical shape. There are not any considerably formation of droplets on this experiment, the behavior of the bubble can be observed on the **Figure 5.28.**

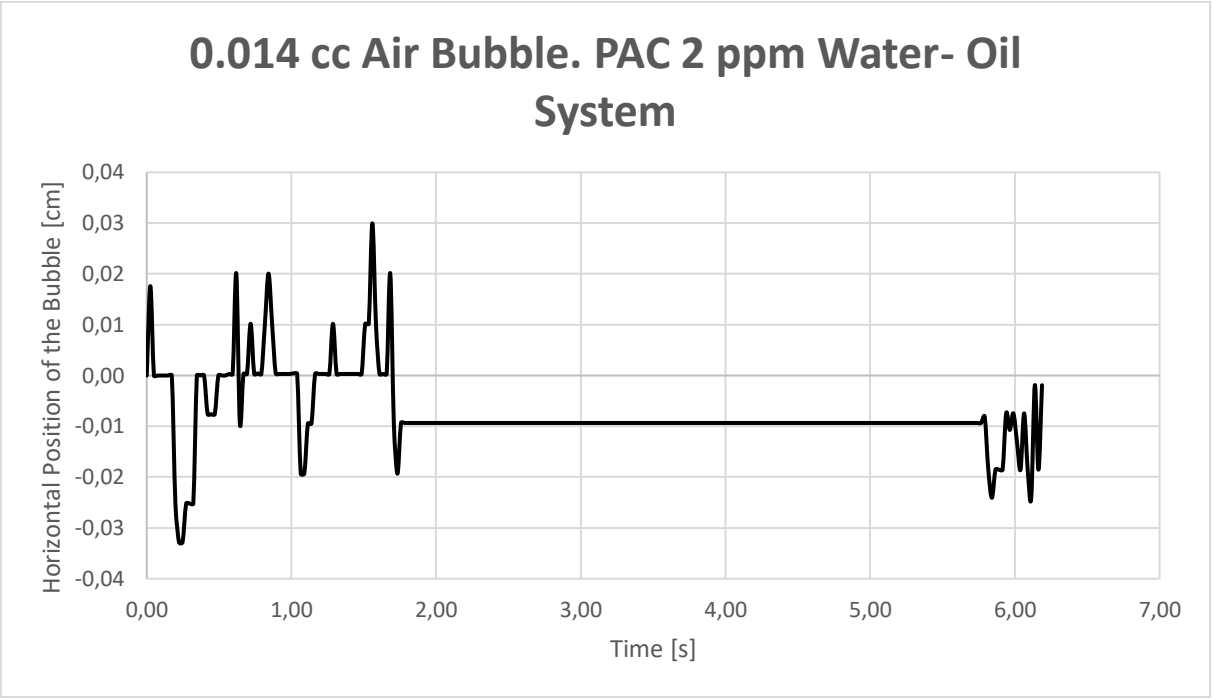


Figure 5.26: *Horizontal Movement vs Time, Bubble of Air 0.014 cc in a polymer 2 ppm – Oil System*

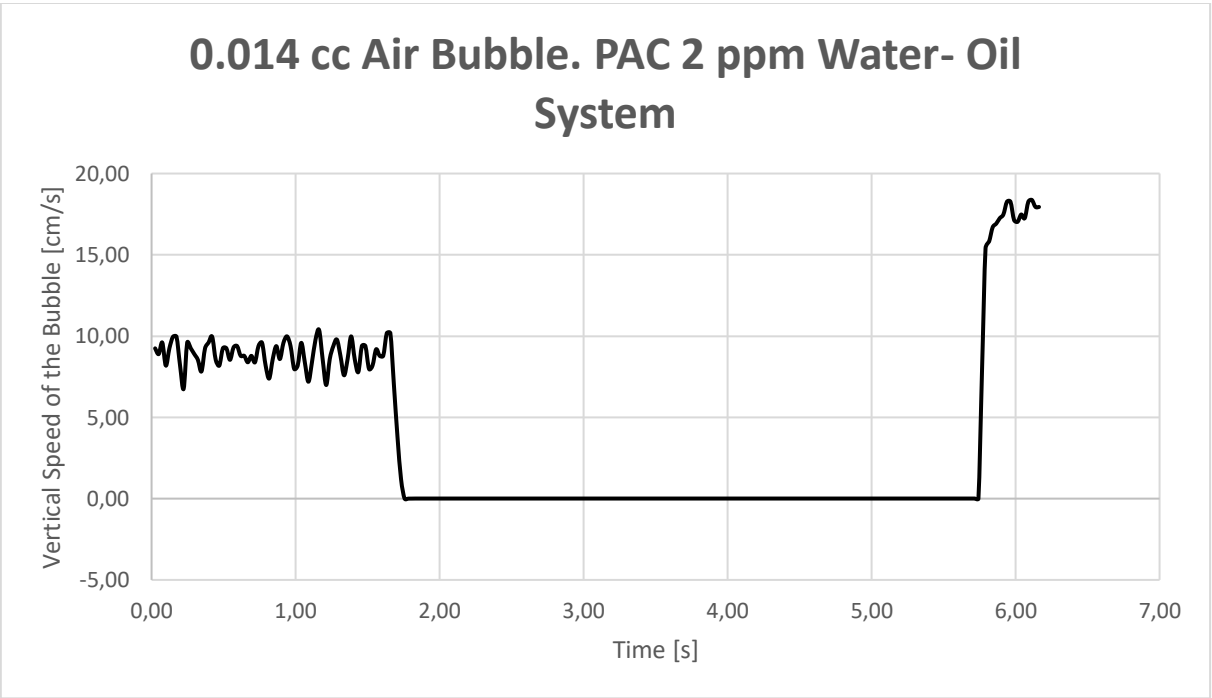


Figure 5.27: *Vertical Speed vs Time, Bubble of Air 0.014 cc in a polymer 2 ppm – Oil System*

$0\ x\frac{0}{240}[s]$ $37\ x\frac{0}{240}[s]$ $100\ x\frac{0}{240}[s]$

$700x\frac{0}{240}[s]$ $1004x\frac{0}{240}[s]$ $1038x\frac{0}{240}[s]$

Figure 5.28: *Bubble of Air 0.014 cc at the interface. in a polymer 2 ppm – Oil System*

5.2.2 Small Size bubble of CO2 in a PAC 2 ppm in Water - Oil system

The 0.014 cc bubble was injected at the bottom of the system and took 1.62 seconds to reach the interface, when the bubble in at this position, there is no fluctuation of the movement and stays there for 4.29 seconds, this can be consider because the vertical forces of the interface are strong enough to stop the movement of the bubble at the interface, but the buoyancy forces continues exerting forces on the bubble until those forces overcome the resistance of the interface, on the **Figure 5.29** is presented the vertical motion of the bubble.

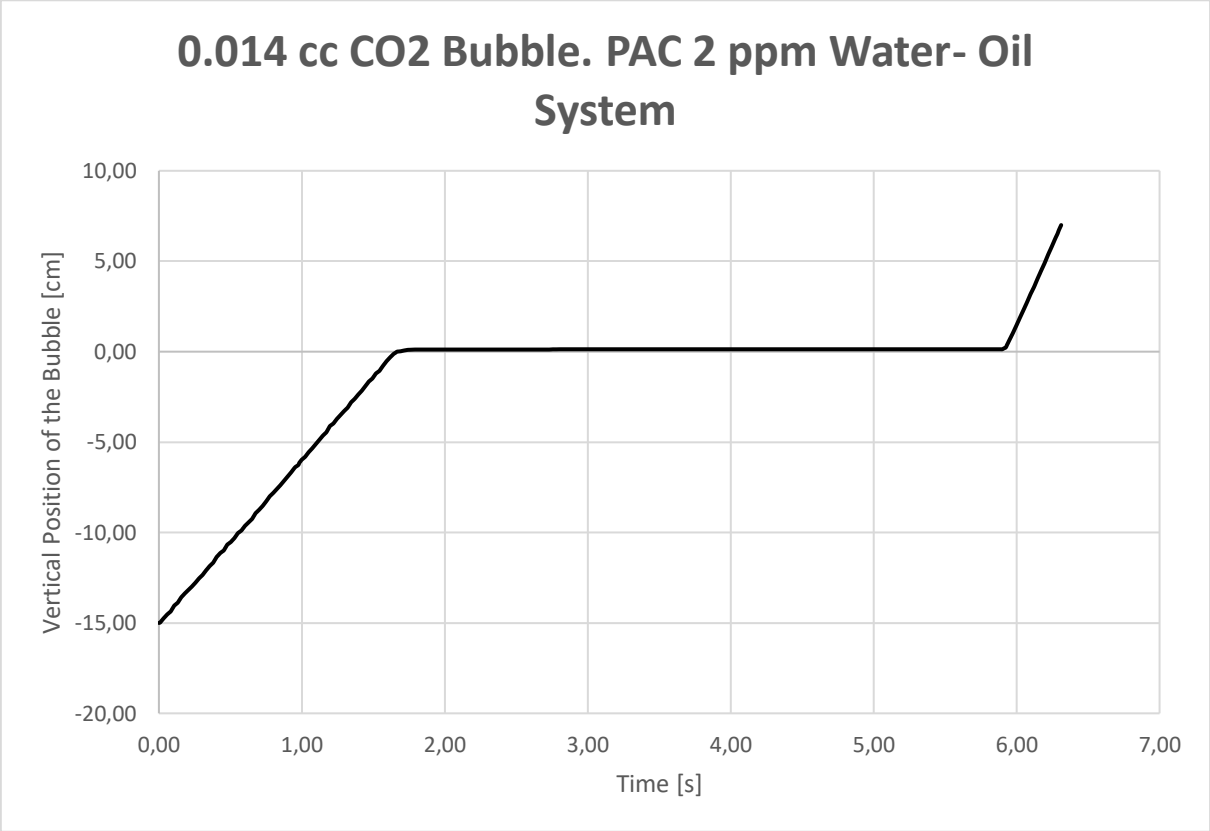


Figure 5.29: *Vertical Movement vs Time, Bubble of CO2 0.014 cc in a polymer 2 ppm – Oil System*

On the **Figure 5.30** can be observed a high fluctuation of the bubble in a 0.02 cm area, even when the graph shows high fluctuation, this movement can be consider almost linear; when the bubble reaches the interface, the bubble stays on the same position until it overcomes the vertical forces, furthermore, the movement of the bubble is even more linear that it was on the heavy liquid zone, and as it can be seen on the **Figure 5.31** the vertical speed of the bubble is considerably lower on the heavy liquid zone that on the lighter one.

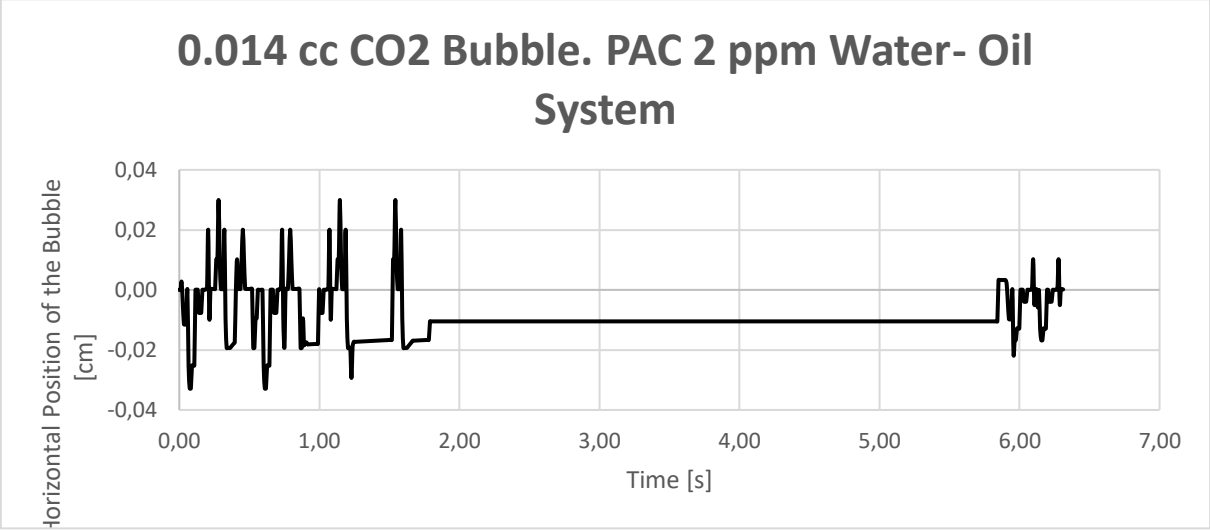


***Figure 5.30**: Horizontal Movement vs Time, Bubble of CO2 0.014 cc in a polymer 2 ppm – Oil System*

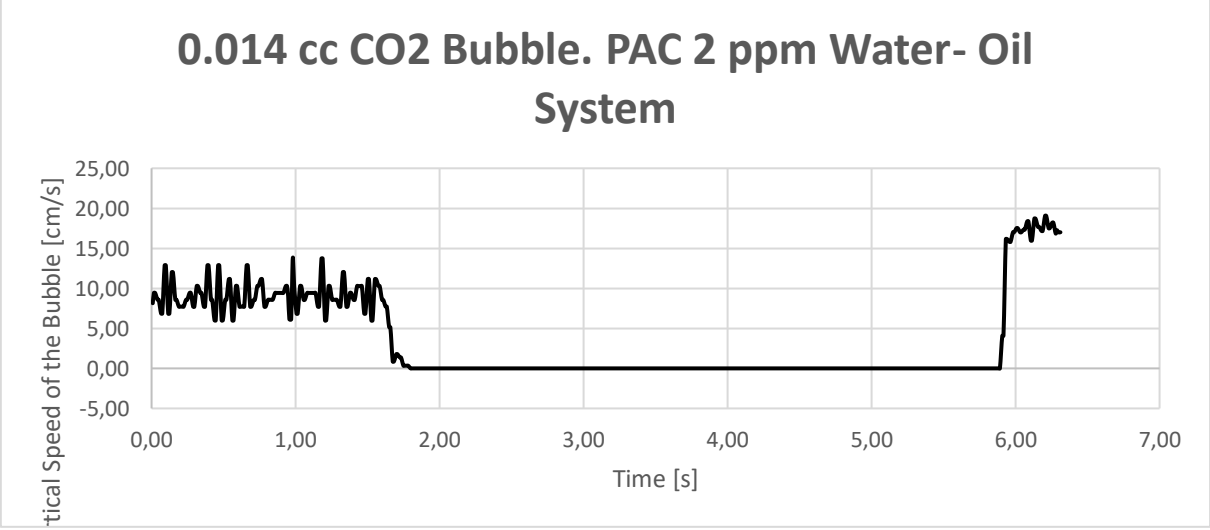


***Figure 5.31:** Vertical Speed vs Time, Bubble of CO2 0.014 cc in a polymer 2 ppm – Oil System*

The time on the interface was 4.29 seconds, where the bubble were completely steady, after that period of time, the bubble continues its path in a vertical path with an spherical shape, as can be observed on the **Figure 5.32**, there is not drag of the heavier liquid into the lighter one, there is not formation of a column of water and there is not film on the bubble, on the lighter zone, the bubble has an lightly elliptical shape util it reaches the surface.

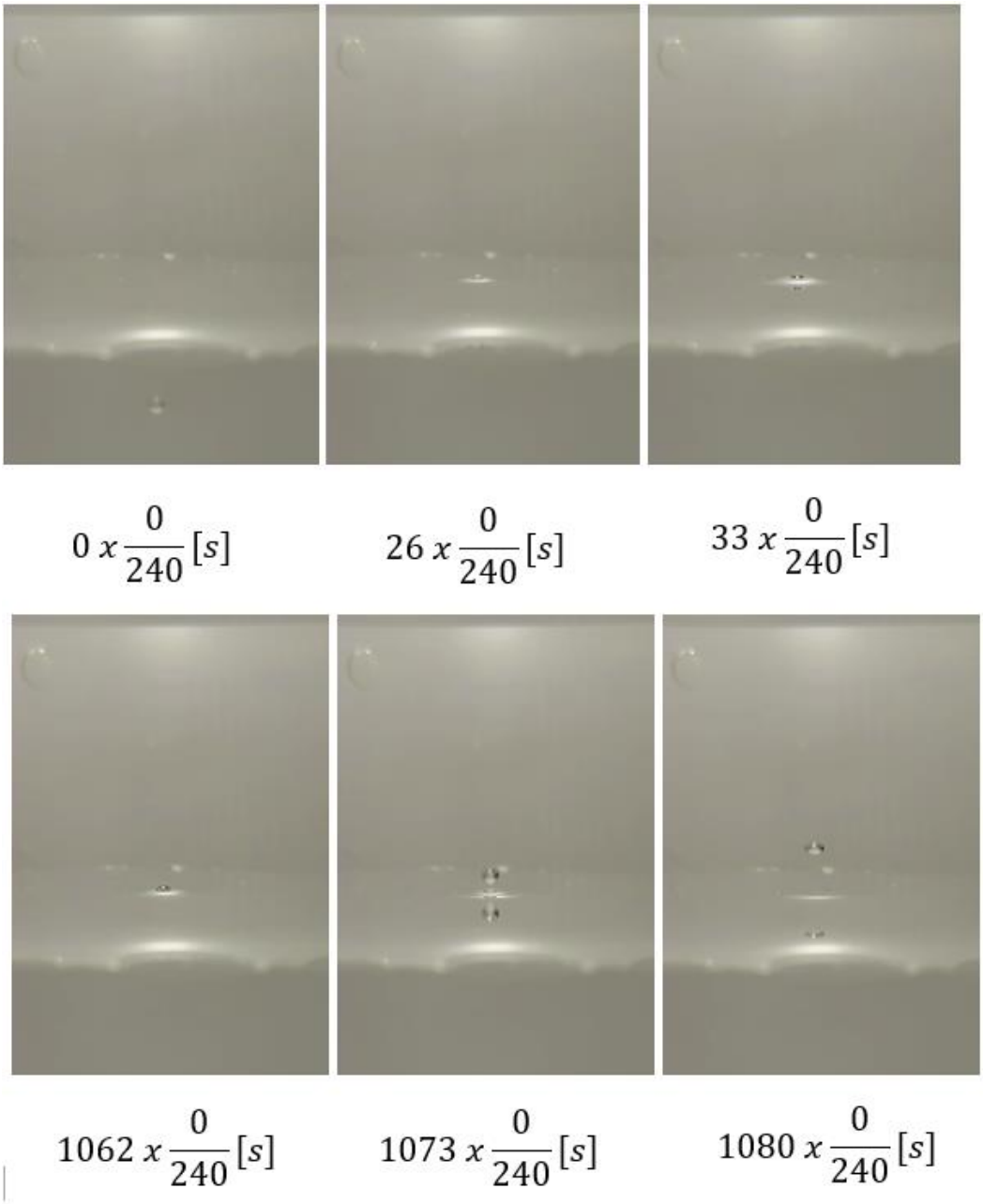


Figure 5.32: *Bubble of CO2 0.014 cc at the interface. in a polymer 2 ppm – Oil System*

5.2.3 Medium Size bubble of Air in a PAC 2 ppm in Water - Oil system

The behavior of the bubble is presented on the **Figure 5.33** here is shown that the bubble reaches the interface at 0.75 seconds, while the bubble is at the interface, holds its position slightly over the interface, for a time gap of 1.94 seconds, afterwards the bubble continues its path and reaches the surface of the lighter fluid at a total time of 3.02 seconds.

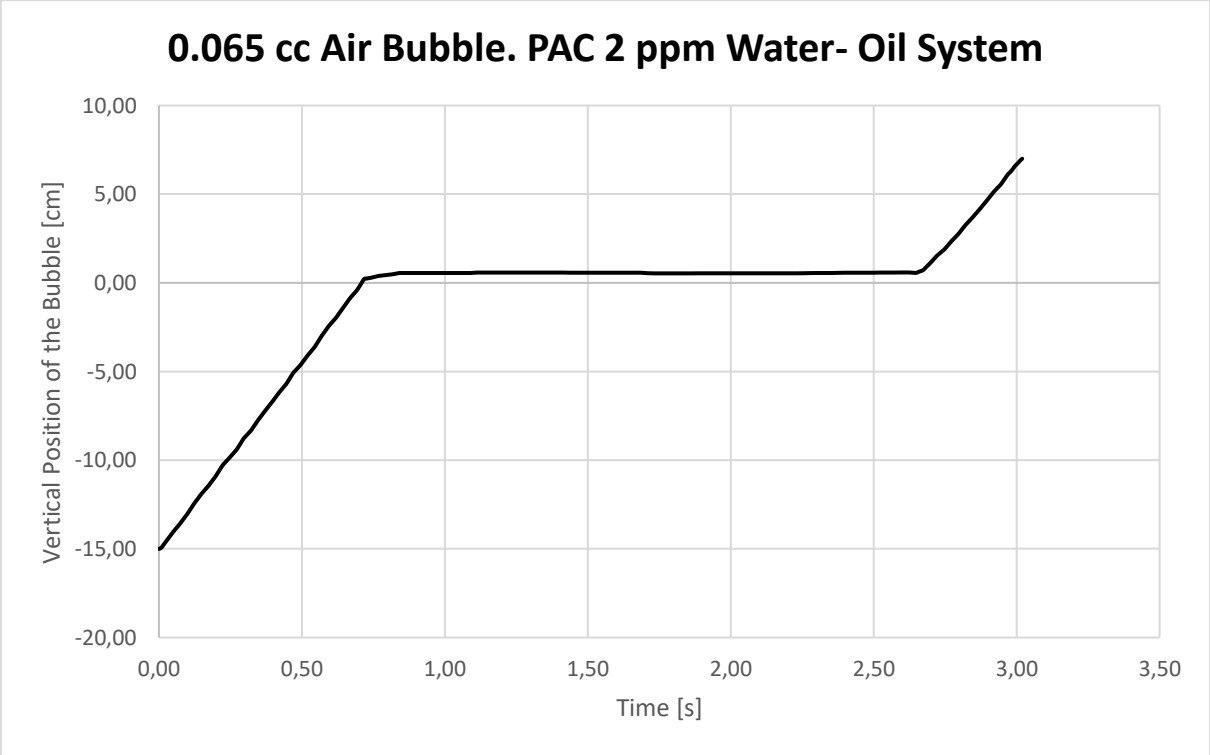


Figure 5.33: *Vertical Movement vs Time, Bubble of Air 0.065 cc in a polymer 2 ppm – Oil System*

On the **Figure 5.34** is observed small fluctuations of the bubble but almost keeping a vertical movement, that and the fluctuations become even smaller after the lighter liquid zone, in addition, on the **Figure 5.35** is observed the behavior of the speed of the bubble, where the instant velocity in both fluids does not have a considerably difference.

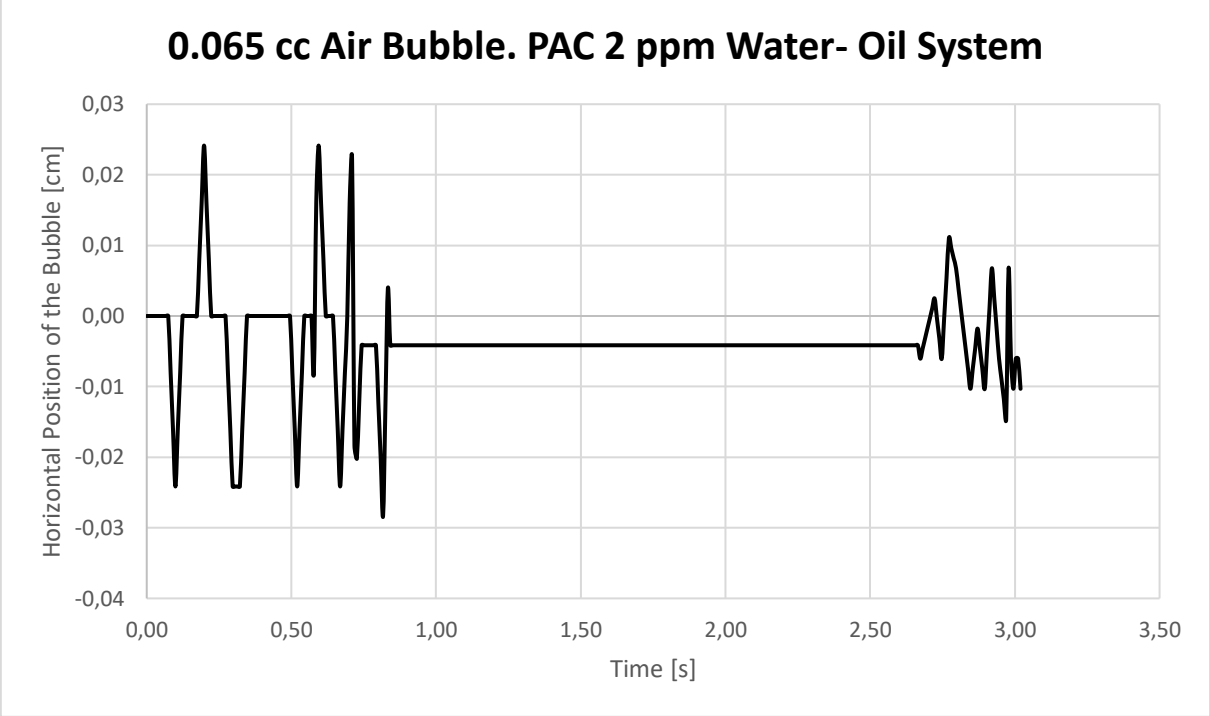


***Figure 5.34**: Horizontal Movement vs Time, Bubble of Air 0.065 cc in a polymer 2 ppm – Oil System*

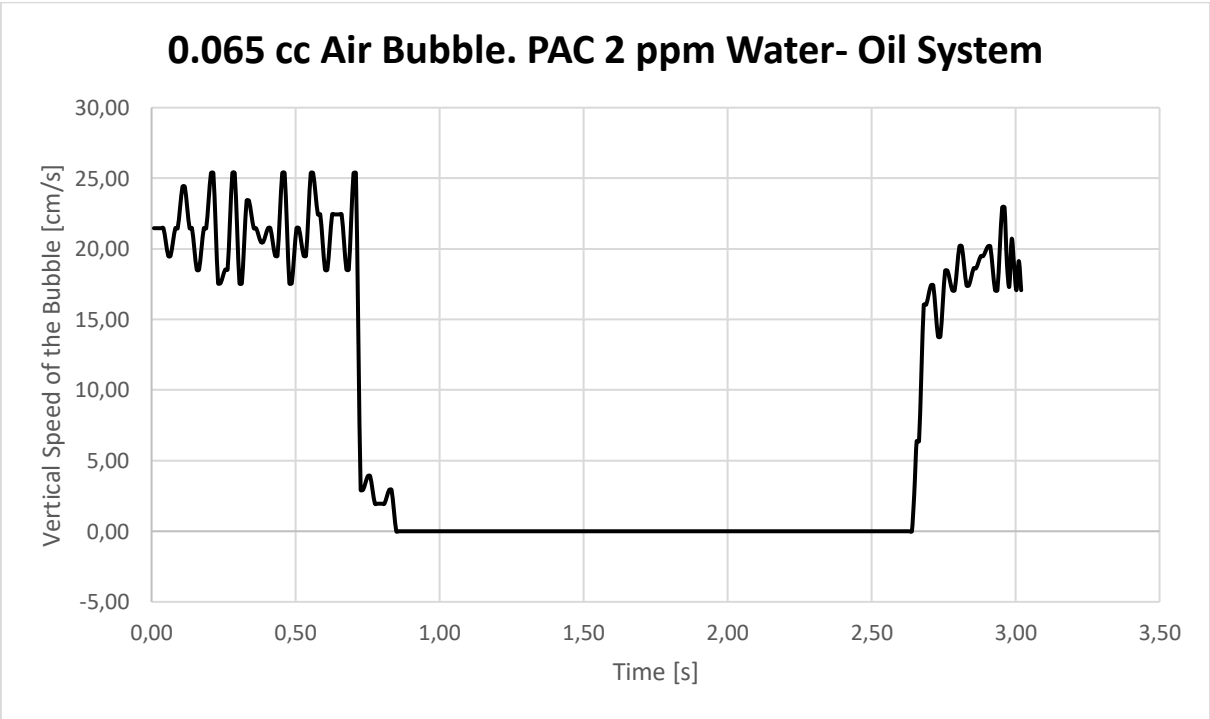


***Figure 5.35:** Vertical Speed vs Time, Bubble of Air 0.065 cc in a polymer 2 ppm – Oil System*

At the interface, the bubble of air of 0.065 cc holds its position slightly over the interface, where after a time gap it breaks with out haaving any kind of drag of the heavy liquid, there is the presence of a soft lifting of a water column but there are not droplets. On the **Figure 5.36** can be observed the behavior of mentioned.

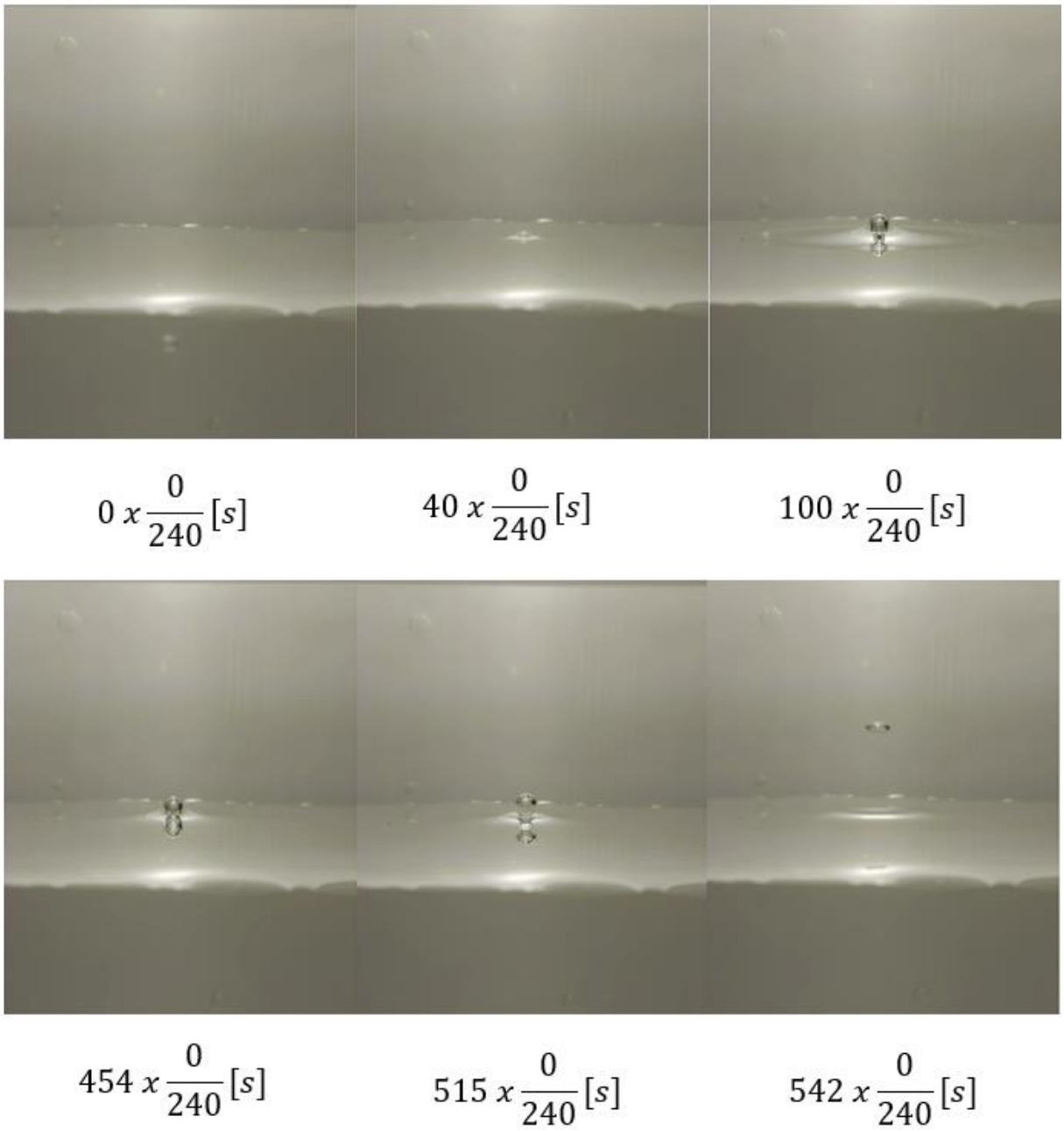


Figure 5.36: *Bubble of Air 0.065 cc at the interface. in a polymer 2 ppm – Oil System*

5.2.4 Medium Size bubble of CO2 in a PAC 2 ppm in Water - Oil system

The time that the bubble of CO2 took to reach the interface was 0.79 seconds, after that, it stays a for a period of 2.92 seconds 0.60 centimeters above the interface, before it breaks due to the buoyancy forces and the bubble continues its path to the top of the system. On the **Figure 5.37** is presented the plot of the vertical position of the bubble vs time.

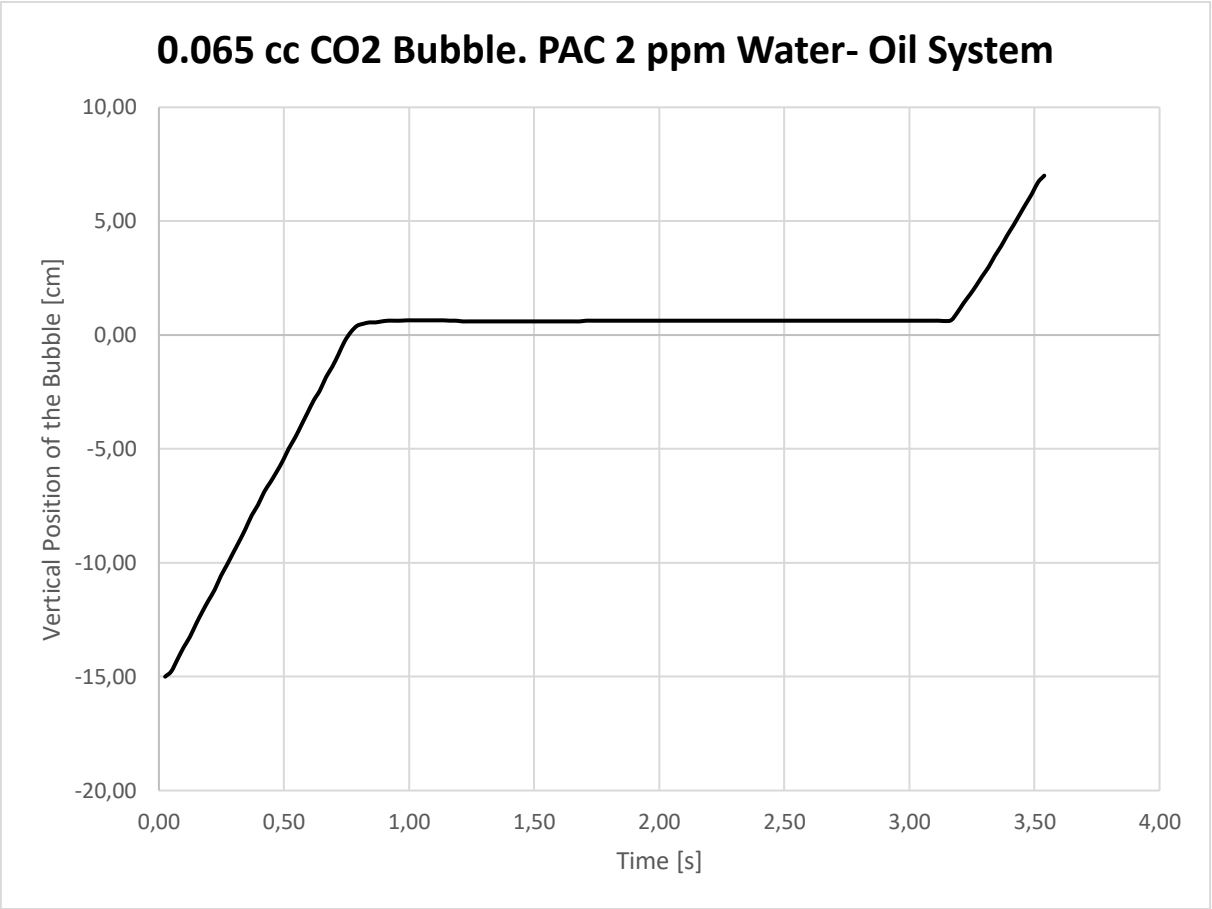


Figure 5.37: *Vertical Movement vs Time, Bubble of CO2 0.065 cc in a polymer 2 ppm – Oil System*

The movement of the bubble tends to have the original position even when it presents a zigzag behavior, that becomes even lower after the bubble passes the interface, where the movement of it can be consider almost linear, with a zigzag movement of just 0.025 cm of amplitude, this can be seen on the **Figure 5.38.** On the other hand, the velocity of the bubble, presented on the **Figure 5.39,** shows the velocity of the bubble through the system, where, on the heavy liquid has a faster movement than in the lighter one, but the difference between both are not abrupt.

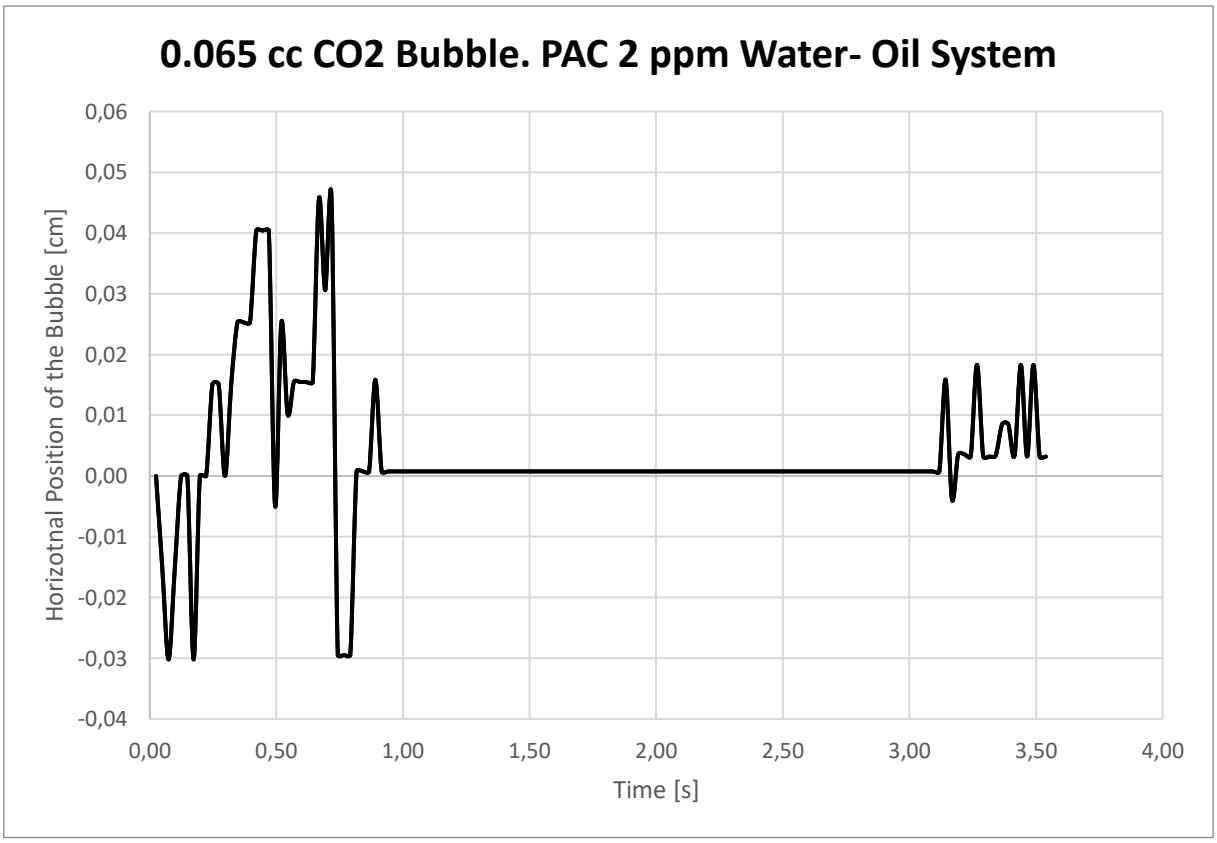


Figure 5.38: *Horizontal Movement vs Time, Bubble of CO2 0.065 cc in a polymer 2 ppm – Oil System*

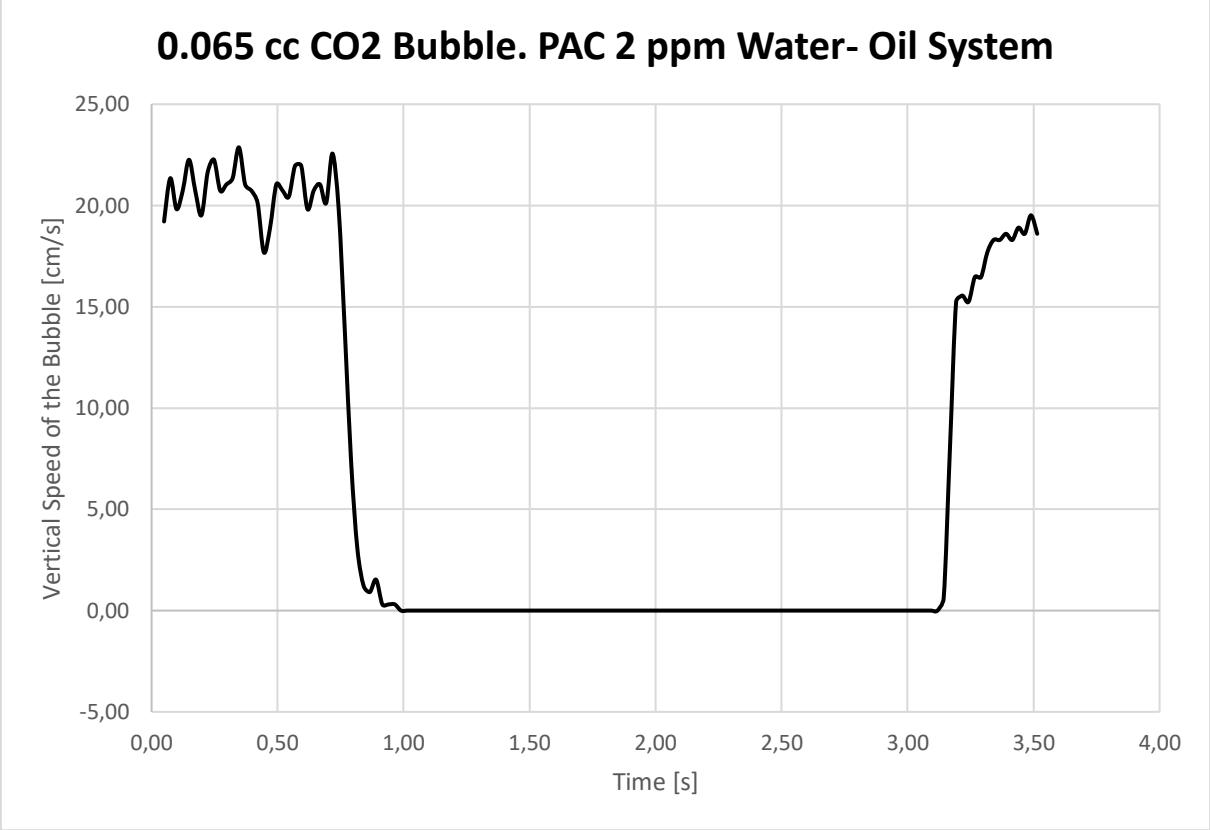


Figure 5.39: *Vertical Speed vs Time, Bubble of CO2 0.065 cc in a polymer 2 ppm – Oil System*

The behavior of the interface of the bubble of CO2 of 0.065cc can be observed on the **Figure 5.40**, where the bubble stays over the surface for a considerably period of time, subsequently, this interface breaks and the bubble rises, dragging a minor column of water, on this test cannot been observed any droplet formation or formation of the TPCL. When is moving on the light liquid zone, the shape of the bubble tends to be elliptical?

$0\ x\frac{0}{240}[s]$ $40\ x\frac{0}{240}[s]$ $69\ x\frac{0}{240}[s]$

$719\ x\frac{0}{240}[s]$ $740\ x\frac{0}{240}[s]$ $750\ x\frac{0}{240}[s]$

Figure 5.40: *Bubble of CO2 0.065 cc at the interface. in a polymer 2 ppm – Oil System*

5.2.5 Big Size bubble of Air in a PAC 2 ppm in Water - Oil system

The bubble of 0.11 cc showed almost a constant rise through the whole system, where at the interface does not present a stop time and continues it rising behavior during the whole test, as is presented on the **Figure 5.41.** The time at the interface is 0.18, here, the buoyancy forces overcome easily all the downward forces presented. The total time of the motion of the bubble from the bottom to the top is 1.13 seconds.

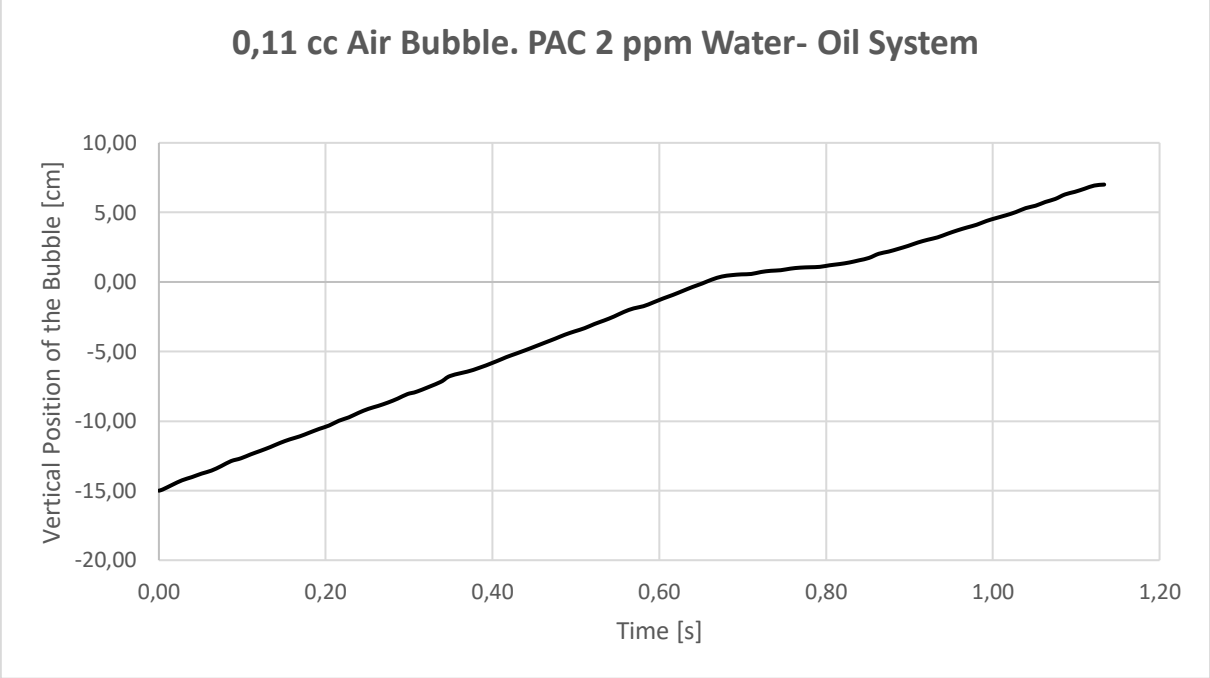


Figure 5.41: *Vertical Movement vs Time, Bubble of Air 0.11 cc in a polymer 2 ppm – Oil System*

On the **Figure 5.42** is presented the motion of the bubble on the horizontal plane, here can be seen numerous fluctuations, that are softly reduced after the interface, it need to be considered, that the range of the zig zag movement is about 0.6 cm, and the radius of the bubble is 0.3 cm, in addition to this, on the **Figure 5.43** can be observed the instant speed of the bubble, where at the interface is reduced considerably, but does not reaches 0. At the moment 0.78 reaches the slowest point, this is because at this moment, the column of water

that is dragging is pulling the most, right after this point, this column of water breaks and is observed a considerable increase of the speed of the bubble.

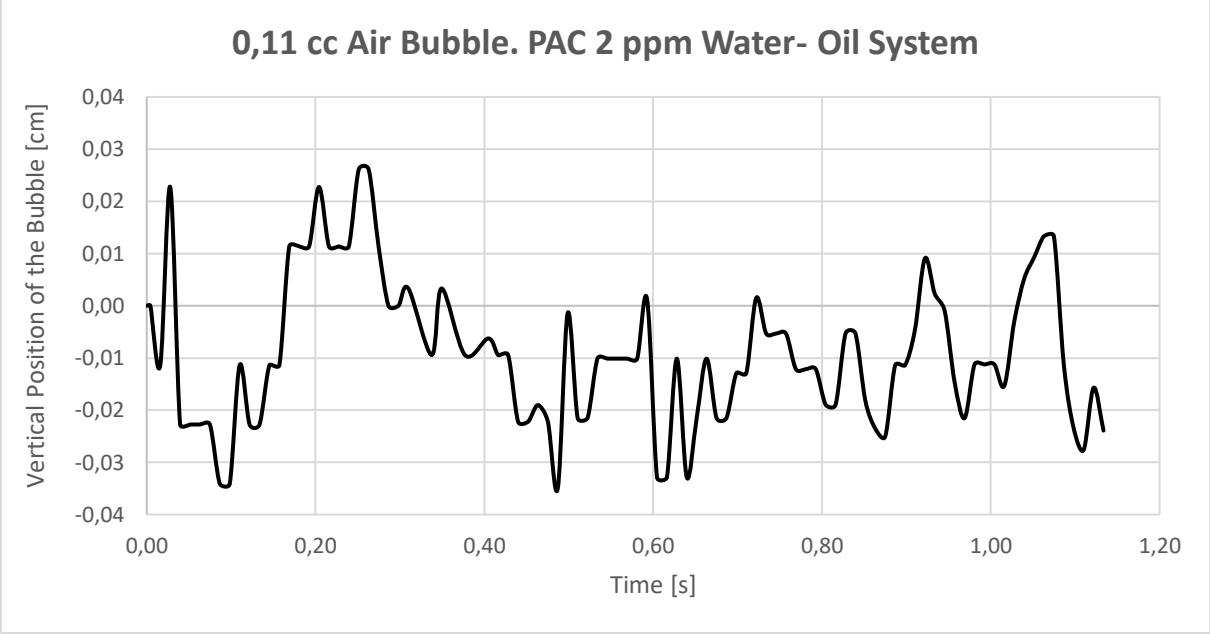


Figure 5.42: *Horizontal Movement vs Time, Bubble of Air 0.11 cc in a polymer 2 ppm – Oil System*

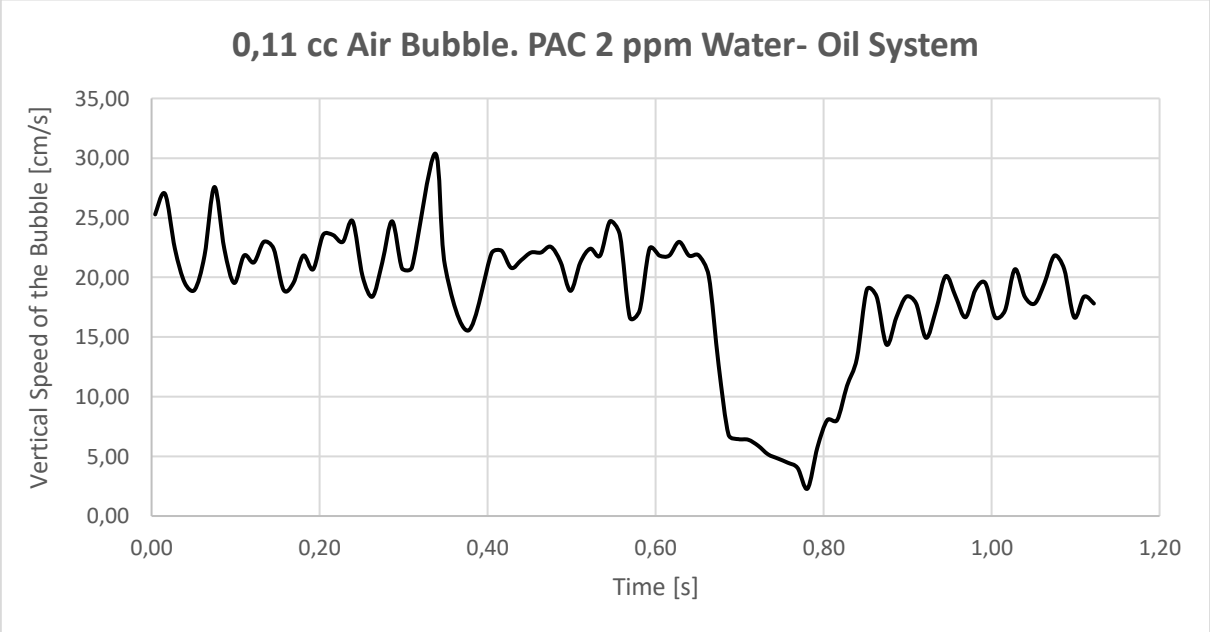


Figure 5.43: *Vertical Speed vs Time, Bubble of Air 0.11 cc in a polymer 2 ppm – Oil System*

The behavior of the bubble at the interface is presented on the **Figure 5.44**, where can be observed motion of the bubble the whole time and the bubble never stops due to the interface of the liquids, due to the speed of the bubble can be observed that a column of water is being drag and breaks at certain point, also due to this disruption of the column of water, it can be observed the rupture of the film of water that was over the bubble, creating the TPCL. When the bubble keeps its path on the light liquid, some droplets from the column falls back to the heavy liquid. The shape of the bubble after the rupture of the interface is elliptical.

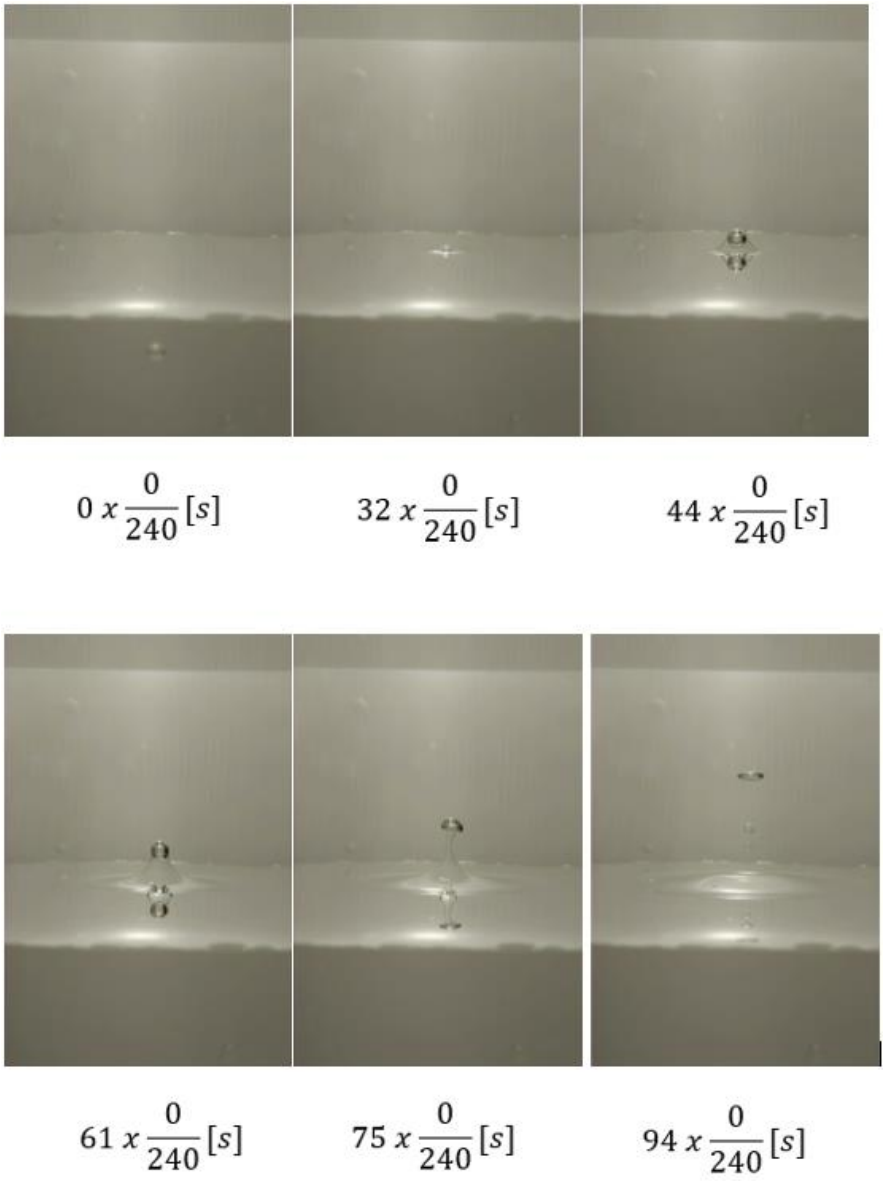


Figure 5.44: *Bubble of Air 0.11 cc at the interface. in a polymer 2 ppm – Oil System*

5.2.6 Big Size bubble of Air in a PAC 2 ppm in Water - Oil system

The bubble of 0.11 CO2 shows a strong influence of the buoyancy forces, due to this the forces exerted by the interface are not strong enough to stop the upward movement of the bubble, where it has a time at the interface of 0.25 seconds, subsequently the bubble continues its movement to the surface of the system in a total time of 1.19 seconds. The **Figure 5.45** shows the vertical position of the bubble along the system

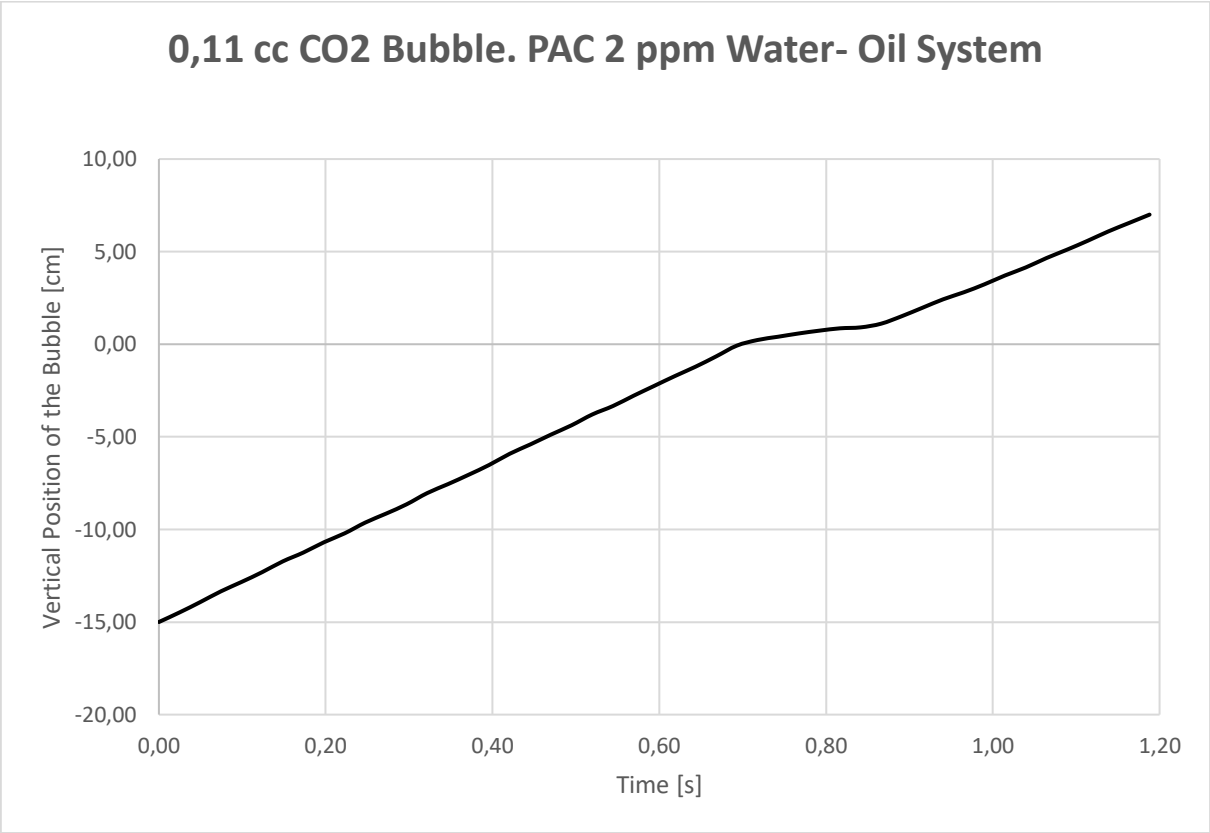


Figure 5.45: *Vertical Movement vs Time, Bubble of CO2 0.11 cc in a polymer 2 ppm – Oil System*

The horizontal motion of the bubble can be considered linear as it only moves in a range of 0.4 cm, while the radius of the bubble is 0.3 cm, on the **Figure 5.46** can be observed this motion of the bubble. Beside this, the speed of the bubble can be observed on the **Figure**

5.47, where is clear that at the interface is a noticeable reduction of the speed of the bubble, though, the speed is never zero, after this point, the increase of the speed is considerable once again, and almost same as before the interface.

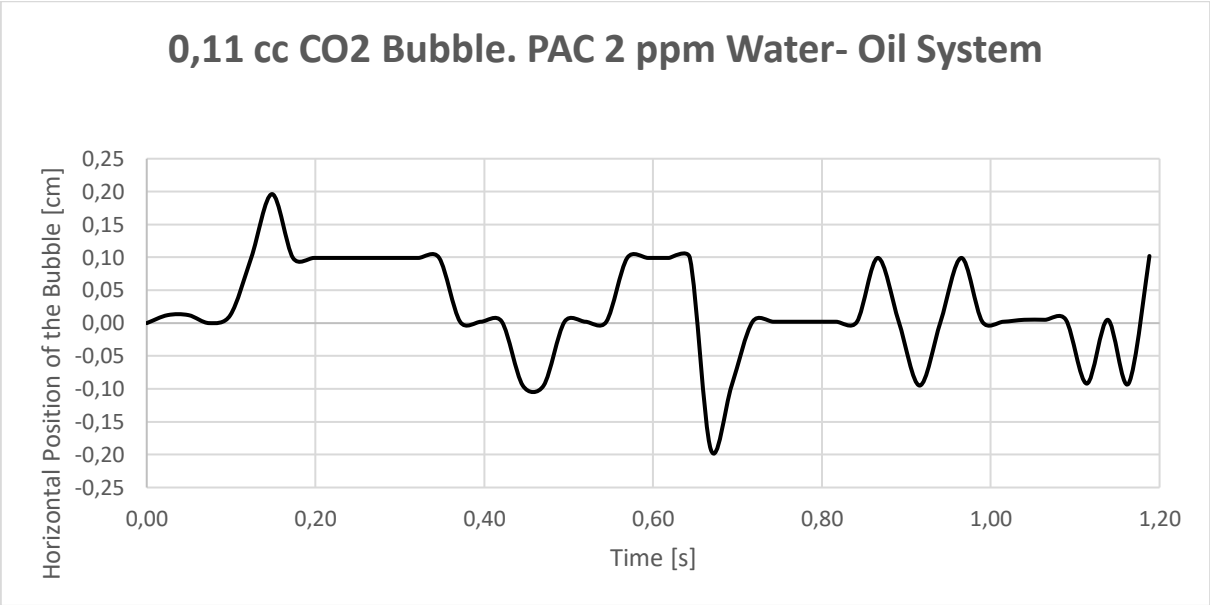


Figure 5.46: *Horizontal Movement vs Time, Bubble of CO2 0.11 cc in a polymer 2 ppm – Oil System.*

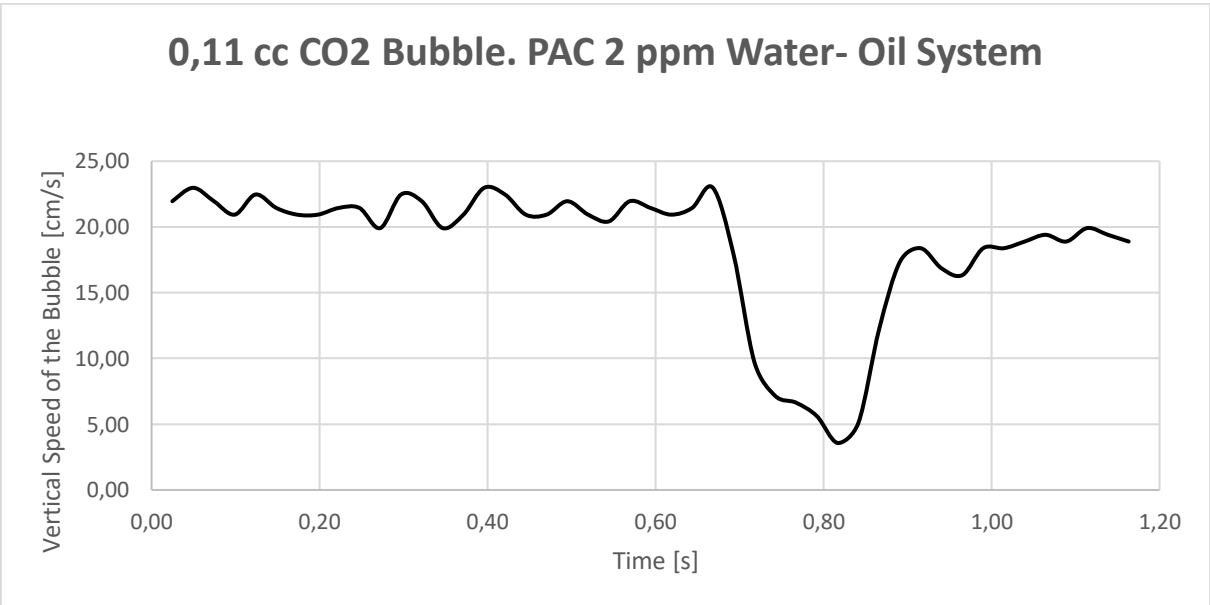


Figure 5.47: *Vertical Speed vs Time, Bubble of CO2 0.11 cc in a polymer 2 ppm – Oil System*

On the **Figure 5.48** is presented the behavior of the bubble along the interface, where there is a clear drag of a water column from the CO2 bubble, that break at a certain time and forms the TPCL on top of the bubble, the reason for this is that the speed of the bubble is strong enough to break the film that is surrounding it, in addition, a particle of the water column continues the upward movement for a while because of the inertial forces. After the interface breaks the shape of the bubble is elliptical until it reaches the surface of the lighter liquid

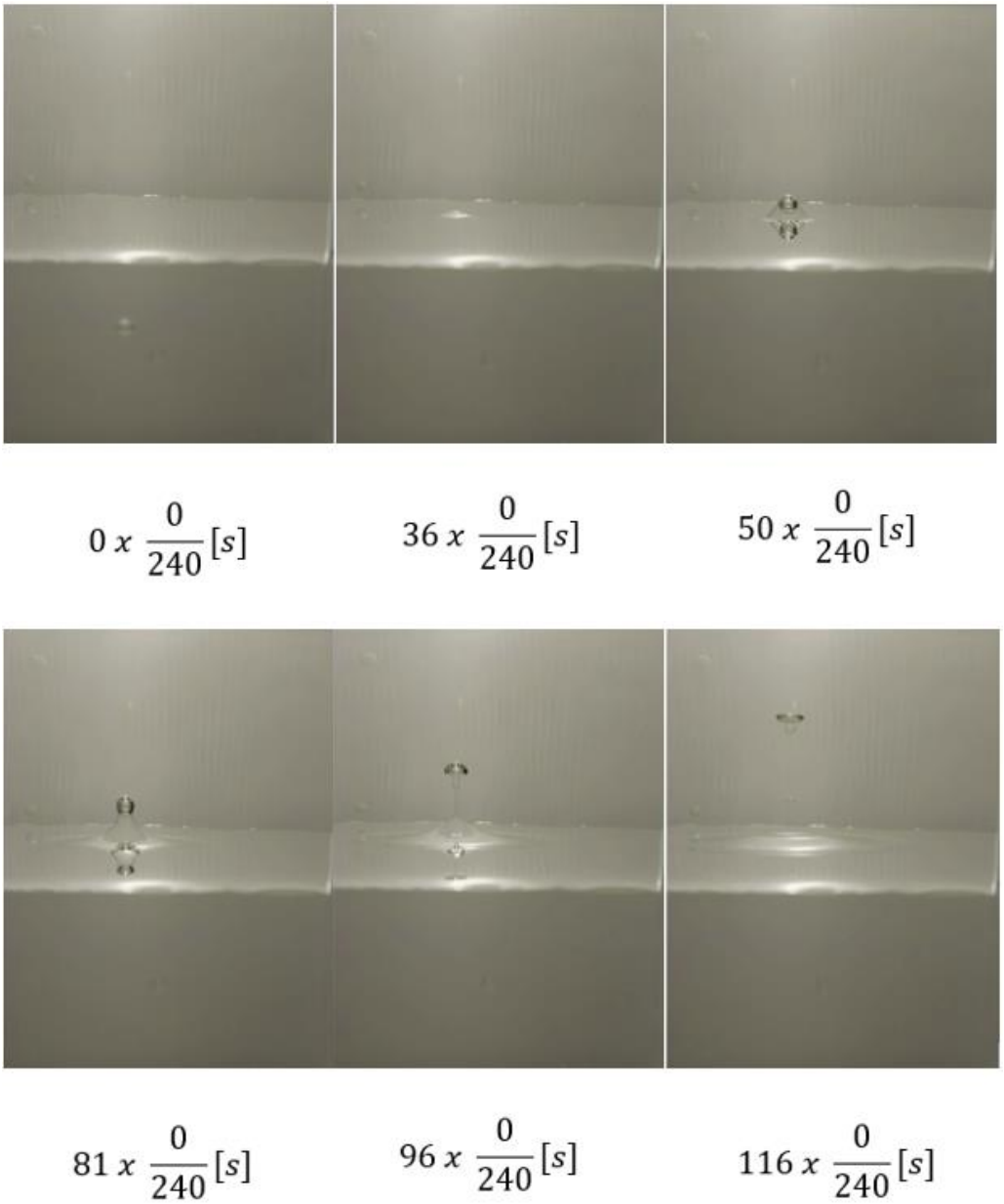


Figure 5.48: *Bubble of CO2 0.11 cc at the interface. in a polymer 2 ppm – Oil System*

5.3PAC 1 ppm diluted in Water - Oil System

Finally, it was decided to reduce the concentration of the polymer so a mixture of water + PAC 1pmm was made in order to have more test to have a comparation, same six experiments were made, with the three different sizes of the bubbles and injection of Air and CO2.

5.3.1 Small Size bubble of Air in a PAC 1 ppm in Water - Oil system

The bubble of air of 0.014 cc needed 1.08 seconds to reach the interface, where can be seen that the buoyancy forces are not strong enough to overcome the tension of the interface right away, therefore, the motion of the bubble is interrupted at this point for 2.89 seconds and stays on the same position on that period of time, right after that, the bubble continues its movement and rises through the lighter liquid as can be seen on the **Figure 5.49.** The total time of the motion of the bubble is 4.37 seconds

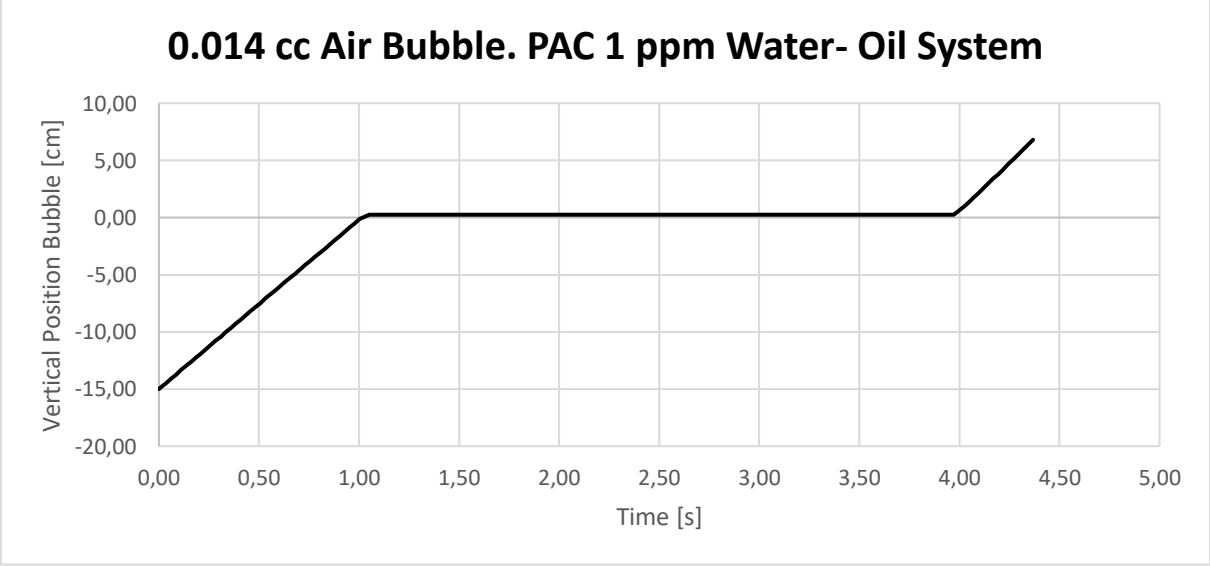


Figure 5.49: *Vertical Movement vs Time, Bubble of Air 0.014 cc. in a polymer 1 ppm – Oil System*

On the **Figure 5.50** is observed the horizontal movement of the bubble, where on the heavy liquid zone, has a zigzag movement than is reduced on the lighter liquid, but in general the movement of the bubble tends to be vertical, on the other hand, on the **Figure 5.51** the speed of the bubble is shown, were is seen that at the interface, there is not motion and there is an slight increase on the speed of the bubble on the lighter fluid compared on the heavier one.

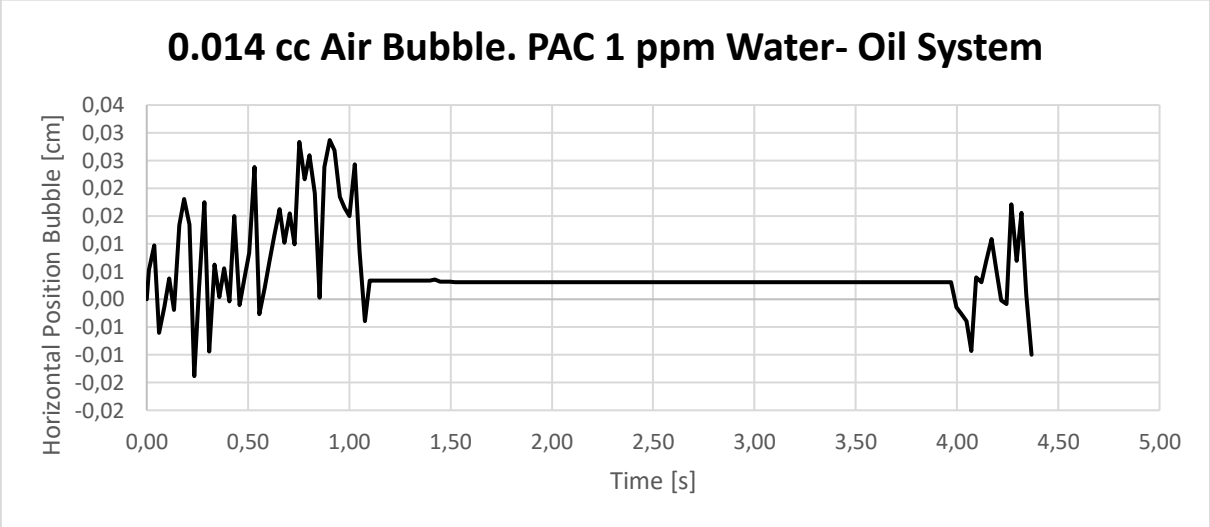


Figure 5.50: *Horizontal Movement vs Time, Bubble of Air 0.014 cc. in a polymer 1 ppm – Oil System*

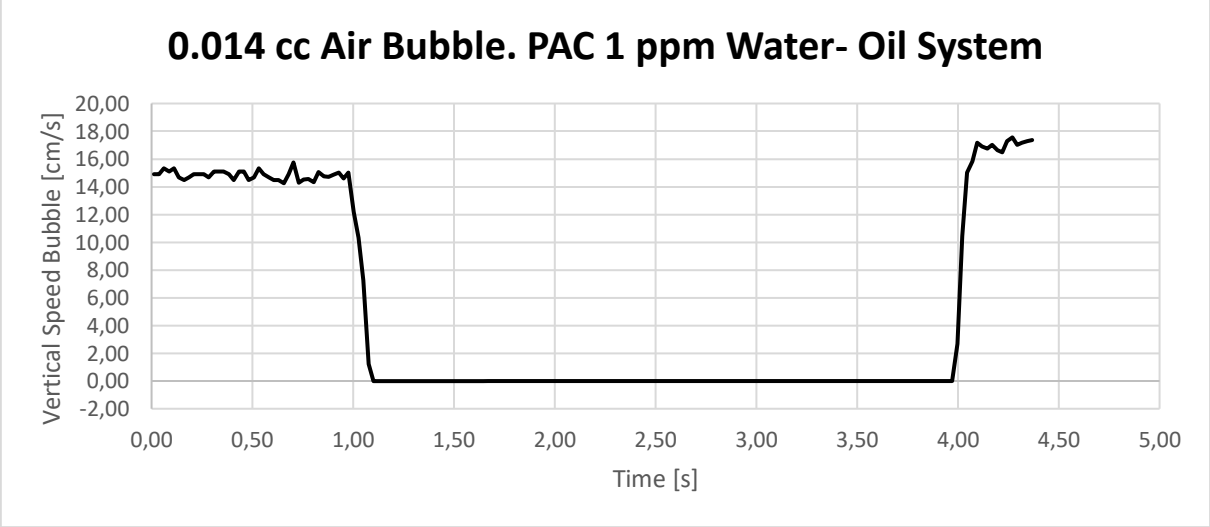


Figure 5.51: *Vertical Speed vs Time, Bubble of Air 0.014 cc. in a polymer 1 ppm – Oil System*

At the interface it can be observed that the bubble stays on the same position for a certain period of time and that, the bubble starts to rise, where there is a small vertical elongation that is almost imperceptible, afterwards, the bubble continues the vertical movement with a semi spherical shape, as can be observed on the **Figure 5.52**

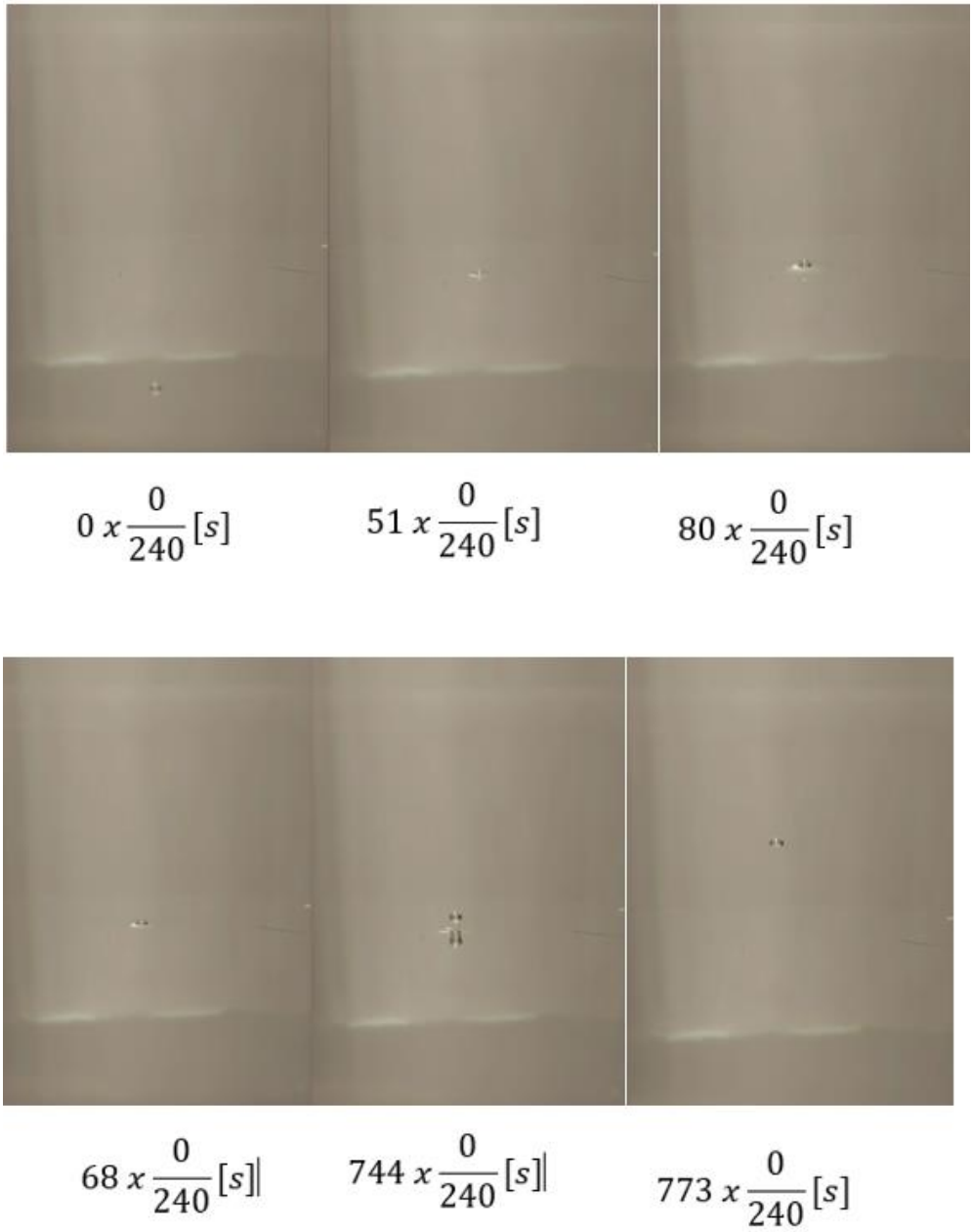


Figure 5.52: *Bubble of Air 0.014 cc at the interface. in a polymer 1 ppm – Oil System*

5.3.2 Small Size bubble of CO2 in a PAC 1 ppm in Water - Oil system

The behavior of the bubble of CO2 of 0.014 cc can be observed on the **Figure 5.53**, here can be seen that the bubble reaches the interface at 1.06 seconds where the downward forces exerted by the interface, are strong enough to stop the bubble at this point for 3.35 seconds, after this time, the bubble overcomes that interruption of the movement and continues its track to the surface.

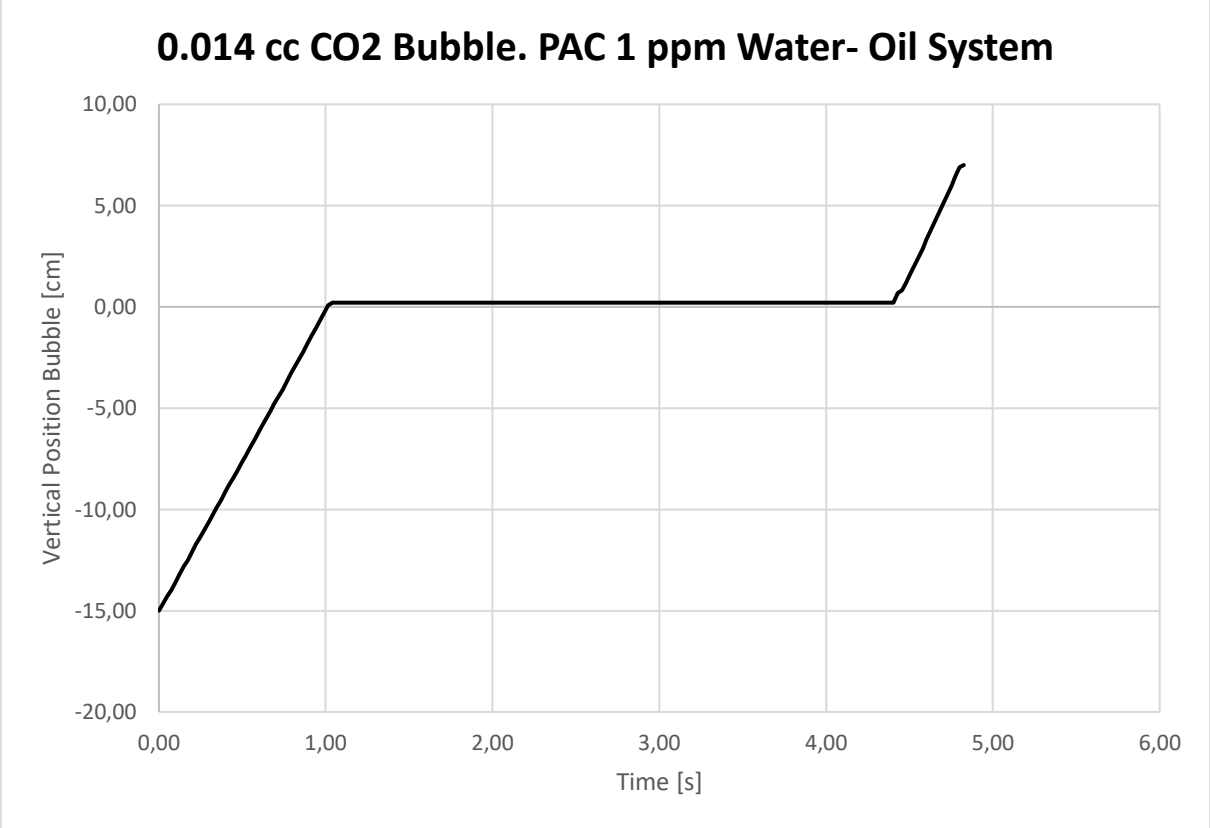


Figure 5.53: *Vertical Movement vs Time, Bubble of CO2 0.014 cc. in a polymer 1 ppm – Oil System*

The horizontal movement of the bubble has a considerably zigzag movement on the heavier liquid zone, and seems reduced after the interface, as is presented on the **Figure 5.54,** in

addition to this, on the **Figure 5.55,** is shown the instant speed of the bubble, that shows how at the interface, is no movement of the bubble and the motion of the bubble is faster on the lighter fluid than on the heavier one

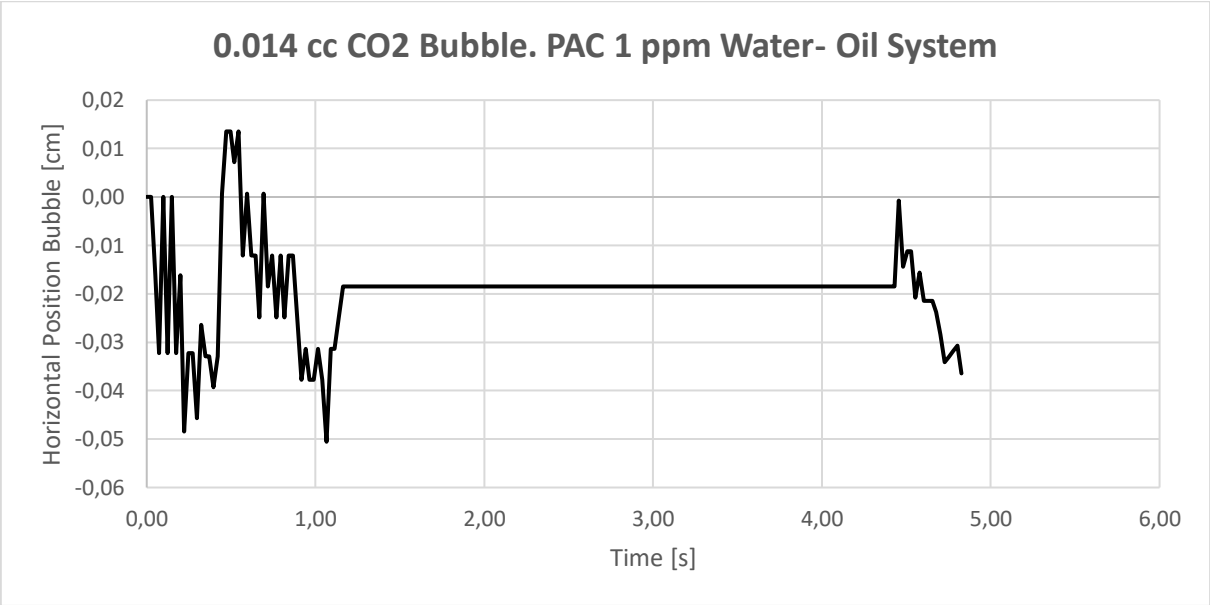


Figure 5.54: *Horizontal Movement vs Time, Bubble of CO2 0.014 cc. in a polymer 1 ppm – Oil System*

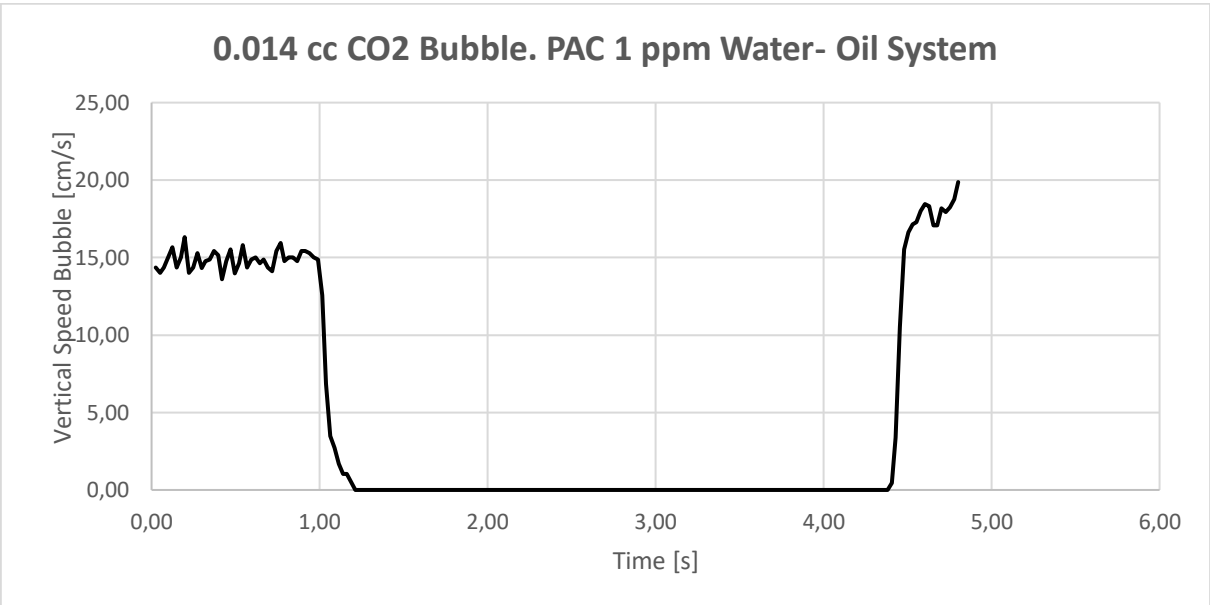


Figure 5.55: *Vertical Speed vs Time, Bubble of CO2 0.014 cc. in a polymer 1 ppm – Oil System*

On the **Figure 5.56** is presented the behavior of the bubble at the interface, here is shown how as the motion of the bubble is interrupted and the buoyancy forces are just slightly above the downward forces, there cannot be presented any drag from the heavier liquid into the lighter one, besides that, there is no formation of droplets, when the bubble overcomes the interface, and continues rising on the lighter fluid, the shape of the bubble is almost spherical.

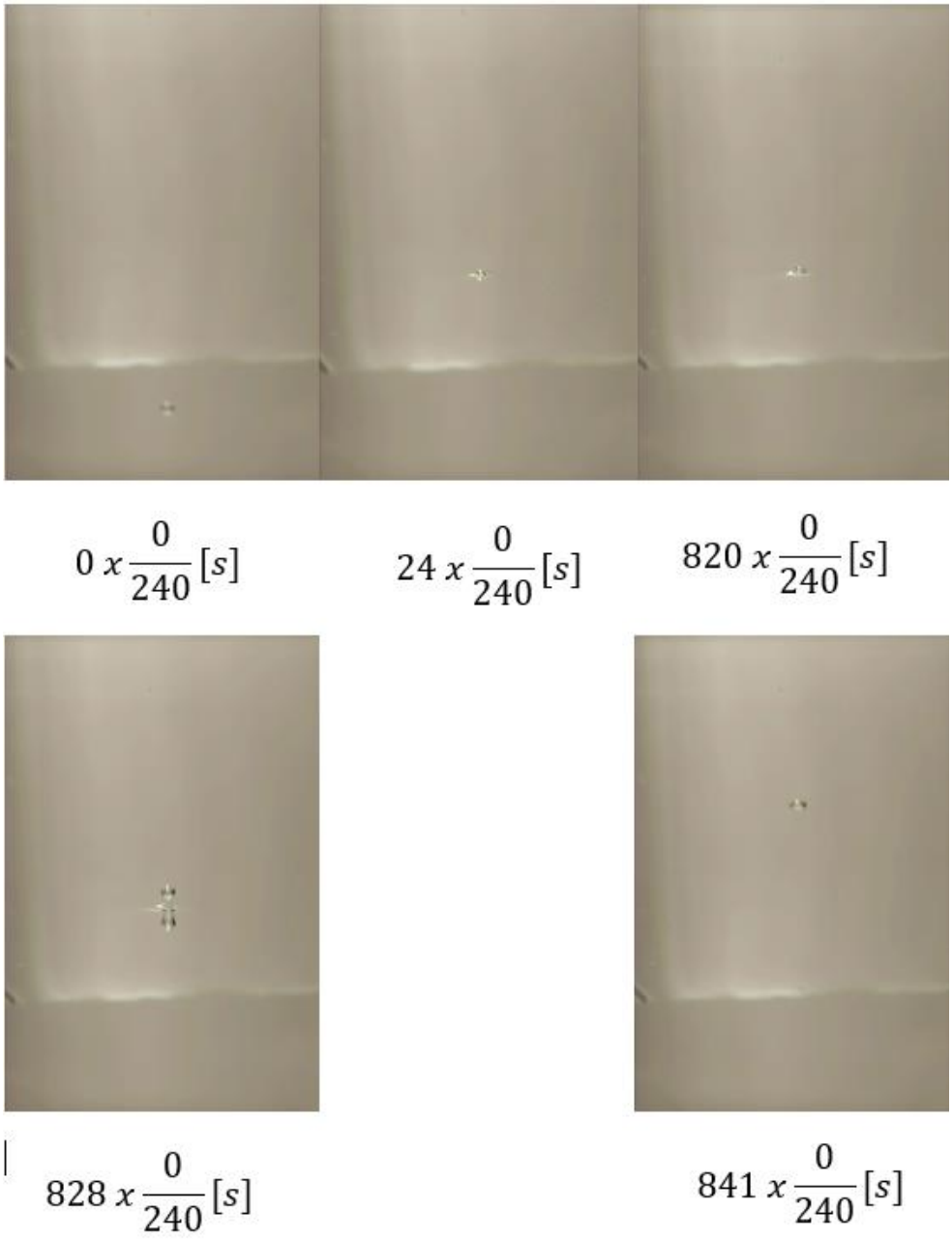


Figure 5.56: *Bubble of CO2 0.014 cc at the interface. in a polymer 1 ppm – Oil System*

5.3.3 Medium Size bubble of Air in a PAC 1 ppm in Water - Oil system

The vertical motion of the bubble is presented on the **Figure 5.57,** where it can be seen that the downward forces interfacial tension stops the path of the bubble at 0.67 seconds, for a total time of 0.76 seconds, after this time interval, the buoyancy forces finally overcome every opposite forces and lead the bubble on the lighter fluid to the surface, for a total time of 1.70 seconds.

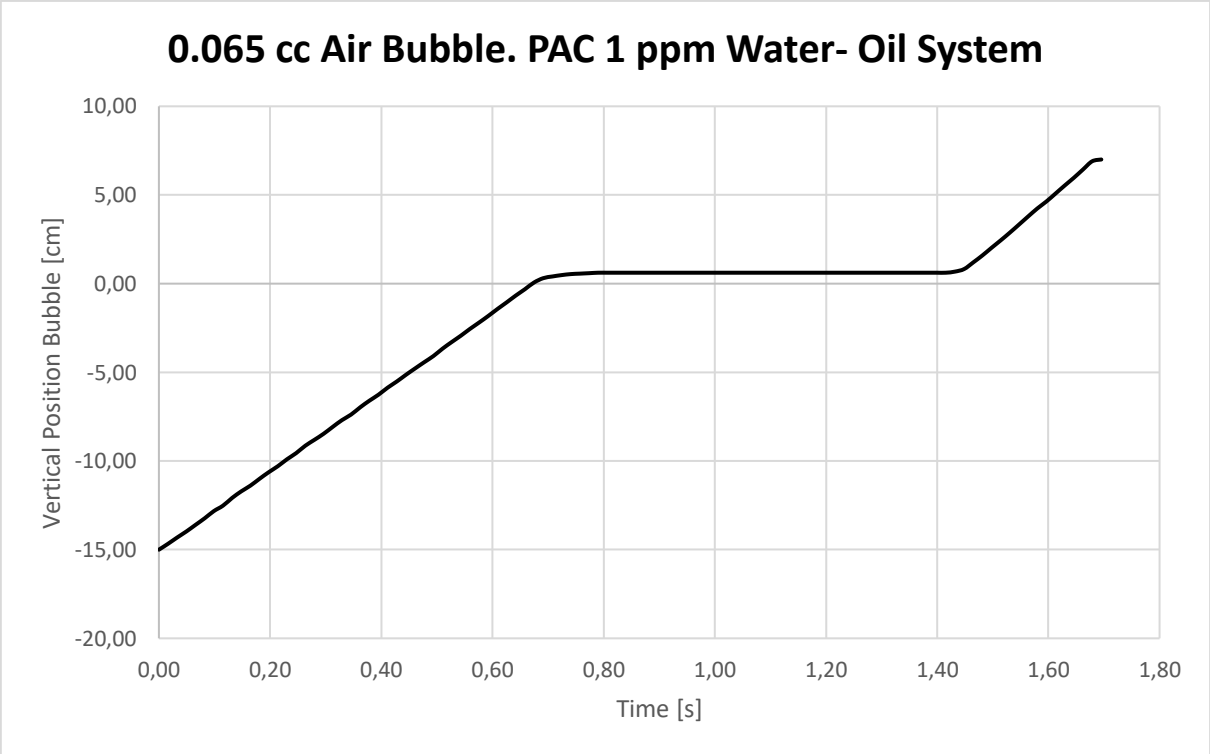


Figure 5.57: *Vertical Movement vs Time, Bubble of Air 0.065 cc. in a polymer 1 ppm – Oil System*

The horizontal movement of the bubble can be considered almost vertical, where there is a zigzag movement with an amplitude of 0.05 cm, that behavior is presented at both liquids, but on the interface is not movement at all, as can be observed on the **Figure 5.58**, moreover,

the instant speed shows that the bubble after a small bouncing. completely stops at the interface and the bubble moves faster on the lighter liquid, compared to the heavier one. **Figure 5.59**

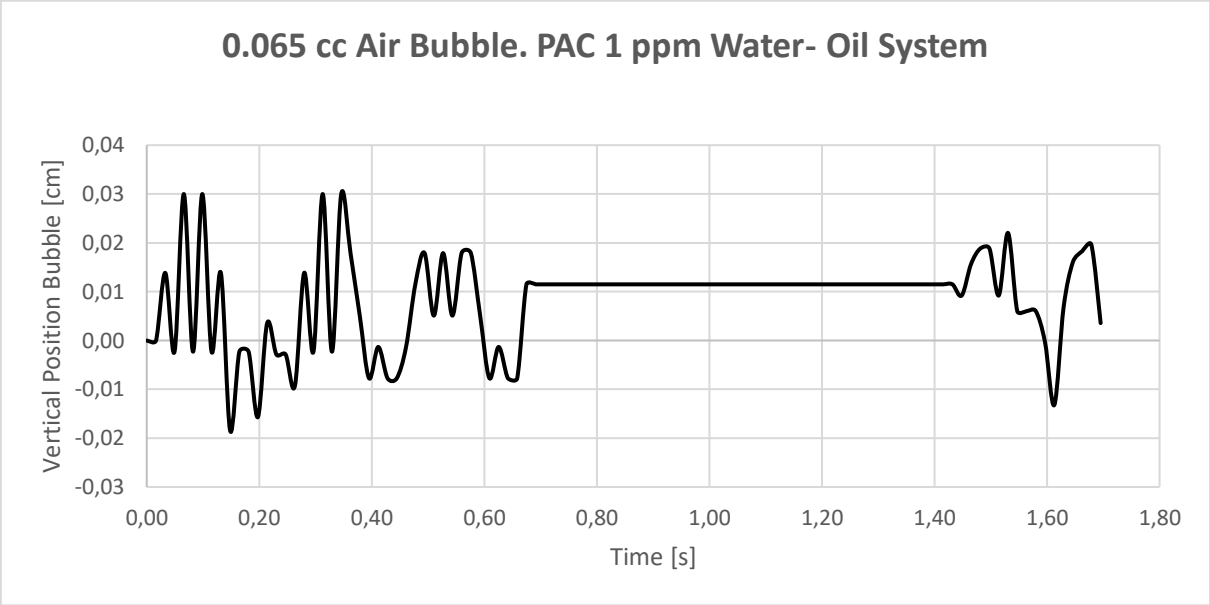


Figure 5.58: *Horizontal Movement vs Time, Bubble of Air 0.065 cc. in a polymer 1 ppm – Oil System*

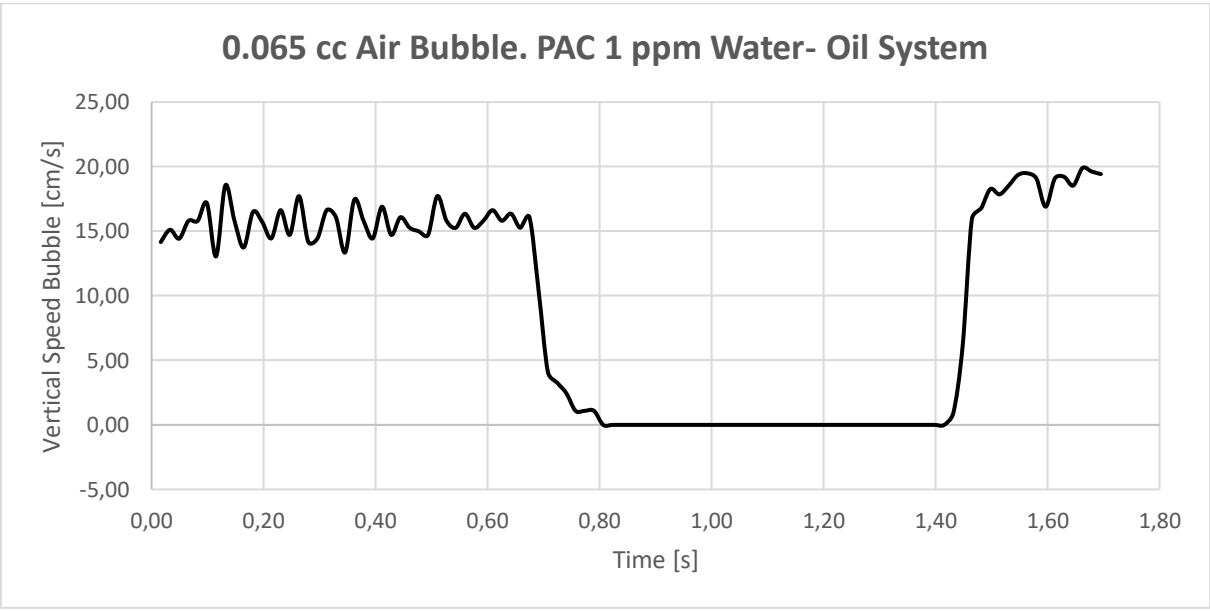


Figure 5.59: *Vertical Speed vs Time, Bubble of Air 0.065 cc. in a polymer 1 ppm – Oil System*

At the interface **Figure 5.60** the bubble of Air presents a small bouncing, before stops, when the bubble overcome the interfaces, it drags a tiny column of water, and the bubble continue rising on the light liquid with an elliptical shape.

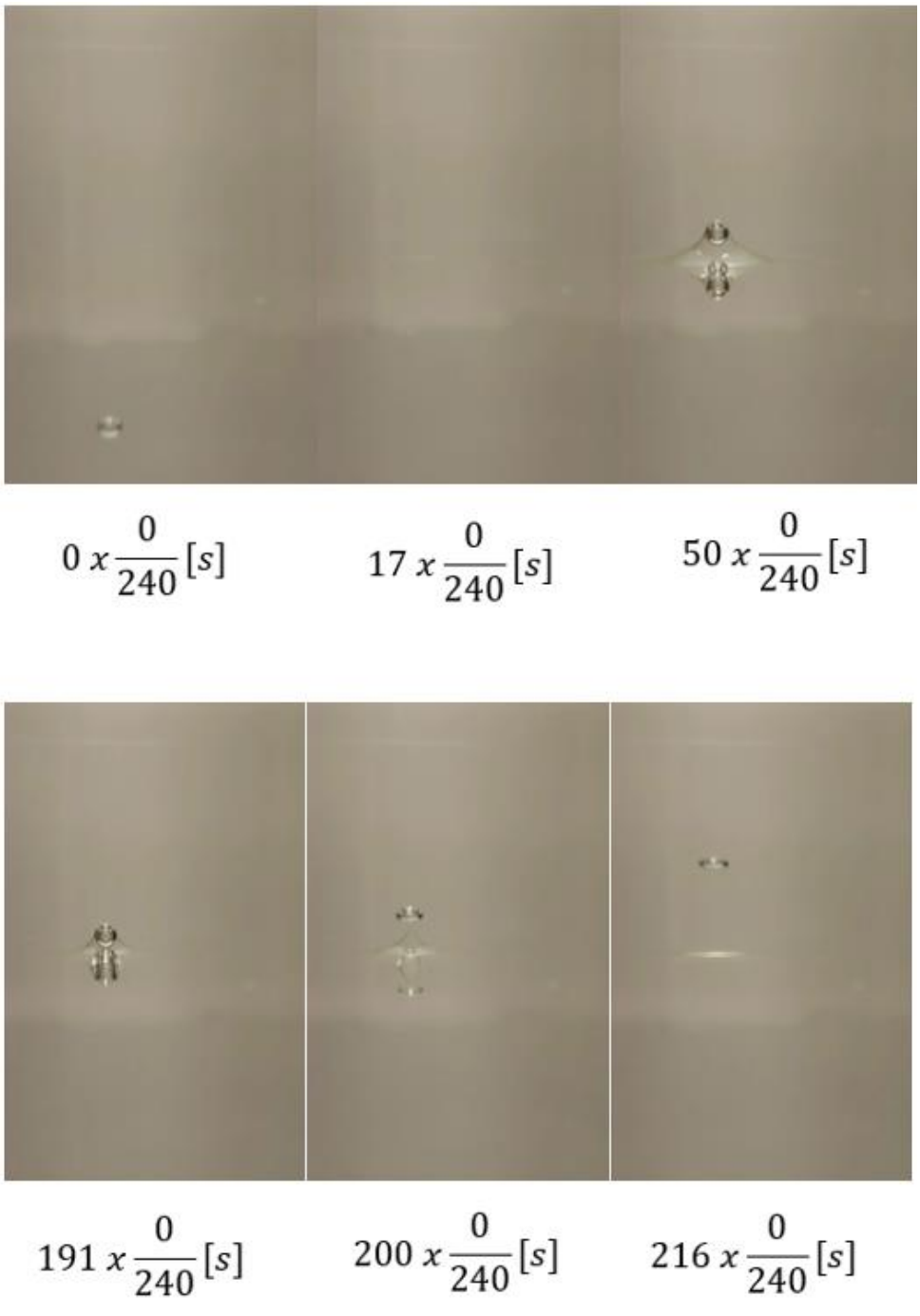


Figure 5.60: *Bubble of Air 0.065 cc at the interface. in a polymer 1 ppm – Oil System*

5.3.4 Medium Size bubble of CO2 in a PAC 1 ppm in Water - Oil system

The 0.065 bubble of CO2 rose to the interface in a time interval of 0.69 seconds, at this position, the upward forces are not strong enough to overcome the interface easily, so the bubble stays on a steady state for 0.8 seconds, right after that, the bubble get over that resistance and continues its path to the surface of the lighter fluid, for a total travel time of 1.88 seconds. On this point, the resting position of the bubble can be found a little above the interface. On the **Figure 5.61** is presented the vertical behavior of the fluid on this test

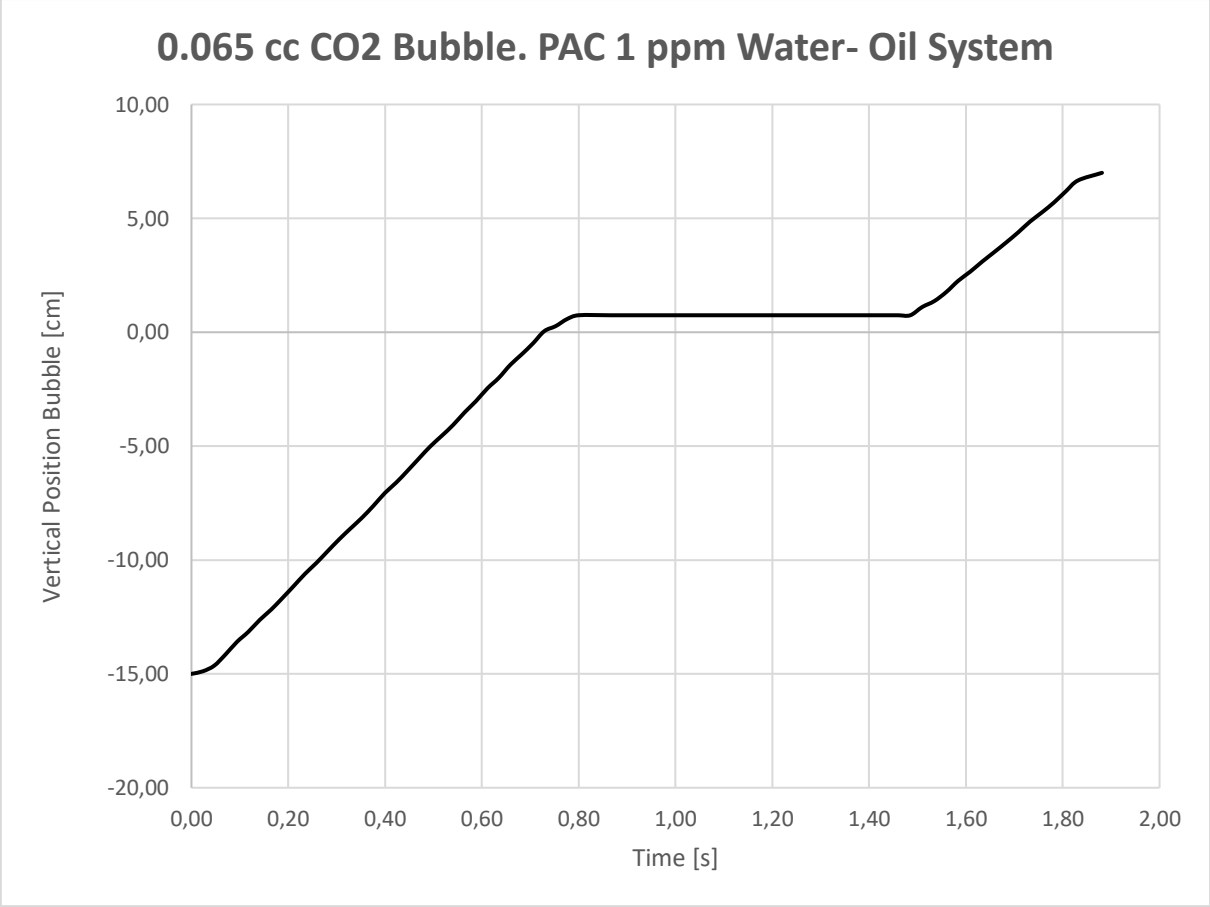


Figure 5.61: *Vertical Movement vs Time, Bubble of CO2 0.065 cc. in a polymer 1 ppm – Oil System*

The motion of the bubble has a hider zigzag movement on the heavier liquid zone, when the bubble passes the interface, the tendency of the movement continues, but now with a lower amplitude, the **Figure 5.62,** shows the behavior mentioned. The instant speed of the bubble can be observed on the **Figure 5.63**, where the speed is almost the same in both fluids, and at the interface is 0, because there no movement of the bubble on that point.

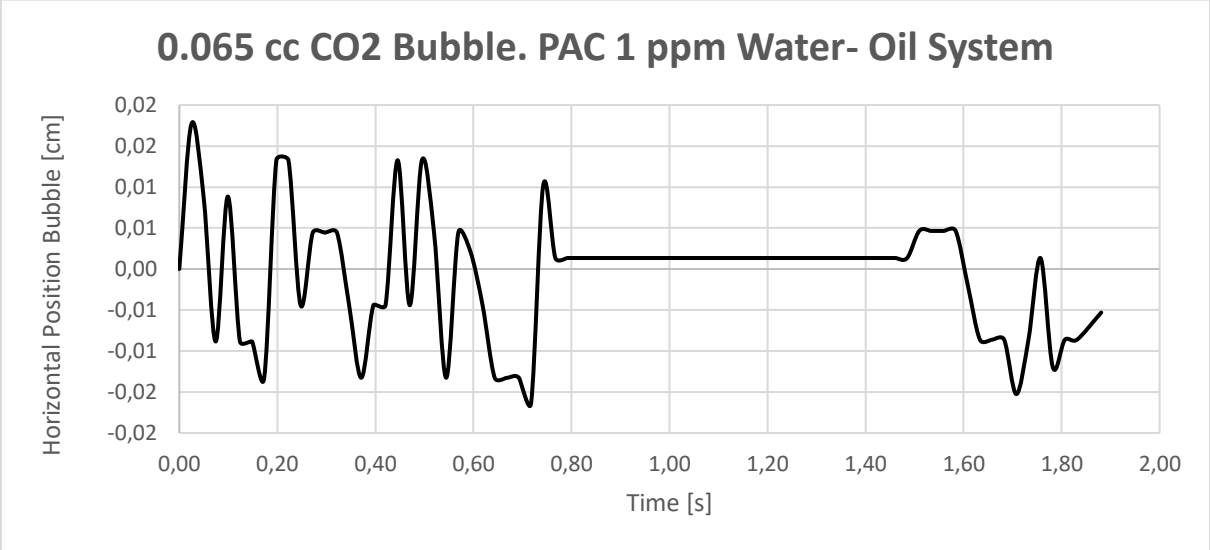


Figure 5.62: *Horizontal Movement vs Time, Bubble of CO2 0.065 cc. in a polymer 1 ppm – Oil System*

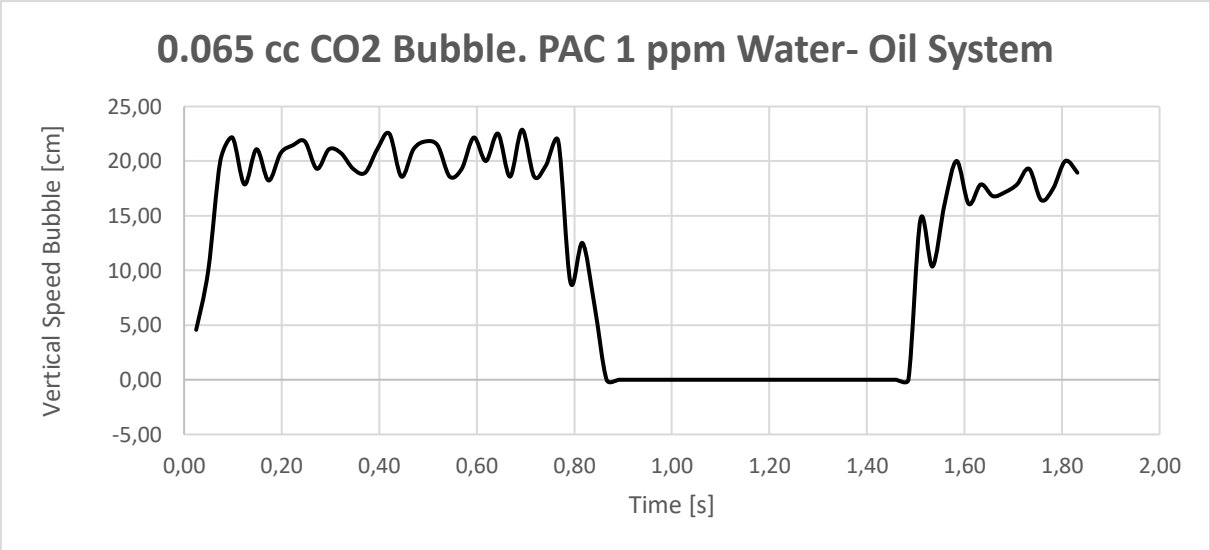
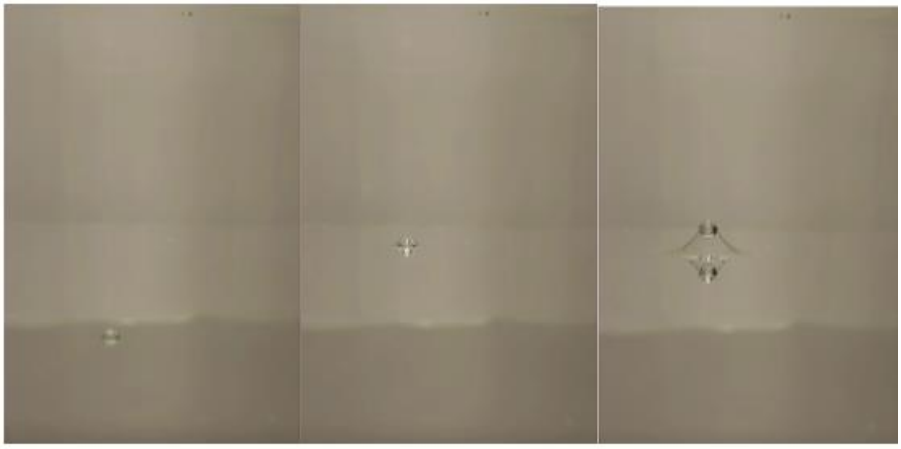
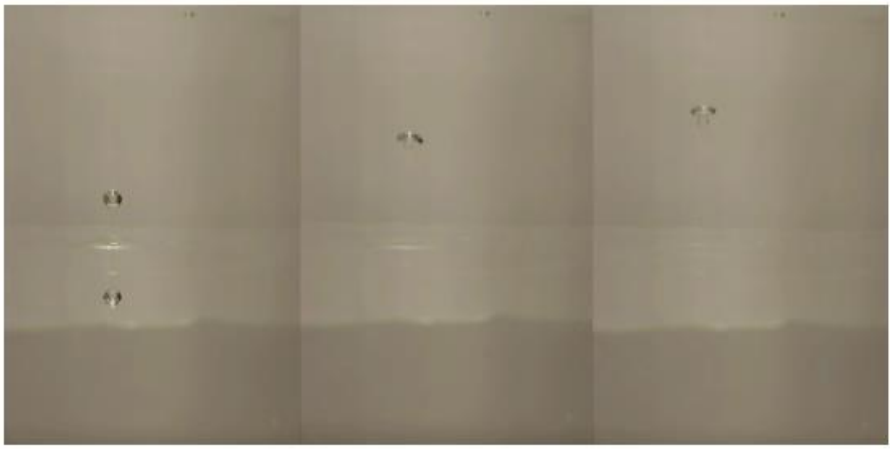


Figure 5.63: *Vertical Speed vs Time, Bubble of CO2 0.065 cc. in a polymer 1 ppm – Oil System*

On the interface can be observed how the resting position of the bubble is some millimeters above the interface, before it breaks the bubble of CO2 drags a column of water, and a film of the heavier liquid covers the bubble, suddenly the film breaks out of the bubble. On the **Figure 5.64** can be observed the behavior explained. At the second 249 x 0/240 is can be seen the rupture of the film that surrounds the bubble, before this the shape of the bubble was almost spherical, however, when it breaks, the shape of the bubble turns to be elliptical.



$0\,x\frac{0}{240}[s]$ $27\,x\frac{0}{240}[s]$ $47\,x\frac{0}{240}[s]$



$230\,x\frac{0}{240}[s]$ $249\,x\frac{0}{240}[s]$ $258\,x\frac{0}{240}[s]$

Figure 5.64: *Bubble of CO2 0.065 cc at the interface. in a polymer 1 ppm – Oil System*

5.3.5 Big Size bubble of Air in a PAC 1 ppm in Water - Oil system

The vertical motion of the bubble of 0.11 of air can be considered as constant through the whole system, where there is not a considerably stop of the movement from the downward forced exerted by the interface. The **Figure 5.65** presents the behavior previously mentioned

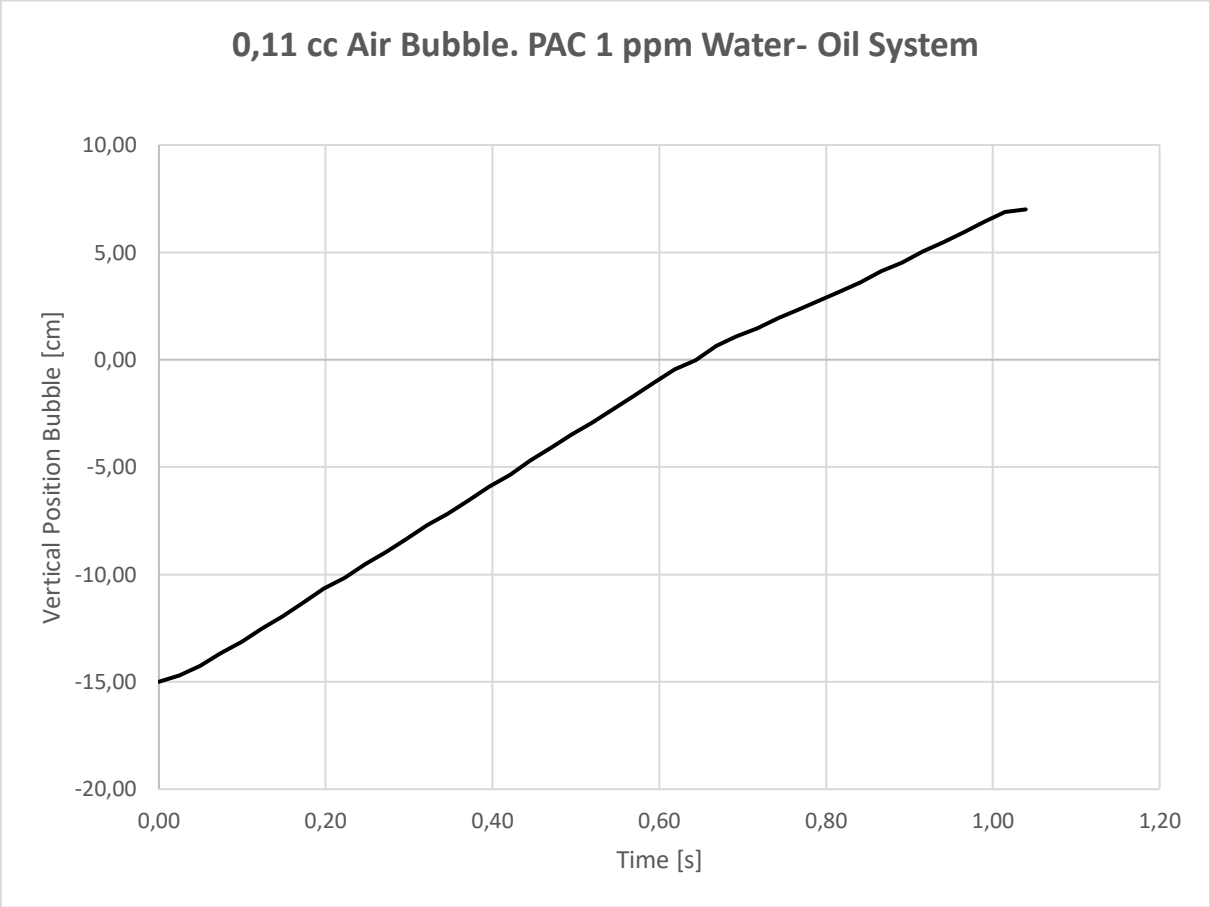


***Figure 5.65**: Vertical Movement vs Time, Bubble of Air 0.11cc. in a polymer 1 ppm – Oil System*

The movement of the bubble does not present a considerably zigzag movement, this can be observed on the **Figure 5.66**, the diameter of the bubble is 0.6 cm, and the amplitude of the

movement is around 0.5. On the other hand, the instant speed of the bubble can be seen on the **Figure 5.67**, where there is a slight reduction of the speed after the interface.

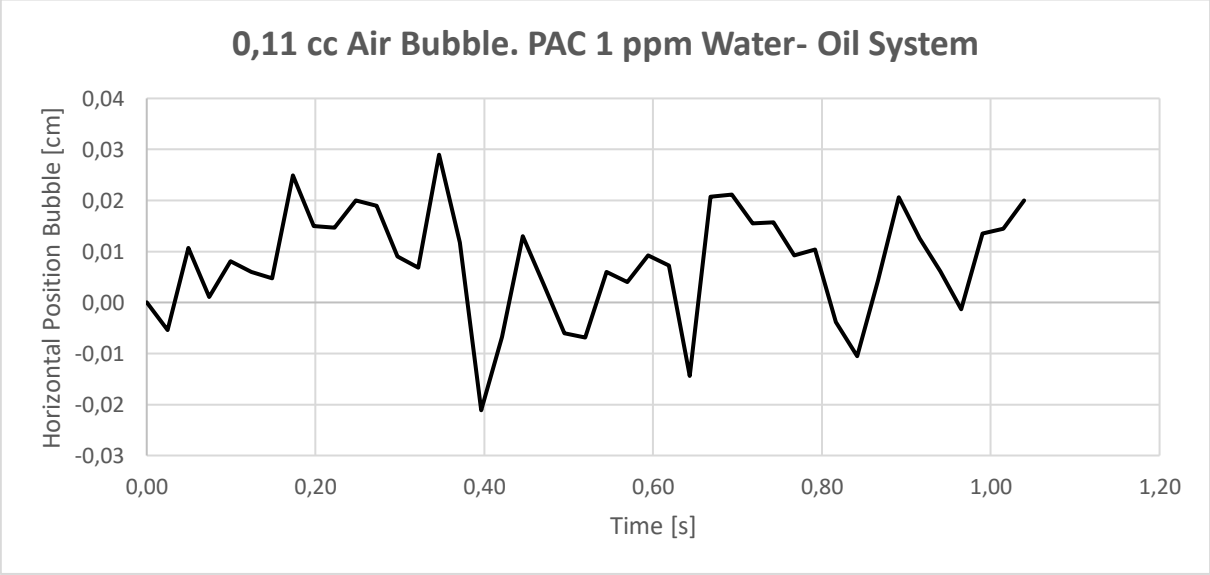


Figure 5.66: *Horizontal Movement vs Time, Bubble of Air 0.11cc*

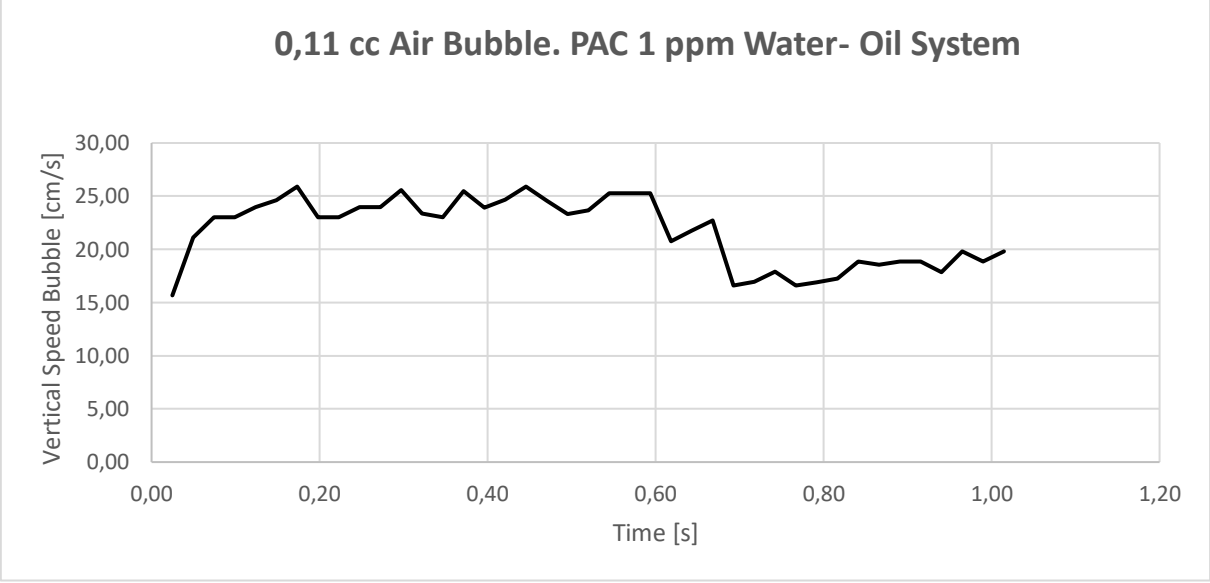


Figure 5.67: *Vertical Speed vs Time, Bubble of Air 0.11cc. in a polymer 1 ppm – Oil System*

On the **Figure 5.68** is presented the behavior of the interface when the bubble of 0.11cc of air is passing through it, here is notorious that the interface does not stop the motion on the bubble, and when this one keeps rising up, it drags a large column of water, that breaks and lead to the formation of drops of water, the formation of the TPCL can be observed when the column breaks, because there is a film of the heavy liquid over the bubble, that breaks when the column cannot resist the motion of the bubble

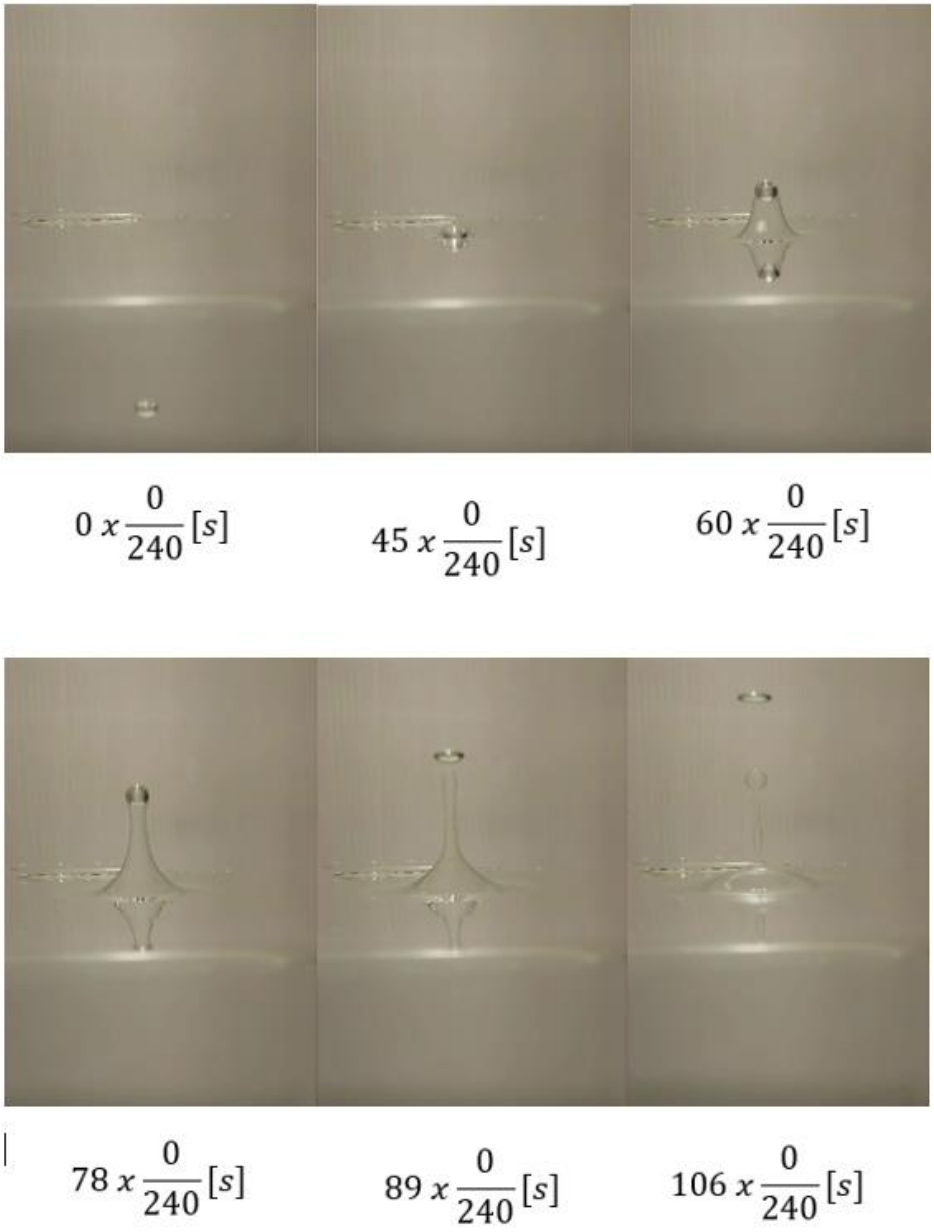


Figure 5.68: *Bubble of Air 0.11 cc at the interface. in a polymer 1 ppm – Oil System*

5.3.6 Big Size bubble of Air in a PAC 1 ppm in Water - Oil system

For the injection of bubble of CO2 with a diameter of 0.11 cc can be observed an almost constant rising along the system, where is clear that the buoyancy forces easily overcomes the interface and this one does not stop the motion of the bubble as can be observed on the **Figure 5.69.**

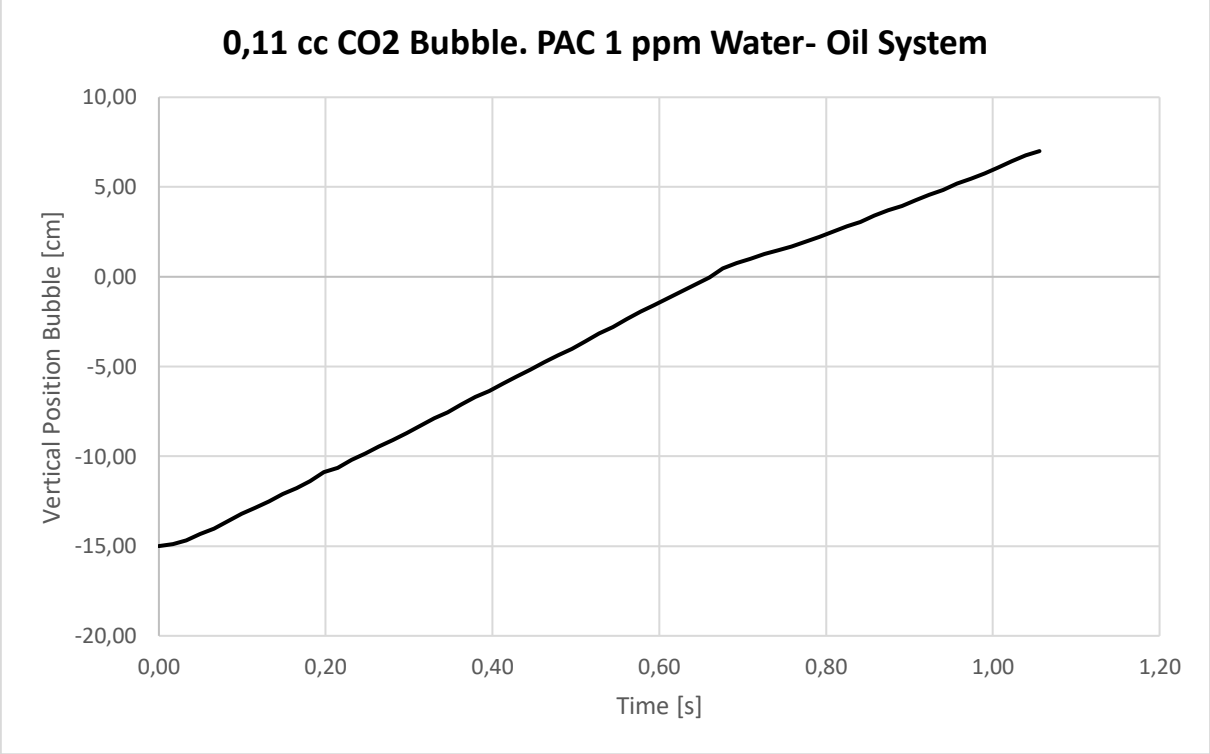


Figure 5.69: *Vertical Movement vs Time, Bubble of CO2 0.11cc. in a polymer 1 ppm – Oil System*

The position of the bubble on the horizontal plane can be considered as constant and almost vertical, where it has some fluctuations on the heavier liquid that become smaller on the lighter one, either way, those fluctuations are un a range on 0.6 cm and the diameter of the bubble is also 0.6 cm, on the **Figure 5.70** is presented the motion of the bubble on the horizontal plane vs time. Additionally, the speed of the bubble is a little bit faster on the

heavier liquid phase, as can be seen on the **Figure 5.71,** however the difference does not have a considerably difference

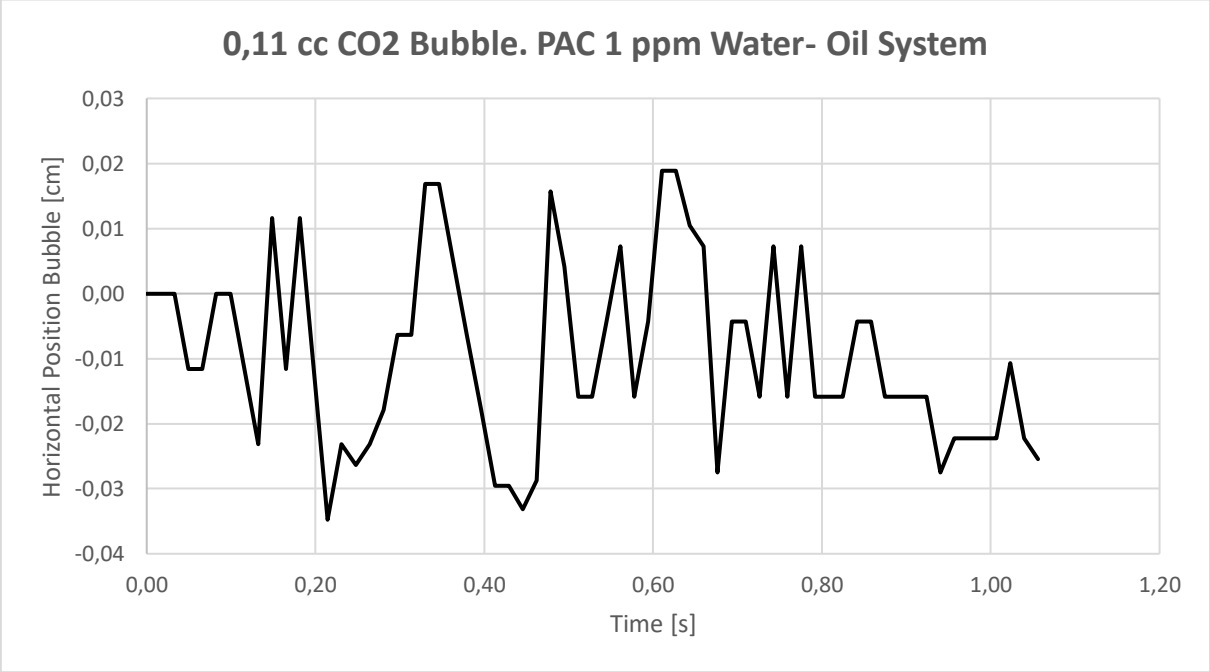


Figure 5.70: *Horizontal Movement vs Time, Bubble of CO2 0.11cc. in a polymer 1 ppm – Oil System*

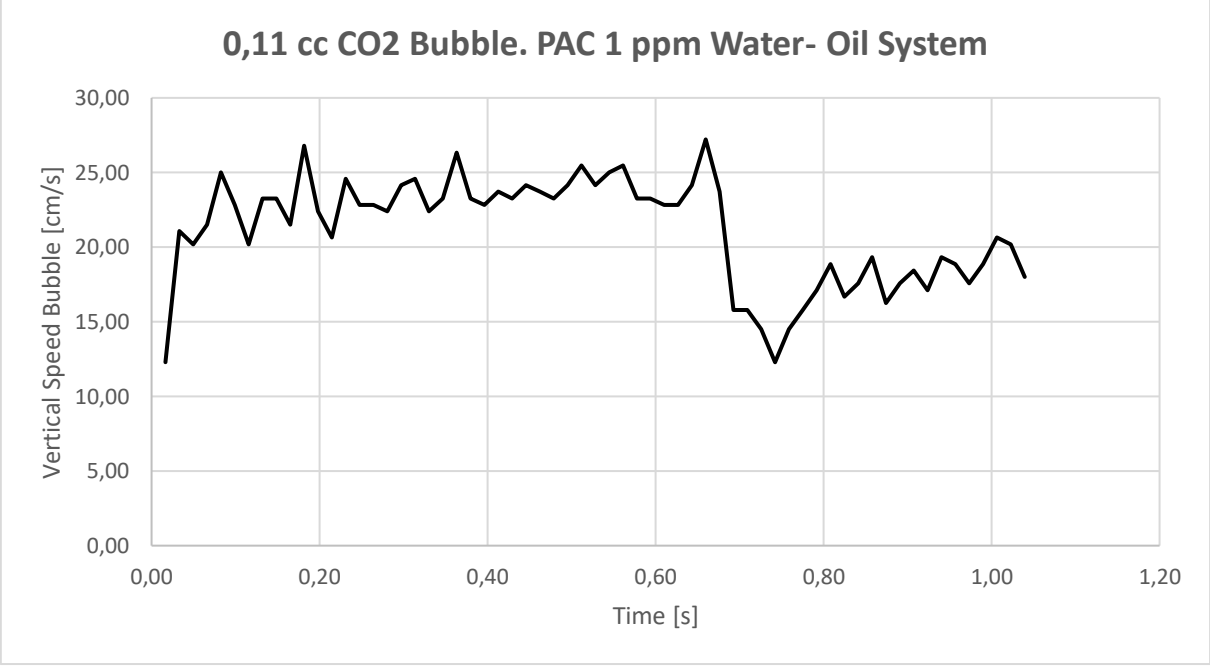


Figure 5.71: *Vertical Speed vs Time, Bubble of CO2 0.11cc. in a polymer 1 ppm – Oil System*

At the interface, can be observed that the forcer exerted by this does not represent a significant reduction of the movement of the rising bubble, that keeps its constant upwards movement, here, the bubble drags a column of water, at a certain length it breaks, leading to the formation of the TPCL, and a big drop of water, that can be related to the film that was surrounding the rising bubble. After the column of water breaks, the bubble continues rising on the lighter liquid zone with an elliptical shape as can be seen on the **Figure 5.72.**

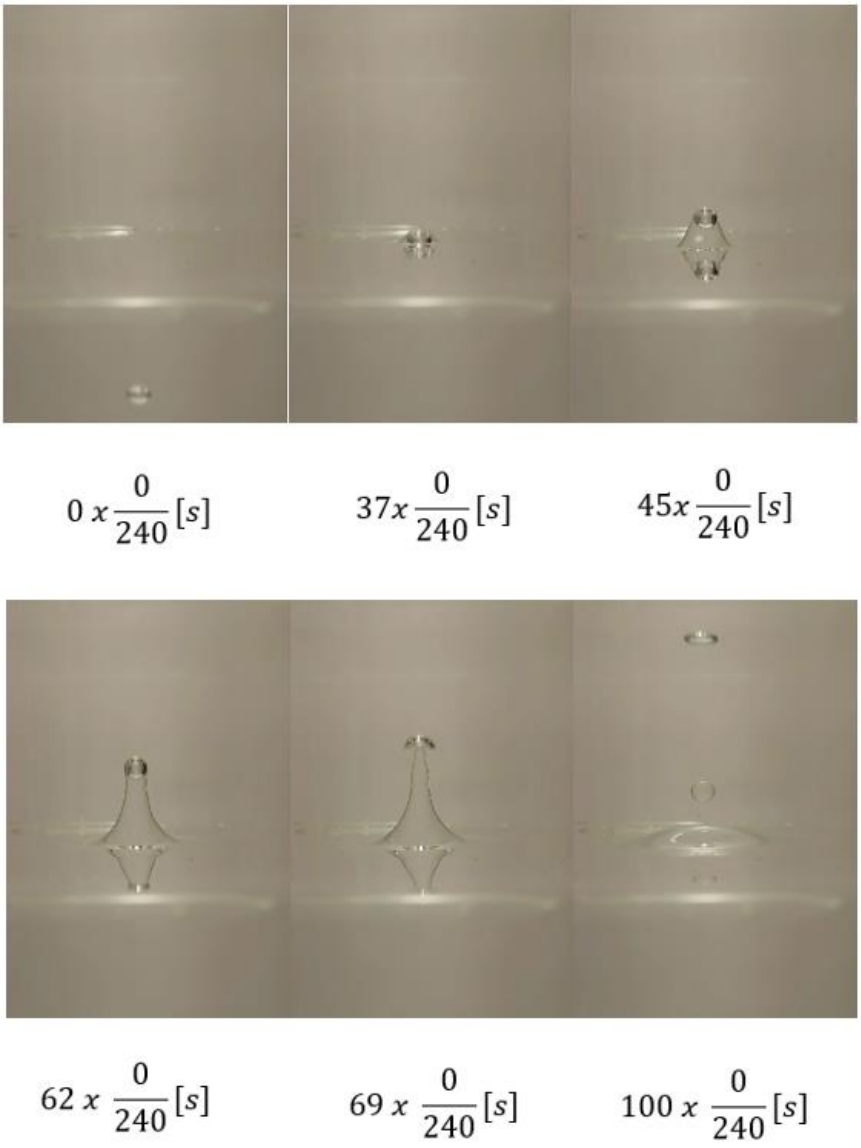


Figure 5.72: *Bubble of CO2 0.11 cc at the interface. in a polymer 1 ppm – Oil System*

5.4Comparation of Results

Once we got the different data, it is necessary to compare the results obtained from the charts, due to this, a three different plots are shown, were compared the time travel and the time at the interface of the 3 different sizes of the bubble, on each plot is presented the 2 different types of bubbles in the 3 different systems where the bubbles were transported.

On the **Figures 5.73, 5.74 and 5.75**, can be observed how the effect of the composition of the rising bubble changed the time at the interface, where the bubbles of CO2 present a longer retention time at the interface compared with the air, moreover, the rising speed of the air, tends to be slightly faster than the CO2.

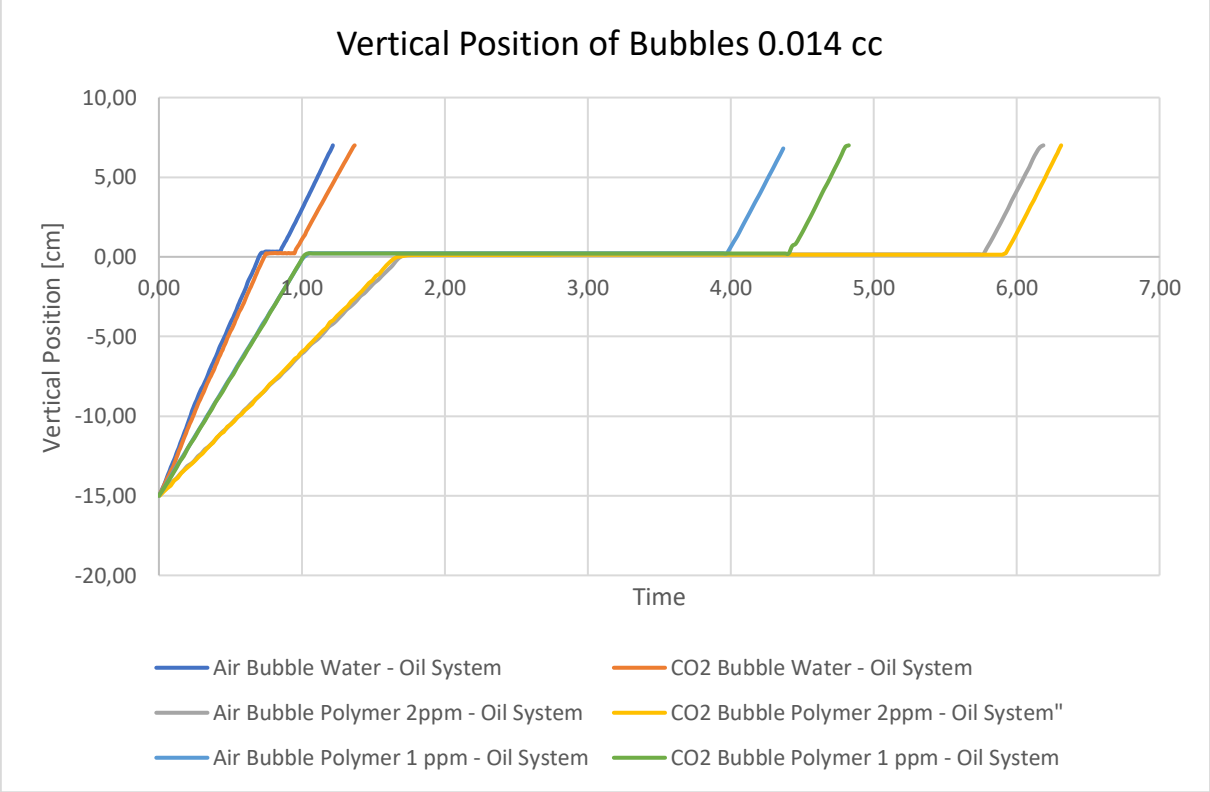


Figure 5.73: *Vertical position of the Bubbles of 0.014cc on the different Systems*

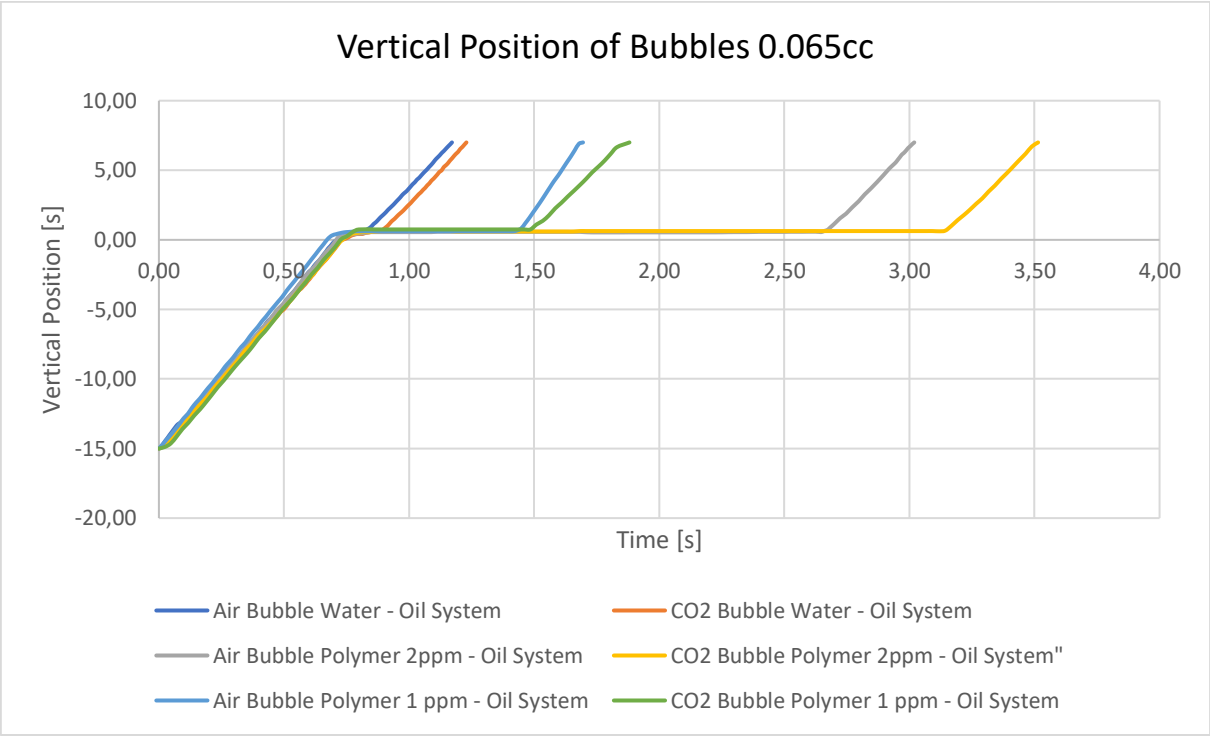


Figure 5.74: *Vertical position of the Bubbles of 0.0.065cc on the different Systems*

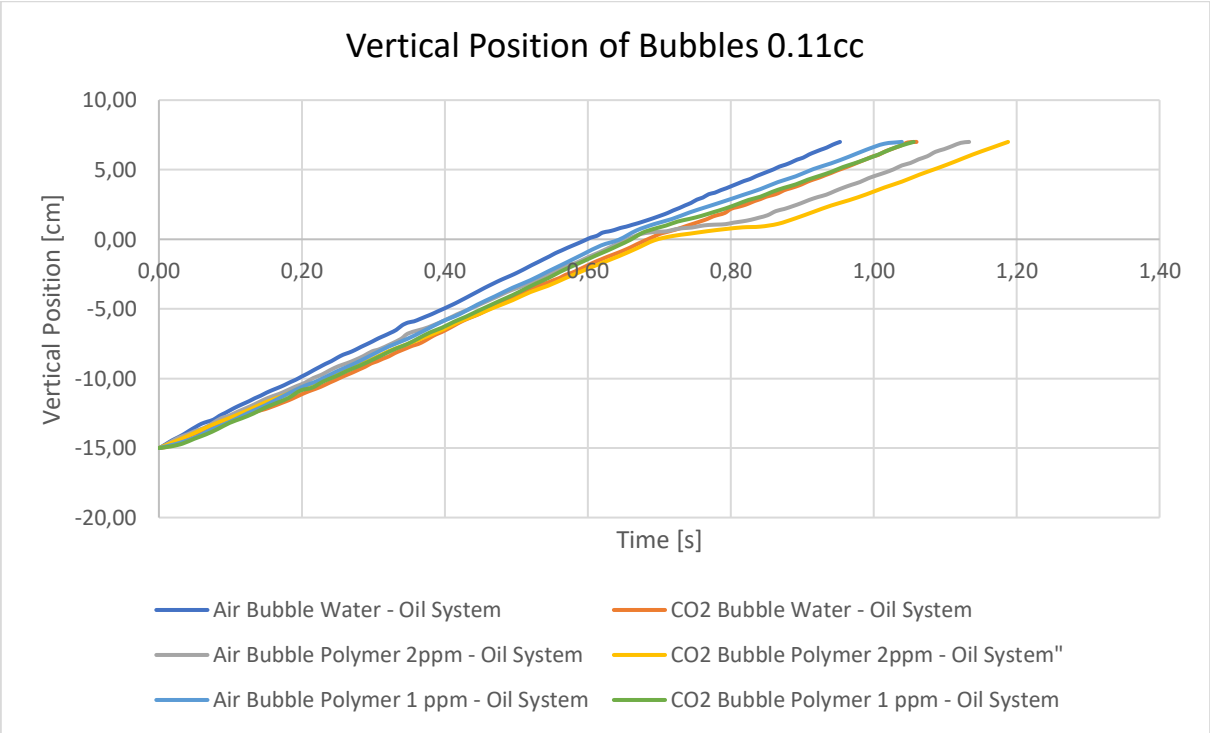


Figure 5.75: *Vertical position of the Bubbles of 0.11cc on the different Systems*

Moreover, the instant speed can be observed on the **Figures 5.76, 5.77 and 5.78** where is presented how the increase of concentration of polymer reduces the speed on the heavier liquid zone, in approximately 70% per each ppm on the small bubble, while on the other two, the speed in the lighter and heavier liquid is similar, however, for the 0.064cc bubble the interface exerts enough resistance to stop the motion of the bubble, mainly in the systems with presence of polymer, and the higher is the concentration, the longest is the time that the bubble has a velocity = 0. On the other hand, the 0.11cc bubble has an almost constant velocity along the system at all the tests.

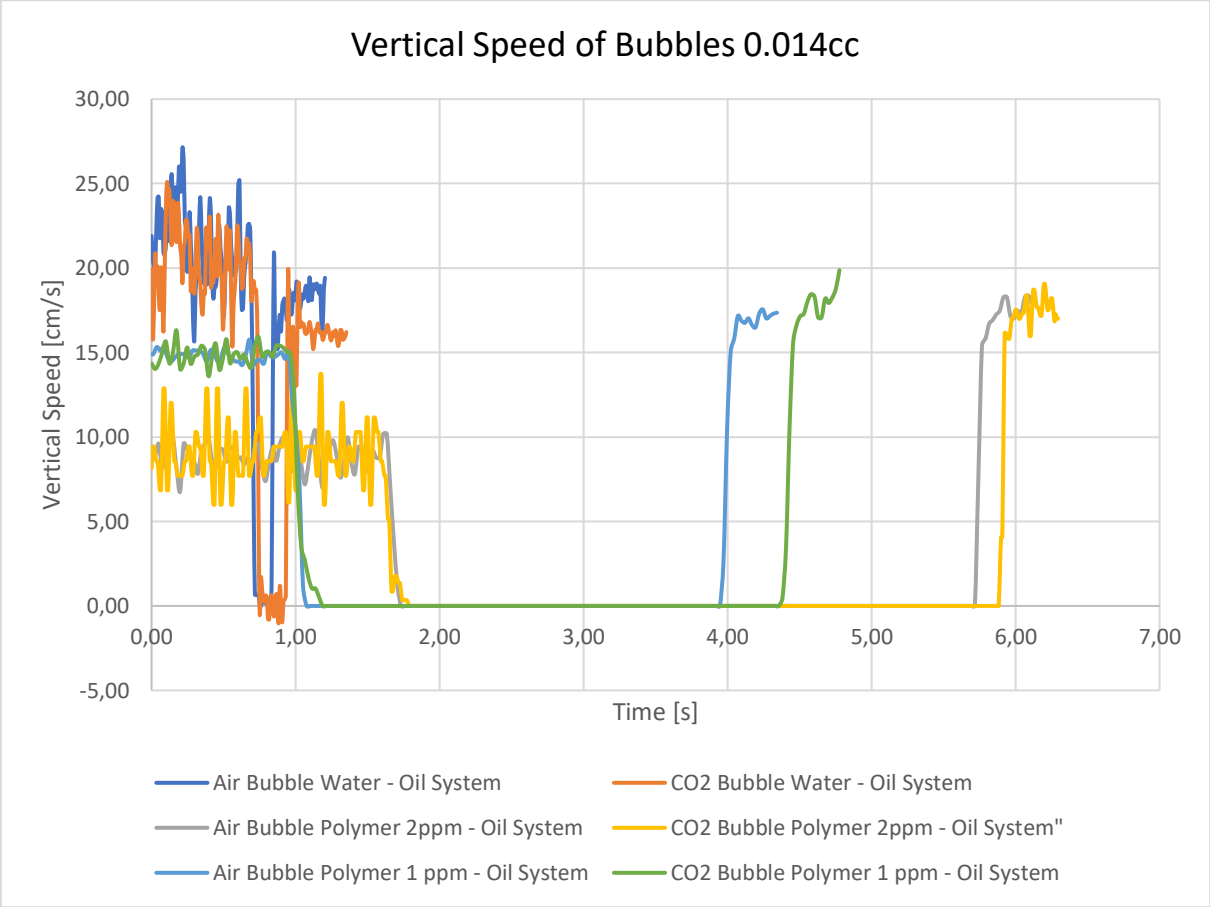


Figure 5.76: *Vertical Speed of the Bubbles of 0.014cc on different Systems*

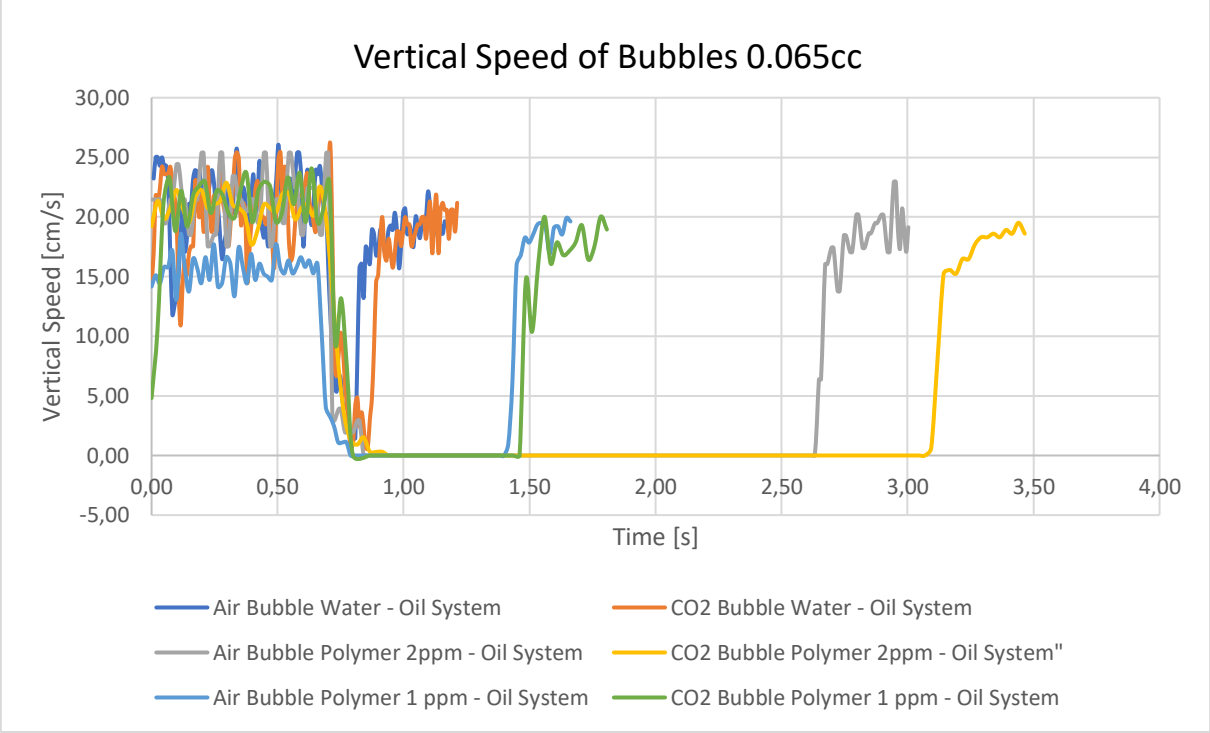


Figure 5.77: *Vertical Speed of the Bubbles of 0.065cc on different Systems*

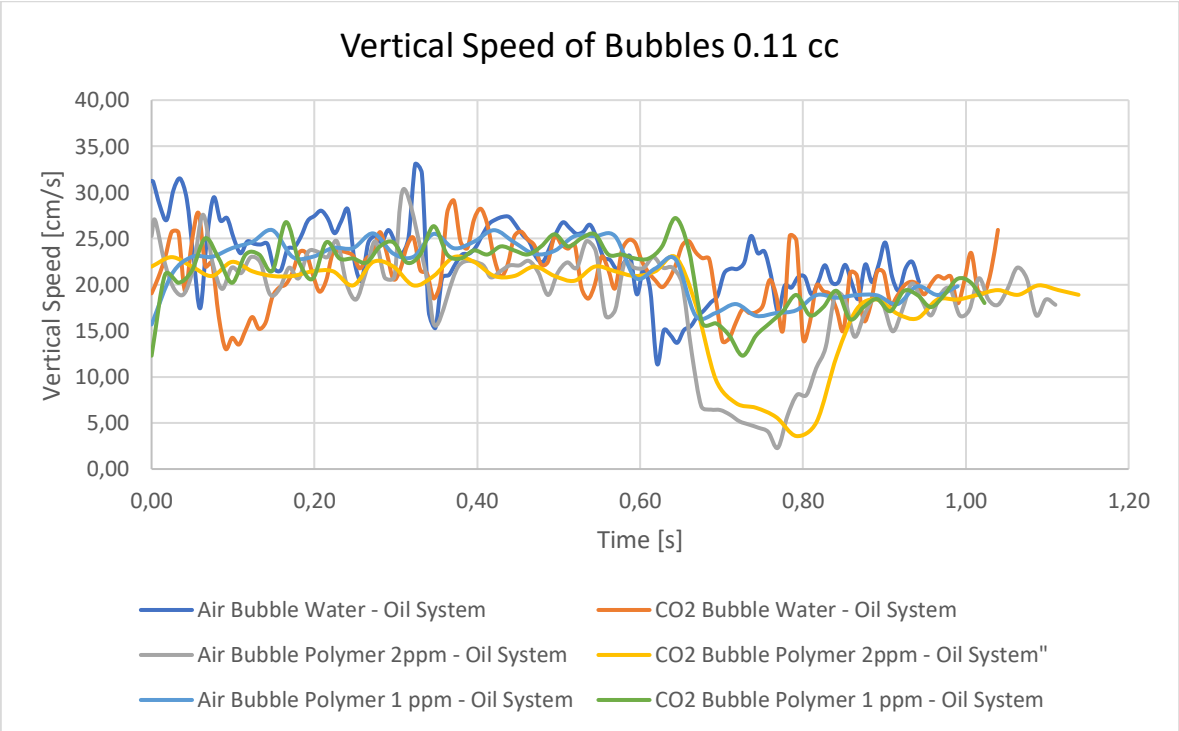


Figure 5.78: *Vertical Speed of the Bubbles of 0.11cc on different Systems*

Chapter 6

6. Conclusions

The fluids dynamic of the bubbles of Air and CO2 on three different systems were studied, and based on the experiments presented by (Greene, Chen, & Conlin, 1988), (Rozario, Viswanathan, & Basu, 2019) and (Edrisi, Dadvar, & Dabir, 2021), (Greene, Chen, & Conlin, 1991)The experimental results for a single bubble of different sizes passing across a liquid-liquid interface have been presented. Newtonian and Non-Newtonian fluids have been considered as the heavy liquid phase

- Different sizes of bubbles, fluids injected and utilization of Newtonian and Non-Newtonian were implemented in order to get different results
- The experiments results shown a logical decrease of the time that the bubble stops at the interface when the diameter of the bubble increases.
- An increase on the concentration of the polymer will lead to an increase of the interface resistance over bubble due to the viscoelastic aspects and the shear-thinning behavior
- An increasing on the diameter of the bubble, is proportional to the drainage height of the heavier column into the lighter liquid
- The resistance of the interface was stronger on the CO2 than on the Air, this can be considered because of the density of the CO2 that is larger than the density of the Air, generating a greater tension between the CO2 and the liquid phases.

- The bubbles of CO2 presented a higher drag of the heavy liquid into the lighter one when the bubbles were raising, generating a larger water column and more formation of heavy liquid drops
- The increase on the viscosity of the heavier liquid reduces the movement of the bubble in the horizontal position, however, it also reduces the speed of the rising bubble.
- A rising bubble carries a film of the heavier liquid when is raising through the lighter liquid, if the upward forces exerted on the bubble are strong enough, this film will break, and create the Three Phase Contact Line (TPCL)

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