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# EXPERIMENTAL OBSERVATIONS OF THE BEHAVIOR OF SINGLE BUBBLES RISING IN CONFINED GEOMETRIES

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*Abstract. In this work, the effect of confinement on the dynamics of single bubbles rising in Newtonian fluids was investigated. A large column with a small gap was employed to perform the study for a gas–liquid system. The confinement parameter s was defined as the ratio of the bubble diameter ($d_b \sim$ 2.5 mm) to the gap width ($w \sim$ 3mm). Hence, the confinement ratio (s) was constant for all the measurements. Bubble size, shape and velocity were measured for different viscosities by means of a high-speed camera. It was found, that for the bubbles size, the bubbles are not distorted and prevails a spherical shape. In addition, the bubble vertical velocity was found to be constant for the different tested liquids. On the other hand, the vertical slip velocity was found to be approximately 50% less in comparison to single bubbles with the same equivalent diameter rising in non-confined geometries. Also, it was noted a decrement in the fluctuating velocities and increasing the viscosity the bubbles paths were modified. Therefore, their trajectories correspond to two different regimes: zigzag and rectilinear.*

*Keywords: Bubbly-flow, confined-geometry, bubble-path, rise-velocity*

## 1. INTRODUCTION

Bubbly flows are widely found in nature and in industrial processes (Schumpe *et al.*, 1979; Dudukovic *et al.*, 1999). One of the main advantages of bubbly column systems is that both phases are in contact without the need of additional mechanical stirring equipment (Deen *et al.*, 2000; Mersmann *et al.*, 1990). In addition, these devices are of interest in industrial mass transfer processes because of their high interfacial area. Such flows are characterized by the presence of air bubbles dispersed in a liquid, where the gas fraction can be dilute or as in industrial operations, reach until 10 to 20%. For such a high void fractions, the fluid agitation is known to be significantly controlled by bubble induced turbulence (Lance and Bataille, 1991; Riboux *et al.*, 2010). It have to be pointed out, that in common practical situations bubbly flows are encountered in confined geometries. This is the case of multiphase flow in oil and gas reservoirs, where the fluid motion is restricted in the underground, such as in the interior of porous, natural channels or fractures. In a general manner, diverse experimental and numerical works of bubbles rising at unconfined environments have been conducted (Ellingsen and Risso, 2001; Sanada *et al.*, 2007; Legendre *et al.*, 2012). It was found that the slip vertical velocity is mainly governed by the balance of diverse forces over the bubbles (e.g. buoyancy, drag and lift forces), while, the shape of the bubbles is dominated by the shear stresses induced by the liquid motion and the surface tension force acting on the surrounding of the bubbles. In addition, it was show that the Eötvös and Morton numbers lead to different bubble paths, which can exhibit rectilinear, zigzag, spiral or helical trajectories. In despite of their importance, most studies have been carried out under non-confined situations, and there are a limited number of studies in confined geometries. Some of them include the works of (Figueroa-Espinoza *et al.*, 2008; Bouche *et al.*, 2012; Keshavarzi *et al.*, 2014). In these research, the effects of the walls on the rise velocity of single gas bubbles in a vertical Hele-Shaw cell were explored. The bubble diameter ($d_b$) and the confinement ratio ($s$) was varied over a wide range, where the diameter of the bubbles were 3 mm to 80 mm and the tube diameter ($D_T$) varied from 10 mm and 630 mm. It was observed that the rise velocity increased with increasing $D_T/d_b$ ratio and became independent of $D_T$ for $D_T/d_b > 8$. (Figueroa-Espinoza *et al.*, 2008) studied the effects of confinement on the motion of a single bubble in inertia dominated regime in vertical rectangular channels and (Roig *et al.*, 2012) analyzed the motion of a flattened bubble rising in a thin gap ($s < 1$) between walls at high Reynolds number. It was shown that bubble deformation and rise are very complex phenomena, governed by fluid properties and confinement ratio. However, not many studies have explored in detail the influence of viscosity on the bubble dynamics under confinement. In this work, it is shown an experimental study of the effect of confinement on bubble dynamics rising in Newtonian fluids. The viscosity was varied in a wide range in order to observe its importance on the characteristic behavior of the bubbles. The results were compared with cases without confinement taken from previous works. The

vertical slip velocity, bubble shape and path instabilities were analyzed.

## 2. METHODOLOGY

The experimental setup used for experimentation is illustrated schematically in Fig. 1. The experimental device consists of a rectangular vertical channel, the thin cell dimensions are 120 cm in height and 20 cm width, with a small separation. The gap between the walls is approximately of 3 mm constant along the channel. This small distance avoids the bubbles superposition, in such way a 2-dimension bubbly flow is ensured. At the bottom of the cell, an air chamber is placed and single bubbles were produced by injecting air through a capillary tube. The position of the capillary was chosen to be at the center of the channel to avoid influence of the lateral walls, in this way it is possible to observe only the influence of the confinement in the x-y axes. The working fluids employed were water and two different water-glycerin mixtures, their physical properties are shown in Tab. 1.
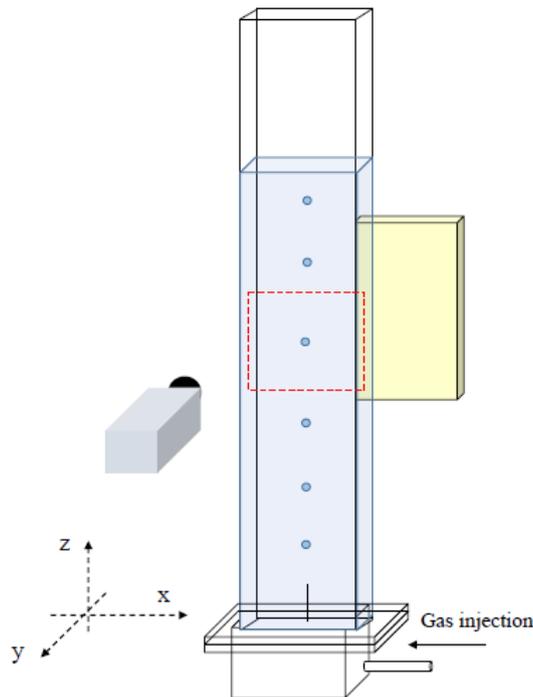


Figure 1. Scheme of the experimental setup: the vertical thin channel; high-speed camera; illumination panel and gas injection method are shown. Also the measurement window is depicted by a red dotted line.

Table 1. Physical properties of the different working liquids, the water-glycerin percentage are in weight/weight.

| Fluid | $\rho[Kg \cdot m^3]$ | $\mu[mPa \cdot s]$ | $\sigma[mN \cdot m^{-1}]$ | Mo [-] |
|---|---|---|---|---|
| Water | 1000 | 1 | 72.75 | $2.5478\,e^{11}$ |
| W-G 25% | 1075 | 2.06 | 70.59 | $4.6715\,e^{10}$ |
| W-G 50%) | 1144 | 7.02 | 68.90 | $6.3659\,e^{08}$ |

[1] properties measured at $22^oC$

The visualization area extends from z = 55 mm to y = 55 mm providing a measurement window of around 20 times the bubble size in each direction. The measurements were carried out at a distance of about 30 times the bubble diameter from the capillary tube. This configuration allows to the bubbles reach their terminal velocities. To obtain measurements of the bubble properties, such as the bubble shape, size, velocity and trajectory; a shadow particle tracking technique was applied. Back lighting was employed to obtain the bubble contours, and then a LED panel and a light diffuser were placed on the back of the test channel. A high-speed camera (Phantom camera SpeedSense) was used to record the bubbles behavior and a digital image processing was performed. A Matlab code was developed to identify the bubbles and measure their shape and velocities.

## 3. RESULTS

In this section are present the results of a study concerning to the effects of the confinement over the shape, characteristic path and vertical velocity of bubbles rising in still Newtonian fluids. From the images analysis, the bubbles characteristics where determined and listed below (Tab. 2). The capillary tube inner diameter (0.35 mm) employed, produces air bubbles with an average size of 2.5 mm. In that manner, the confinement ratio was defined as $s= d_b/w$, where $d_b$ is the bubble diameter and w is the distance between the walls. Hence, the s parameter was fixed constant $\sim 0.80$ for all the tested cases. It was found that in all the experiments the bubble size was nearly constant.

### 3.1 Bubble shape

An interesting feature encountered was that bubble aspect ratio $\chi$ is constant and around 1.1 for the different liquids. If $\chi$ is defined as the ratio between the major and minor axes of the bubble, this value corresponds to nearly spherical bubbles. In previous works, it has been shown that for the mentioned bubble diameter; when it is rising in quiescent water, the $\chi$ parameter was found approximately to be 2 and exhibit a clearly oblate shape.

Table 2. Physical properties of the different working liquids, the water-glycerin percentage are in weight/weight.

| Fluid | $d_b$[mm] | mean vertical velocity $V_z$[mm/s] | $\chi$ [-] |
|---|---|---|---|
| Water | 2.56 | 163 | 1.15 |
| W-G 25% | 2.53 | 159 | 1.10 |
| W-G 50%) | 2.46 | 160 | 1.10 |

The bubble shape is leaded by the flow field around the bubble and is a function of its diameter. A phenomenological explanation of the spherical shape of the bubbles under confinement can be observed in Fig. 2. Here, it is show the stretching of streamlines around the bubbles surface due to the presence of the walls, where the fluid is passing through both sides of the bubbles. It is supposed, that, due to the presence of the walls, a reduction of the free flow of the fluid around the bubbles is produced. This contraction of the flow induces forces in the normal direction of the walls, pushing the bubble to its centroid; which conducts to a more spherical shape.
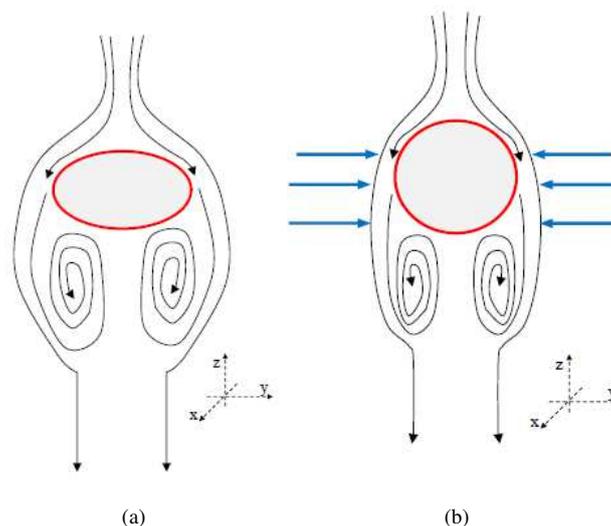


(a)          (b)

Figure 2. Mechanism of restoring bubble shape. The bubble shape is denoted by a continuous red line and the liquid streamlines are depicted by arrows.

### 3.2 Bubbles rising path

On the other hand, by analyzing the bubbles paths at the different tested liquids, as it is expected, the path shapes are modified. In Figs. 3a) and b), which correspond to the case of water and a mixture of glycerin and water (25%), respectively, a similar trend is noted and a zigzagging motion is observed. Once again, by observing Fig. 3, as the bubbles passed through the liquid, coherent structures are formed and two pair of vortex are formed in the back region of the bubbles, which producing an instability as a result it perturbs the bubbles rising (Figueroa-Espinoza et al., 2008). Moreover, the bubbles path for a large viscosity (mixture glycerin-water 50-50%) a rectilinear bubbles displacement is noticed (Figs. 3c). Such a behavior, corresponds to an increase on the dissipation rate of the vortical structures formed at

the rear of the bubbles. The aforementioned instabilities are rapidly vanished by the viscous forces opposed to the shear stresses.
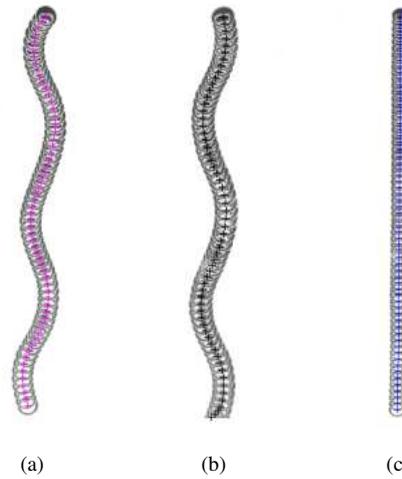


(a)          (b)          (c)

Figure 3. Bubbles rising paths for the three different viscosities of the liquids: a) water; b) W-G:25%; c) W-G:50%.

## 3.3 Bubbles rising velocity

As the motion of the bubbles are governed by the external forces acting on them, it is expected that viscosity increasing leads to a diminishing of the terminal velocity.Figure 4, shows the vertical and fluctuating velocities for the single bubbles rising in the different tested fluids. In Fig. 4a, vertical velocities are depicted. Here, it is appreciated no significant changes in their magnitudes, even at the high viscosity case (7 times higher than the lower one). In Tab. 2 are shown the average values of the vertical velocities for each case. Slight differences can be notice that can be attributed to the experimental error. On the other hand, it had to be mentioned that by comparing to the case of a bubble rising in water in an unconfined geometry, it was possible to observed a reduction of around 50% is observed. These deviations are attributed to the increase of the drag forces on the bubbles due to their interactions with the channel walls. It has been reported to be at least 6 times larger in the confined systems (Figueroa-Espinoza et al., 2008).



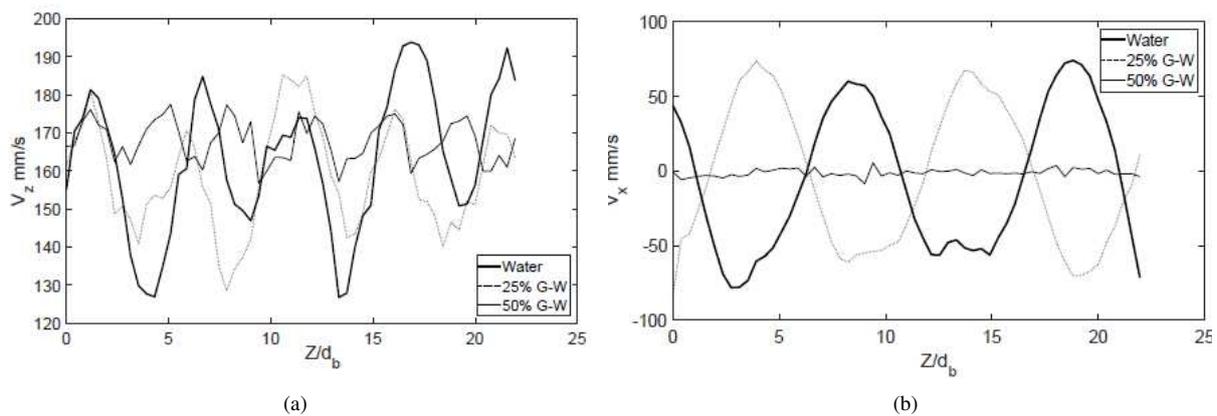(a)                                   (b)

Figure 4. Experimental velocities of single bubbles rising in the different fluids: a) Vertical velocity; b) Fluctuating velocities. The x-axis was made dimensionless with the average bubble diameter.

On the otherwise, by observing Fig. 4b, the fluctuating velocities exhibit a different response. Here, mainly for water and low concentration of glycerin the same trend is followed, whilst large fluctuating velocities in x-axis are noted. This is clearly due to the large instabilities and vortex formation in the rear of the bubbles, which directly influence the bubbles movement to the sides, generating the liquid perturbation. The influence of viscous force is reflected in the case of 50% of glycerin, where an attenuation of fluctuating velocity is noted (thin black line). Clearly, at this situation, the bubble rises in a straight pathway and no oscillatory motion is observed, avoiding the liquid disturbance.

## 4. SUMMARY

In the present paper, the characteristic behavior of single bubbles rising in a thin vertical channel is shown. The working liquids were Newtonian fluids and their viscosities were varied in a wide range. The effects of the confinement and fluid viscosities were studied analyzing the shape, path behavior and velocities of the bubbles. The vertical channel was a Hele-Shaw cell of $3 \times 200 \times 800$ mm, and the gas was injected by blowing nitrogen through a capillary tube, which produces single bubbles of 2.5 mm in average diameter. In this way, the confinement ratio was defined as $s = d_b/w$, where $d_b$ is the bubble diameter and $w$ is the walls distance, in this work the s parameter was kept constant $\sim 0.80$. The experimental study was carried out by means a high-speed camera and images processing technique. The existence of physical boundaries, which restrict the fluid movement around bubbles surfaces, modify drastically their shapes. The confined geometry contributes directly to the leading mechanism that originates the stretching of the streamlines, which exerts forces on the bubbles surfaces, modifying its final shape leading to the spherical form. Influence area and the structure of the bubbles wakes are governed by the falling liquid film velocity through the gap between bubble and the channel walls. At a larger liquid velocity flowing from narrower gap by bubbles passing, it induces larger a vortex and more influence area than in unconfined cases. Additionally, the bubble paths change from zigzagging to rectilinear as a direct result of viscosity increment. In this manner, the wake influenced area; vorticity intensity and path instability are reduced. Several competing forces directly influence the bubbles velocities as they rise through the fluid (i.e. buoyant force due to density difference in upward direction; the viscous force on the bubble surface; and the surface tension that promotes that the bubbles acquire a spherical form, reducing the bubble deformation). Confinement reduce significantly rising velocities in comparison of unconfined cases. The drag on the bubble increases with an increase in the confinement ratio, modifying their velocity, it was observed that by an increasing in viscosity the fluctuating velocities are dissipated and no agitation in the liquid is induced. However, further studies have to be carried out to verify our findings and the exposed assumption about the bubble shape restoring mechanism. In addition, a research concerning to the velocity fields of the fluids have to be realize in order to clarify its influence on bubbles velocity behavior.

## 5. ACKNOWLEDGEMENTS

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