THREE-DIMENSIONAL FLOW IN THE WAKE OF TAYLOR BUBBLES RISING THROUGH STAGNANT BOGER FLUIDS

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Abstract. *The flow in the wake of Taylor bubbles rising through stagnant Boger fluids was experimentally investigated aiming to characterize the flow pattern and the size of the wakes. A photographic study of the wakes of slugs rising in tubes of 32 mm internal diameter is presented. The results are compared with the wakes of Taylor bubbles, rising through a Newtonian fluid with similar viscosity, and with previous works in shear thinning fluids. In this work, the influence of the elastic component of the Boger fluids, in the hydrodynamics of the wake region, is presented for the first time. The elastic enhancement in the present viscoelastic fluid (PAA300) was responsible for the formation of a complex three-dimensional flow structure, in the region below the bottom of the bubbles, with the formation of a small cusp. This cusp was observed in different orientations, during the bubble rise, indicating a fast rotational movement.*

Keywords*: Boger fluid, visualization, multiphase flow, non-Newtonian fluids, 3D flow structure, Taylor bubble*

1. INTRODUCTION

Slug-flow is a two-phase flow pattern observed when gas and liquid flow simultaneously in a tube. The slug-flow regime is characterized by a series of individual large bubbles, also called Taylor bubbles or gas slugs, with an elongated shape, witch almost fill the available flow cross section. Familiar examples are found in the neck of a bottle which is being emptied too rapidly, air-lift reactors, cooling system of nuclear power plants, and geothermal processes among others.

Flow visualizations have a vast practical relevance in fluid mechanics providing a clear insight of many phenomena, and supporting elaborated mathematics. Non-Newtonian fluids are usually liquids with high viscosity, which leads the majority of the viscoelastic flows to occur in the laminar regime, facilitating the use of visualization techniques. Boger and Walters (1993) published a benchmark compilation of flow visualization studies dedicated to non-Newtonian fluids. On the other hand, the available literature dealing with the flow around Taylor bubbles in non-Newtonian liquids is scarce, and inexistent with respect to single gas slugs rising through stagnant Boger fluids.

A Boger fluid is an elastic liquid having a constant shear viscosity. Since the viscosity is independent (or nearly so) of the shear rate, then the elastic effects can be separated from viscous effects in viscoelastic flows, with the latter effects being determined with Newtonian fluids. Boger fluids are dilute polymer solutions, generally made with a solvent viscous enough to promote measurable stresses due to elasticity (James, 2009).

This paper examines the wake of gas slugs rising through a stagnant Boger fluid «PAA300» (Alves, 2004). The present results are compared with the results of Sousa *et al.* (2004, 2005 and 2006), which used simultaneous Particle Image Velocimetry (PIV) and shadowgraphy techniques, to characterize the flow pattern around Taylor bubbles rising in stagnant shear thinning fluids (aqueous solutions of low concentrations in carboxymethyl cellulose, CMC, and polyacrylamide, PAA). A photographic study of the wakes of slugs rising through a Newtonian fluid (N91), with a viscosity similar to PAA300, was also performed for comparative analysis.

2. EXPERIMENTAL TECHNIQUE

The experimental technique adopted to help visualize the flow of liquid in the wake of a single gas slug was inspired by the work of Campos and Guedes de Carvalho (1988). The experimental apparatus is depicted in Figure 1. Two sections of transparent acrylic tube (1), with 32 mm internal diameter, were connected by a stainless steel ball valve (V2). This ball valve had a 32 mm bore so, when fully open, it did not disturb the rising slugs.

At the bottom of the column, there was a section used to feed coloured liquid and compressed air. This part consists of a conical contraction (3) connected to a larger cylindrical tube, inside which a hemispherical cup (4) could be rotated, manually, above the injection nozzle of air. The injection nozzle was connected to a compressed air-line by means of a solenoid valve (VS). The opening time of VS can be adjusted to control the volume of the injected gas.

The liquids used in the present work were an aqueous glycerol solution with 90.99 wt% in glycerine – the Newtonian fluid N91 – and the Boger fluid PAA300. In all the experiments, a certain volume of liquid was taken and divided in two fractions: a small amount (0.175 wt%) of a strong red dye of Rouge Solophenyle powder, 4AGE from

Huntsman, was added to one of the fractions, meanwhile the other portion rested colourless. The two portions of liquid were placed in separated reservoirs - bottles 5 and 6, respectively.

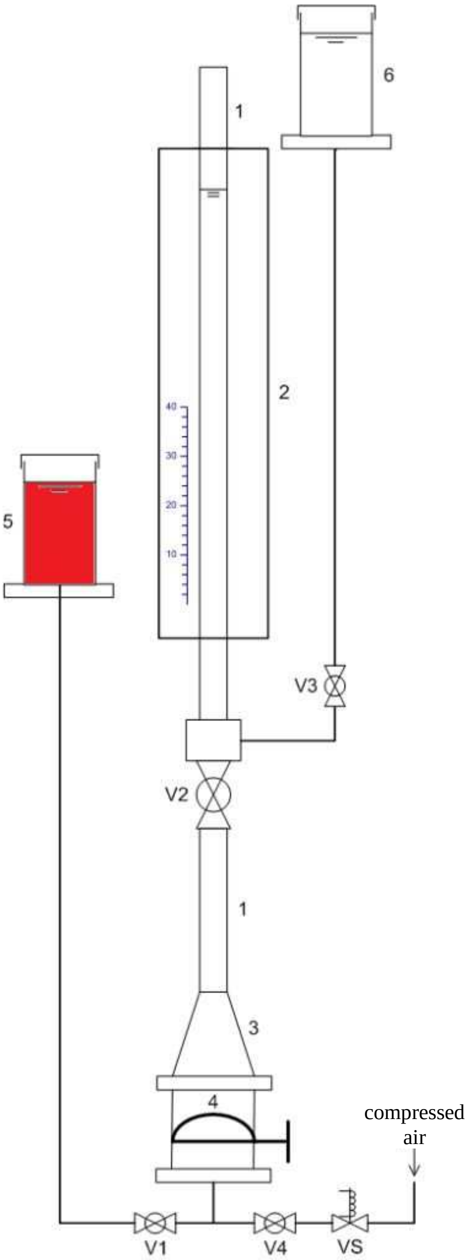


Figure 1. Experimental set-up; 32 mm i.d. column (1 – acrylic column; 2 – acrylic box; 3 – conical contraction; 4 – hemispherical cup; 5 – bottle containing the coloured liquid; 6 – bottle containing the colourless liquid; V1 to V4 – ball valves; VS – solenoid valve).

The red coloured liquid was fed to the column, by gravity, throughout the path containing ball valve V1, until its free surface came above the ball valve V2. This latter valve was then closed, and the reminiscent red liquid above it completely removed. Then, the upper section of the column was filled, up to some level and also by gravity, with the colourless liquid stored at reservoir (6), through the path containing ball valve V3. The ball valve V2 was again fully opened, and a controlled volume of gas was injected through the nozzle below the downward-facing cup (4). Rotating gently the cup, the gas bubble was liberated, and rose through the coloured liquid into the colourless liquid. A series of photographs (5 shutting per second) were taken, as the bubble passed the section surrounded by an acrylic box, filled with water, to minimize distortion due to the curved wall of the column.

The photographs of the wake of the gas slugs were captured, in a fixed frame of reference, using a digital camera (Canon EOS300) equipped with a macro lens (Canon EF100 mm, f/2.8), that was placed against an illuminated white background. The exposure time was adjusted to 1/500 s. This gave red-and-white images of good contrast, putting in evidence a well-defined portion of liquid – the wake – attached to the bottom of the bubble, moving up at the rise bubble velocity.

A metric scale, fixed at the acrylic box front-face (2) made possible to scale down the images and determine the gas slug length and wake length.

There are two important aspects that had been considered, during the project of the experimental set-up, which must be emphasised. In one hand, the fact of the test fluids being fed to the column by gravity, without significant constrictions (such as valves, pumps, etc), that would eventually degrade the polymer molecules (for the case of the Boger fluid). On the other side, the fact of the test fluids being hygroscopic, obliged bottles 5 and 6 to be kept closed, minimizing the contact of fluids with fresh air.

In all tests the fluid temperature was measured, and the fluid properties were taken from the rheological characterization, shown in the next section.

3. FLUID COMPOSITION AND CHARACTERIZATION

A viscous Newtonian fluid (N91) or a viscoelastic Boger fluid (PAA300), both based on mixtures of glycerine and water were used in all the experiments. A summary of the composition of the fluids, inspired in the PhD Thesis of Alves (2004), is given in Table 1.

Table 1. Composition of fluids, in mass concentrations, and density.

Fluid	PAA [ppm]	Glycerine [%]	Water [%]	NaCl [%]	Kathon [ppm]	$\rho^{(1)}$ [kg/m^3]
Newtonian (N91)	-	90.99	7.51	1.50	25	1235
Boger (PAA300)	300	90.97	7.50	1.50	25	1248

$^{(1)}$: measured at 300 K.

The Boger fluid PAA300 was prepared by dissolving a small amount of polyacrylamide (PAA; Separan AP30 produced by SNF Floerger) in the Newtonian solvent N91. To minimize the intensity of shear thinning, a small amount of NaCl was added. To reduce bacteriological degradation of the solutions, biocide Kathon LXE, produced by Rohm and Haas, was also added.

The liquid density (ρ) was measured using a hydrometer (readability of 0.001 kg/m^3; range 1200–1300 kg/m^3).

For the N91 Newtonian fluid, the measured shear viscosity was 0.167 ± 0.05 Pa.s, at 27 °C, the same temperature at which the visualizations took place. It was used a falling ball viscometer from Gilmont Instruments (model GV-2200).

The viscoelastic Boger fluid PAA300 was characterized rheologically using a shear rheometer (Anton Paar, model Physica MCR301) with a cone-plate geometry (75 mm diameter and 1º angle). The shear viscosity (η) was measured at 27.0 ºC, and the results are shown in Figure 2.

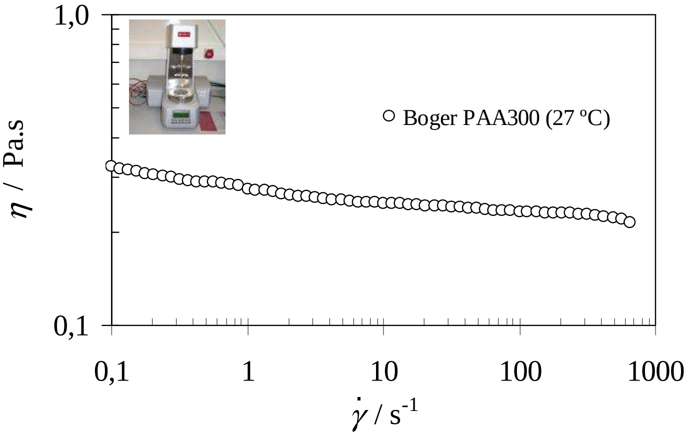


Figure 2. Steady shear data of the viscoelastic Boger PAA300 fluid. The rheological characterization was performed at 27.0 ºC.

An important aspect, during the experimental tests, is to guarantee that the visualizations are made in isothermal conditions. In the case of temperature variations, the steady shear tests should be carried out for the measured range of temperatures.

The data in Fig.2 clearly show the limiting performance of the measured property in steady shear flow. The reduced shear viscosity, for the Boger PAA300 fluid, decreases approximately 10 % per decade of reduced shear rate ($\dot{\gamma}$). This behaviour is frequently observed with a 'limiting' Boger fluid in cone-plate geometry (Alves, 2004). Hence, the reduced shear viscosity can be considered approximately constant, at reduced shear rates ($\dot{\gamma}$), confirming PAA300 as a Boger liquid.

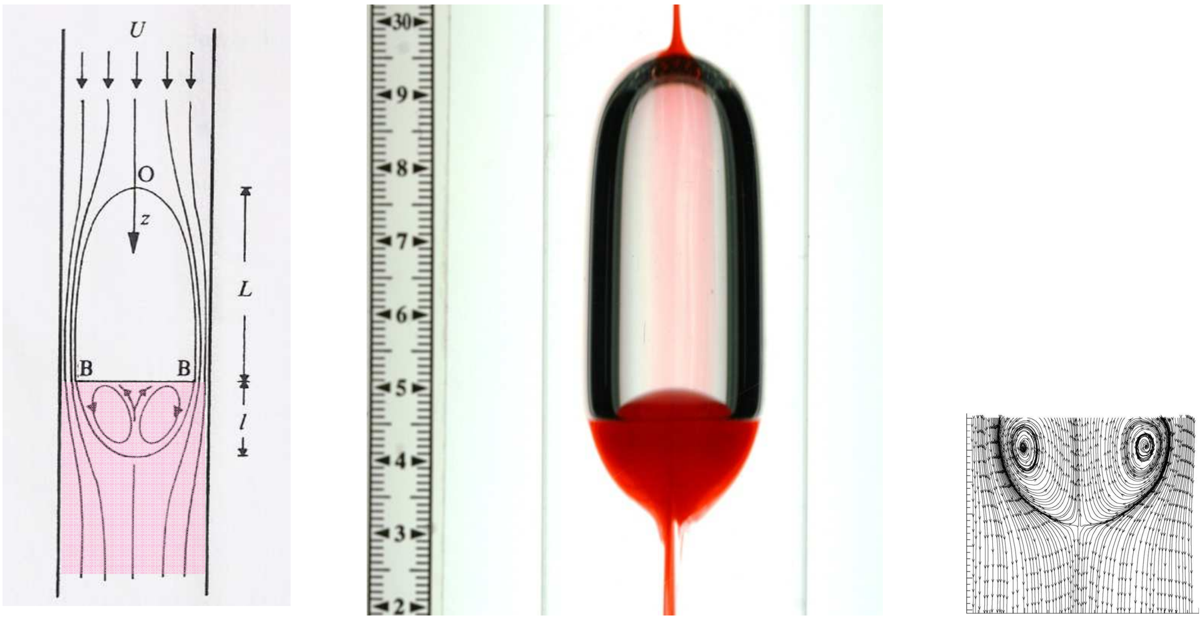
To complete the rheological characterization of the studied Boger fluid, the relaxation time (λ) of the viscoelastic solution was determined under extensional flow conditions, using a capillary-breakup extensional rheometer (Haake CaBER 1, Thermo Scientific). These measurements were performed using circular plates with a diameter D_p = 6 mm at 27.0 ºC. The average relaxation time for the viscoelastic PAA300 fluid was λ= 0.227 s.

4. FLOW VISUALIZATION RESULTS

Flow visualizations were carried out first for the Newtonian fluid N91, to assess the effect of inertia on the flow structure, and to serve as a reference for comparison against the results of the elastic Boger fluid PAA300. This comparison is summarized at the end of the section (Table 2), presenting also results obtained by Sousa *et al.* (2004, 2005 and 2006) in shear thinning liquids.

4.1. Newtonian fluid

The flow pattern around a Taylor bubble, rising at velocity U , in a vertical column of stagnant Newtonian liquid, is sketched in Figure 3, and diagrammatically represented in Fig. 3a. The photograph in Fig. 3b shows the shape of the slug body and wake, in the 32 mm i.d. column, for the Newtonian fluid N91.



(a) (b) (c)

Figure 3. Gas slugs rising in stagnant Newtonian fluid: (a) flow pattern around a slug using a frame of reference that moves with the bubble (courtesy from Campos and Guedes de Carvalho, 1988); (b) photograph of the slug wake in N91 fluid, performed in a 32 mm i.d. column, at 27 ºC, in a fixed frame of reference and (c) streamlines in the bubble wake, in a 32 mm i.d. column (N_f =505, courtesy from Nogueira *et al.*, 2006).

As can be seen in Fig.3b, there is a presence of a well-defined wake, attached to the bottom of the bubble, rising up at the same velocity of the bubble.

For the Taylor bubble illustrated in Fig.3b, the average values of *L*=5.5 cm and *l*=1.1 cm, for the slug length and wake length were respectively found.

Campos and Guedes de Carvalho (1988) studied the flow pattern in the wake of individual long bubbles rising through stagnant Newtonian liquids. These authors identified three different flow patterns in the wake (laminar, transitional and turbulent), and concluded that the flow pattern depends on the dimensionless parameter N_f, given by:

$$N_f = \sqrt{gD^3} / \nu \, , \tag{1}$$

where g is the acceleration due to gravity (m^2/s), D the internal column diameter (m) and ν the liquid kinematic viscosity (m^2/s). For $N_f < 500$, the pattern in the wake is laminar, with a closed and axisymmetric wake, and with internal recirculation flow (Fig. 3c).

For the specific case of the experiment reported in Fig. 3b, $N_f = 133$ and the Reynolds number is $Re = 41$. The Reynolds number is defined by:

$$\mathrm{Re} = \rho U D / \eta_f \, , \tag{2}$$

where U is the Taylor bubble velocity (m/s) and η_f is the liquid absolute viscosity (Pa.s). Note that the latter will be the shear viscosity (η), for a certain shear rate ($\dot{\gamma}$), in the case of the Boger PAA300 fluid.

It can be concluded that the flow pattern, in the wake of an individual Taylor bubble, rising through stagnant N91 fluid, is laminar and axisymmetric, with an enclosed vortex ring of coloured liquid (Fig. 3b).

4.2. Boger fluids

Figure 4 shows a sequence of five photographs, from (a) to (e), for one single Taylor bubble rising through stagnant Boger fluid PAA300, in the 32 mm i.d. column (at 27 ºC), and using a fixed frame of reference.

(a) (b) (c) (d) (e)

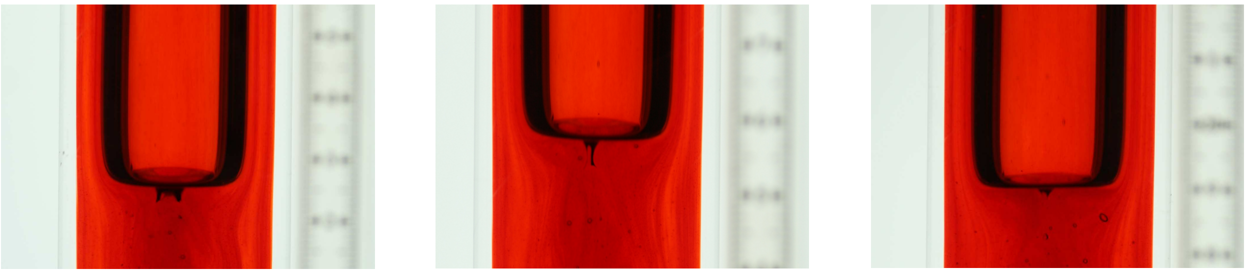
Figure 4. Gas slug rising in stagnant Boger fluid PAA300, in a 32 mm i.d. column, at 27 ºC using a fixed frame of reference.

As can be observed, the shape of the trailing wake of the Taylor bubble changed drastically: there is no defined wake and no upward coloured liquid transport. Instead, in the bubble tail, was visualized a cusp of small dimensions (see Fig. 4e).

The cusp is seen in different orientations during the bubble rise, indicating a fast rotational movement. Therefore, it can be concluded that the flow pattern in the wake of an individual Taylor bubble, rising through stagnant Boger fluid, is complex and asymmetrical. In Figure 5 below, a sequence of three photographs (see from a→c) of a long individual gas slug is shown, rising through Boger PAA300 fluid, with an enlarged view of the cusp.

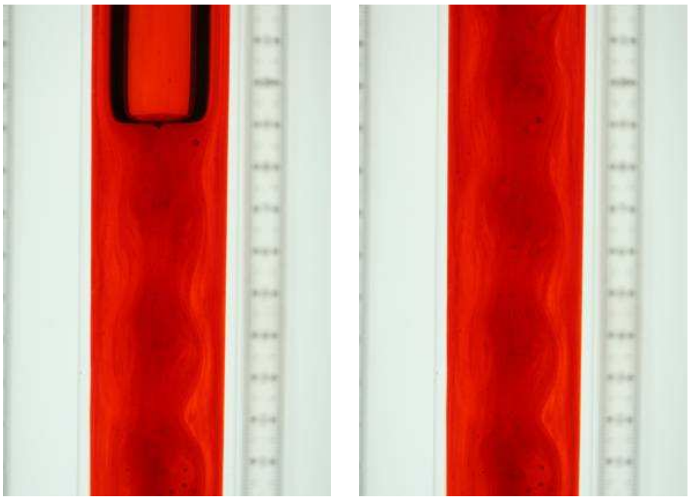
The images in Fig.5 were taken for a 39th single bubble, of a sequential series of runs, using the same Boger PAA300, and Fig.4 matches to the 8th single bubble. That is the reason why the Boger PAA300 liquid in Fig.5 is almost completely red.

The asymmetrical shape of the trailing cusp, patent in the images of Fig. 5, may be responsible for small asymmetries in the flow in the wake region, leading to a three-dimensional flow. In addition, the asymmetrical shape associated with the rotational movement, could be responsible for an observed unsteady flow of small amplitude: an axial oscillation of the trailing edge was seen, with successive periodic expansion and contraction, and with capacity of gas disrupting (Fig.5 a→b). In fact, this oscillatory movement is responsible for an unsteady flow of small amplitude in the wake region – see Figure 6.



(a) (b) (c)

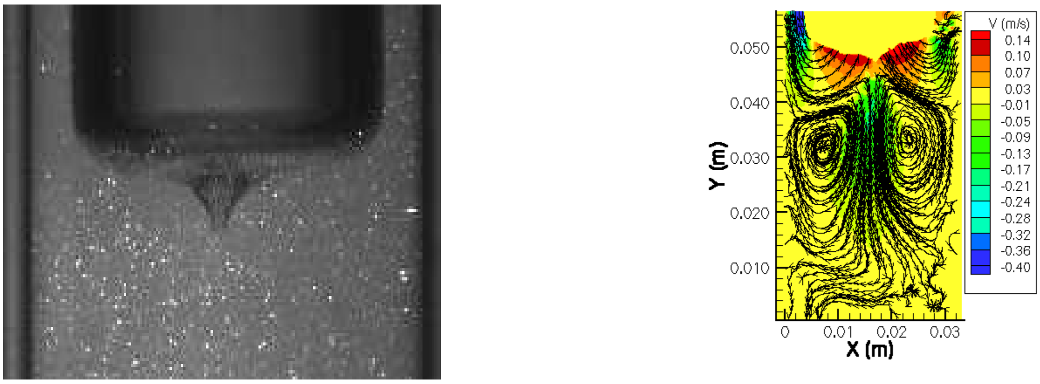
Figure 5. Enlarged view of the wake of the 39th gas single bubble, rising through stagnant Boger fluid PAA300, in a 32 mm i.d. column, at 27 ºC, in a fixed frame of reference.



(c) (d)

Figure 6. Wake of the 39th gas bubble, rising through stagnant Boger fluid PAA300, in a 32 mm i.d. column, at 27ºC (continuing from Fig.5): *magnificence* of the trailing edge, with oscillatory movement in the wake region.

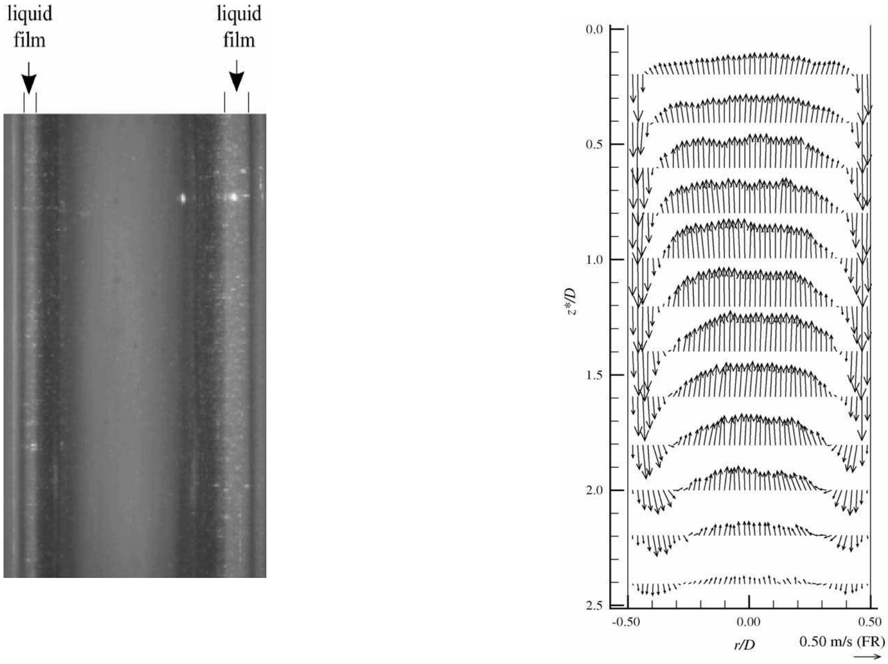
Sousa *et al.* (2004 and 2005a) reported a similar behaviour in the wake of a single Taylor bubble, rising in viscoelastic carboxymethyl cellulose (CMC) solutions. In Figure 7, beneath, the results found by these authors for an aqueous solution of 0.8 wt% CMC are depicted.



(a) (b)

Figure 7. Wake of a single air bubble, rising through stagnant viscoelastic 0.8 wt% CMC aqueous solution, in a 32 mm i.d. column: (a) cusp photograph and (b) streamlines in a frame of reference moving with the bubble (courtesy from Sousa *et al.*, 2005b).

With the help of PIV and shadowgraphy measurements, Sousa *et al.* (2004, 2005a and 2006) mentioned the existence of a *negative wake* downstream the gas slugs: below the bubble trailing edge, along the axis region, the fluid flows in the opposite direction to the bubble - *negative wake* - originating rotational liquid movements in adjacent regions. Figure 8 shows the results found by Sousa *et al.* (2006), for an elastic aqueous solution of 0.01 wt% PAA, in a 32 mm i.d. vertical column.



(a)

(b)

Figure 8. Wake of a single Taylor bubble, rising through stagnant 0.01 wt% PAA aqueous solution, in a 32 mm i.d. column: (a) asymmetric flow and (b) average velocity field in a fixed frame of reference (courtesy from Sousa *et al.*, 2006).

To quantify the strength of elastic effects with Boger fluids, it is convenient to use a single relaxation time in the definition of the Deborah number, *De*. In the present work, the Deborah number is based on flow conditions, and on the average relaxation time obtained by shear rheology, as quantified above:

$$De = \lambda \dot{\gamma}_f , \tag{3}$$

where $\dot{\gamma}_f$ is a deformation rate characteristic of the flow, given by:

$$\dot{\gamma}_f = U / D , \tag{4}$$

express in units of s^{-1}.

In Table 2, the main operating conditions and the dimensionless numbers, *Re* and *De*, for the test fluids mentioned on the present work are presented, as well as for those referred by Sousa *et al.* (2004, 2005a and 2006) for comparison analysis.

In the case of viscoelastic fluids, the corresponding elasticity number (*El*), which is independent of flow rate, is defined as

$$El = De / \mathrm{Re} , \tag{5}$$

assuming a constant value for each fluid/column combination.

By analyzing the values presented in Table 2, it appears that, despite the similar occurrence in the form of a small cusp at the base of the slug, the values of parameters λ and *De* for the fluids PAA300 (Boger fluid) and 0.8 wt% CMC (shear thinning fluid), show a difference of one order of magnitude. Indeed, the original form of the small cusp, whose formation occurs at the base of the Taylor bubble, on the rise in Boger fluid PAA300 and on the 0.8 wt% CMC aqueous solution, can be caused by an elastic effect. In the solution of 0.8 wt% CMC, it was reported the occurrence of a *negative wake* (fluid flow in the opposite direction of the rising bubble). In fact, the visualization technique used in the present study - contrast colour on a background of white light (with constant intensity), and photography in a fixed frame of reference - did not allow us to conclude about the incidence of a *negative wake*. The calculation of elasticity number *El*, given by *De/Re*, shows that, in the two fluids mentioned above, the predominance of elastic effects compared to viscous effects is similar (0.04 and 0.03, respectively, for Boger PAA300 and 0.8 wt% CMC fluids).

Table 2. Main operating conditions, dimensionless numbers *Re* and *De* and the corresponding elasticity number *El*, for the flow of Taylor bubbles, rising through stagnant N91 and Boger PAA300 fluids, in a vertical 32 mm i.d column. Comparison with the results published by Sousa *et al.* (2004, 2005a and 2006).

Fluid	Glycerine [%]	PAA [%]	CMC [%]	T [K]	$\dot{\gamma}$ [s^{-1}]	λ [s]	U [m/s]	*Re*	*De*	*El*
Newtonian N91	90.99	-	-	300.15	-	-	0.174	41	-	-
Boger PAA300	90.97	0.03	-	300.15	0.1 - 650	0.227	0.160	26	1.1	0.04
Shear thinning 0.80 wt% CMC (1)	-	-	0.80	295.5	0.04 - 4000	0.029	0.182	8	0.2	0.03
Shear thinning 0.01 wt% PAA (2)	-	0.01	-	294.05	30 - 400	2.3	0.196	41	14	0.34

(1) : Sousa *et al.* (2004 and 2005a).
(2) : Sousa *et al.* (2006).

For the shear thinning fluid 0.01 wt% PAA, a high value of Deborah was found (*De*=14), indicative of a very elastic solution (*De/Re*=0.34). Sousa *et al.* (2006) reported the presence of very long wakes, with liquid rising along the column, as if it was 'pulled' by the bubble (see Fig.8).

Summarizing, the fluid elasticity definitely enhances the formation of complex structures - three dimensional flows - in the wake region of a single Taylor bubble, rising through stagnant viscoelastic fluids, which includes Boger PAA300 (see Fig. 5-6).

5. CONCLUSIONS AND OUTLOOK

In this study, the structure and stability of the wake of single Taylor bubbles, rising through a stagnant Boger fluid, was investigated for the first time, using a simple photographic technique (contrast colour on a background of white light), in a fixed frame of reference. The flow patterns of the wakes of single gas slugs, rising through a vertical column of 32 mm i.d., and obtained under the operating conditions of the present work for Newtonian fluid N91 and Boger fluid PAA300, proved to be very different, as it was expected. In the case of fluid N91, where the elastic component does not exist, the shear viscous effects prevailed on the wake flow patterns. Contrarily to that observed with Newtonian liquids, where the decrease of the shear viscosity leads to a progressive growth of the wake recirculation length (with the possibility of oscillation from a certain critical value of Re; Campos and Guedes de Carvalho, 1988), in the Boger fluid PAA300, the pattern of the wake flow was more complex: the occurrence of a small cusp at the rear of the rising bubble was observed, not stationary and with small areas of open recirculation upstream.

In fact, working with the Boger PAA300 fluid, which has a negligible shear viscosity variation, but with significant elastic component, allows us to isolate the effect of the elastic properties on the flow pattern around the Taylor bubbles, and put in evidence the physical phenomena that induce differences in the wake flow patterns relatively to Newtonian fluids.

Future work will involve experiments in vertical columns with different internal diameters (19 and 52 mm), both in fixed and moving frames of reference, joining expertise of PIV and streak-line photography, to further document the flow pattern in the wake of individual Taylor bubbles, rising through stagnant Boger fluids. We also hope to make use of other viscoelastic fluids (such as Boger fluids with different polymers and different concentrations), to investigate the flow patterns near the bubble rear and the corresponding flow stability.

6. ACKNOWLEDGEMENTS

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