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EXPERIMENTAL INVESTIGATIONS OF A LIQUID MENISCUS FORMED BY CLOSE COLLIDING VISCOUS AND VISCOELASTIC JETS

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Abstract: When two horizontally-aligned liquid jets are brought into close contact, the outcome is a coalescent state that is maintained as long as the distance between the nozzles does not change. Increasing this distance causes the upper meniscus to break once a critical value is reached. The present paper investigates the dependence of this critical distance with flow rate and material properties (e.g. density, viscosity, elasticity). Close to break-up, the maximum vertical displacement of the upper meniscus that connects the nozzles is found to be smaller than the break-up distance, in the case of Newtonian ligaments. When elasticity is present, the vertical displacement increases, exceeding at break-up the critical distance.

Key words: liquid meniscus, colliding jets, break-up, elasticity.

1. INTRODUCTION

Ligament stretching can be encountered both in natural flows, for example elongated ligaments in the vicinity of volcanoes [1], and in manufacturing processes such as optical fire production. The subject has received both experimental and theoretical attention, focusing on: the evolution of viscous threads hanging between two walls [2], asymptotic techniques in determining the shape of suspended liquid bridges [3], forced and free oscillations of a cylindrical liquid bridge [4], maximum trapping capacity of horizontal cylinders [5], dynamics of a stretched liquid filament [6], deformation and break-up [7, 8]. Also, liquid bridges are an essential part of microgravity technology and lung mechanics1. The present paper is focused on the study of the coalescence of two horizontally aligned fluid jets immersed in a Newtonian fluid. The influence on the upper meniscus of different control parameters (*e.g.* flow rate, material properties, distance between nozzles) is also investigated.

In the case of close coalescent fluid jets the following non-dimensional groups are used to describe the phenomenon:

$$\mathrm{Re} = \frac{\rho V D}{\eta},\ \mathrm{Bo} = \frac{\Delta\rho g \delta^2}{\sigma},\ \mathrm{Ca} = \frac{\eta V}{\sigma}, \tag{1}$$

where Re is the Reynolds number, the ratio between inertial effects and viscous stresses, Bo is the Bond number, inertial and buoyant effects relative to capillary effects and *Ca* is the capillary number and combines capillary and viscous effects. In (1) ρ is the density of the injected fluid, η is the viscosity of the injected fluid, V is the average velocity within the needle, l the length of the upper meniscus, σ the interfacial tension coefficient, D the inner diameter of the nozzle and δ the distance between the nozzles.

We considered two horizontally aligned nozzles, through which a Newtonian or a viscoelastic fluid was injected, in a viscous outer fluid. By adjusting the flow rate and the distance between the nozzles a fluid coalescent mass forms, undergoing either dripping or jetting depending on the momentum and the material properties that characterize the fluid (Fig. 1a). The curvature of the interface that appears at the upper edge

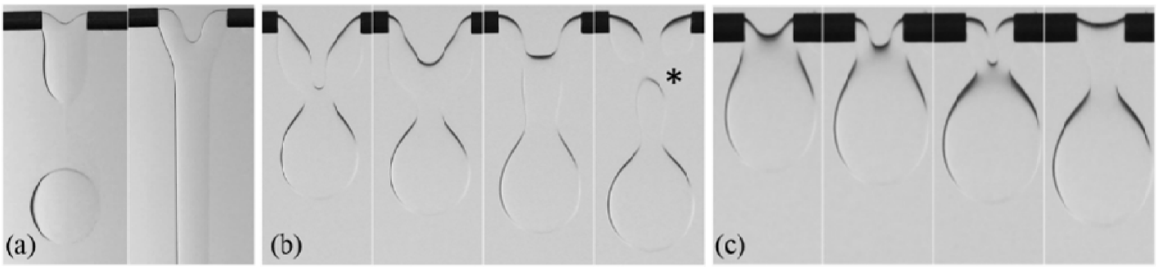

Fig. 1 – a) Dripping coalescent mass of a water-glycerin mixture at 5 ml/min (left) and a jetting coalescent mass at 10 ml/min (right); irreversible break-up (b) – marked with * – in the case of a water-glycerin solution at a flow rate of 5 ml/min and reversible break-up (c) of the upper meniscus (50% concentration of glycerin by volume; frames separated by 33 ms).

varies in time as the bulk accumulates mass. By modifying the distance that separates the nozzles the meniscus undergoes instability and break-up, which leaves the jets in an irreversible non-coalescent state, (Fig. 1b). There is also an intermediate phase in which although break-up occurs, the interface bounces back into a coalescent state due to inertial and capillary effects as presented in Fig. 1c.

2. EXPERIMENTAL SET-UP AND FLUID PROPERTIES

The experimental setup involves two horizontally aligned nozzles with an inner diameter D = 0.838 mm, submerged in mineral oil. The fluid was injected at the same flow rate and at the same time through both nozzles by a Harvard Apparatus 33 double syringe pump. Images were taken with a Nikon 1 J5 camera recording at 400 fps. The samples are mixtures of water and glycerin, Newtonian in nature, and viscoelastic polyacrylamide solutions with two different molecular weights of 0.27×10^6 and 18×10^6 g/mol (denoted P1 and P2 therein, in concentrations of 0.03, 0.25, 0.5 wt. % and 0.01, 0.03, 0.06 wt. % respectively).

By increasing the concentration of glycerin in water, viscosity and density were increased. Viscosity was measured with a rotational Anton Paar Physica MCR301 rheometer using a cone plate geometry. As expected, viscoelastic samples in rotational tests display a shear thinning behavior, as shown in Fig. 2a. With a "mass per volume" method, density was determined by measuring the weight of a fixed volume of fluid with a Radwag scale. The input value of volume was injected with a Hamilton microsyringe Gastight #1725 of 0.25 ml.

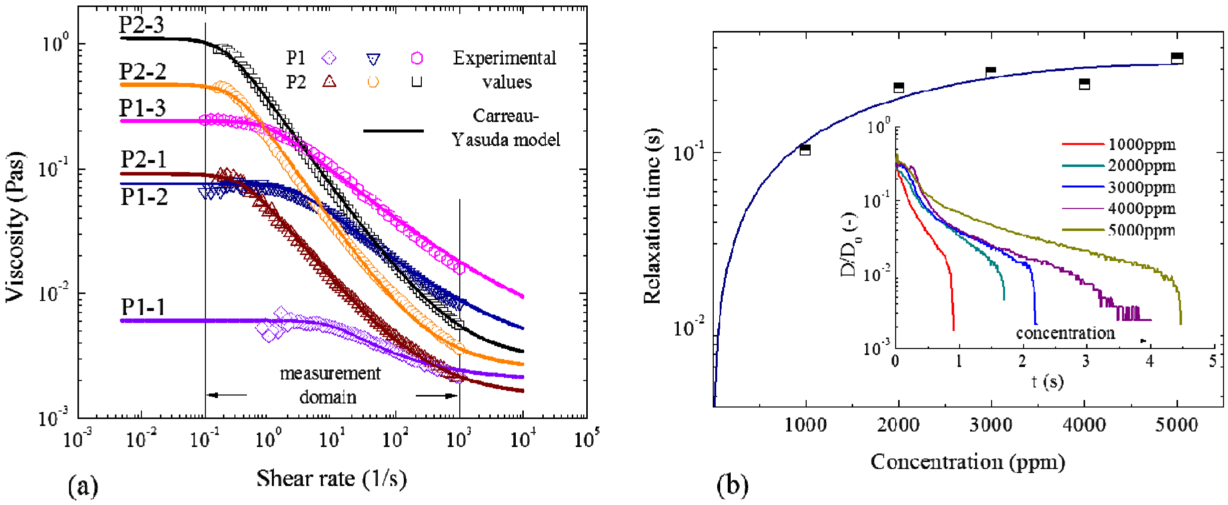

Fig. 2 – a) Shear thinning behavior of polyacrylamide solutions (fitted experimental values with Carreau-Yasuda model); b) CaBER measurements of filament thinning and relaxation time variation with concentration (inset graph) for polyacrylamide solutions (all measurements and experiments were performed at a temperature of 25° C).

Interfacial tension coefficients were determined using a pendant drop method [9]. Measurements of interfacial tension coefficients reveal a linear decrease with concentration for both water-glycerin mixtures and viscoelastic fluids, ranging from 0.026 to 0.02 N/m. The relaxation time of polymer solutions, λ, shown in Fig. 2b, was approximated by extrapolating the results obtained from CaBER measurements of filament thinning [10]. The external medium is represented by a mineral oil with a density of 920 kg/m^3 and a viscosity of 55 mPas.

3. ELASTICITY INFLUENCE ON THE UPPER MENISCUS

The instability and break-up is seen at a critical distance δ and is investigated in relation with the maximum vertical displacement z_M and the length of the upper meniscus l. Fig. 3a shows the dependence of z_M on δ for a Newtonian fluid (water-glycerin mixture) in comparison with a viscoelastic polyacrylamide solution. As the distance is increased the maximum vertical displacement also increases until the critical distance is reached and the liquid bridge experiences break-up.

When comparing Newtonian and viscoelastic fluids, a more evident difference in the behavior of the upper ligament is seen in the vicinity of drop detachment. Immediately after break-up the meniscus is undergoing a sudden recoil from its maximum until it reaches the lowest possible value, a volume of fluid remaining attached to the nozzles, if the upper meniscus does not break. After recoil, the curvature may or may not remain negative, depending on the mass of the liquid bridge that remains attached. If one measures the period of oscillation T of the upper ligament and the diameter of the drop D_d, that is being created within that period, for a certain flow rate Q_0, one can calculate the volume of the bridge that remains attached by subtracting the volume of the drop from the total volume injected within one period:

$$\Delta V = 2Q_0 T - \frac{\pi D_d^{\,3}}{6}. \qquad (2)$$

As it can be seen in Fig. 3b, the volume of the bridge, relative to total injected volume, decreases as Reynolds number increases. When increasing the distance between the nozzles, the period of oscillation does not display significant change, opposed to the situation in which the flow rate is increased, the effect of the latter being a decrease in period, as shown in the inset graph of Fig. 3b. It is worth mentioning that increasing elasticity causes the drop diameter to slightly increase.

Current investigations regarding coalescent liquid masses [11] follow previous observations

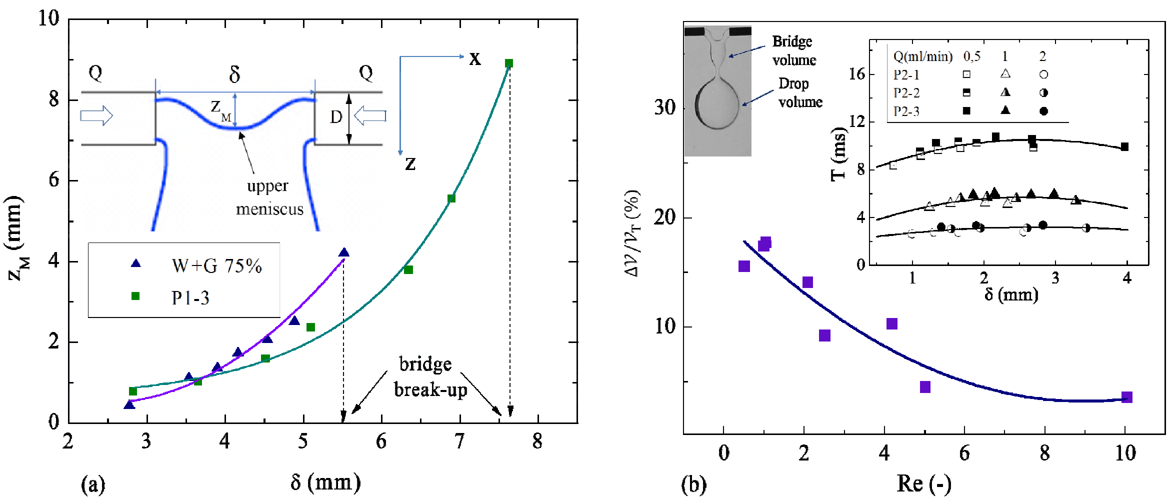

Fig. 3 – a) Maximum observed values for the vertical displacement z_M of the upper meniscus as function of the distance between the nozzles δ (comparison between a Newtonian and a viscoelastic fluid); b) volume of the bridge in the vicinity of break-up when increasing Reynolds number, in the case of viscoelastic fluids, measured period of oscillation when increasing the flow rate and distance between the nozzles, for three viscoelastic samples (inset graph).

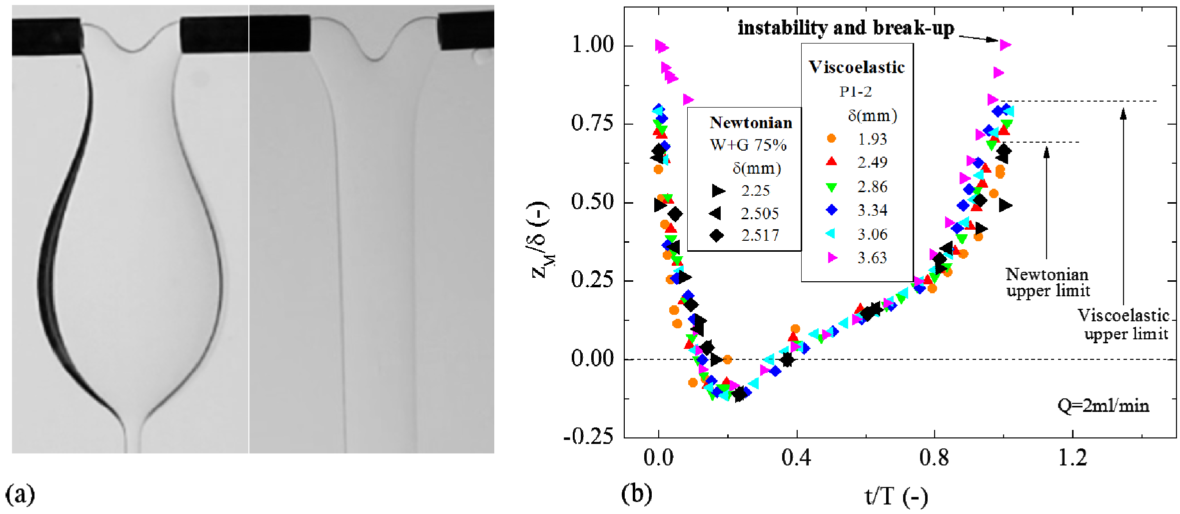

Fig. 4 – a) Comparison between a viscoelastic solution (P1-2, left) and a Newtonian water-glycerin mixture (75%, right) at a flow rate of 10 ml/min. (both samples present the same zero shear viscosity of 80 mPas); b) time evolution of z_M within one period of oscillation (viscoelastic and Newtonian behavior being presented).

involving the time evolution of liquid bridges when elasticity and viscosity are increased. Increasing the concentration of polyacrylamide has an increasing effect on viscosity, which ultimately influences the time evolution of the upper meniscus. The interface becomes more stable and the maximum radius of curvature decreases. By preparing a Newtonian water-glycerin sample in such a way that its viscosity equals that of a certain viscoelastic mixture (*e.g.* P1-2 with W-G 75%), one can get an estimate of the influence of elasticity only.

Figure 4a presents such a comparison and it reveals that the coalescent mass of fluid is in a state of prolongated dripping regime in the case of the viscoelastic mixture, large drops detaching from the bulk, whereas its pair Newtonian sample is in a jetting state, drops detaching from the liquid jet far downstream due to Rayleigh instability.

When analyzing the transient behavior of viscoelastic and purely viscous liquid bridges, differences are observed in the maximum radius of curvature that the bridge can exhibit, as it results from Fig. 4b. The time evolution of the interface is similar for both fluids, slightly bigger values in z_M are recorded for viscoelastic fluids. The only behavior that separates from the general time evolution is that of the instability near breakup.

In conclusion, the main observable effects of the presence of elasticity in low concentrations are (i) an increase of the maximum vertical displacement and (ii) a modification of the subsequent dynamics that follows after coalescence, in terms of the dripping and jetting states.

4. BREAK-UP REGIME: TRANSITION FROM COALESCENCE TO NON-COALESCENCE

The coalescent state of the bulk, sustained by the injection of fluid, is maintained as long as the distance between the nozzles is kept below a critical value. The value of the vertical displacement and the length of the interface at their maximum (*i.e.* near drop detachment), were measured at different distances between the nozzles until break-up, for both Newtonian and viscoelastic samples. In Fig. 5a we present their ratio as a function of Bond number, break-up of both Newtonian and viscoelastic ligaments occurring near the same upper limit of 0.5. This is merely a geometrical constraint because the maximum radius of curvature cannot physically exceed half the length of the interface.

An interesting fact arises when one investigates the relation between the ratio z_M/δ at break-up, and Reynolds number (Fig. 5b). It suggests that the critical ratio does not depend on the Reynolds number. It is also remarkable that the values for the Newtonian ligaments are lower than those of viscoelastic fluids. For Newtonian coalescent masses, at break-up, the maximum vertical displacement does not exceed the value of

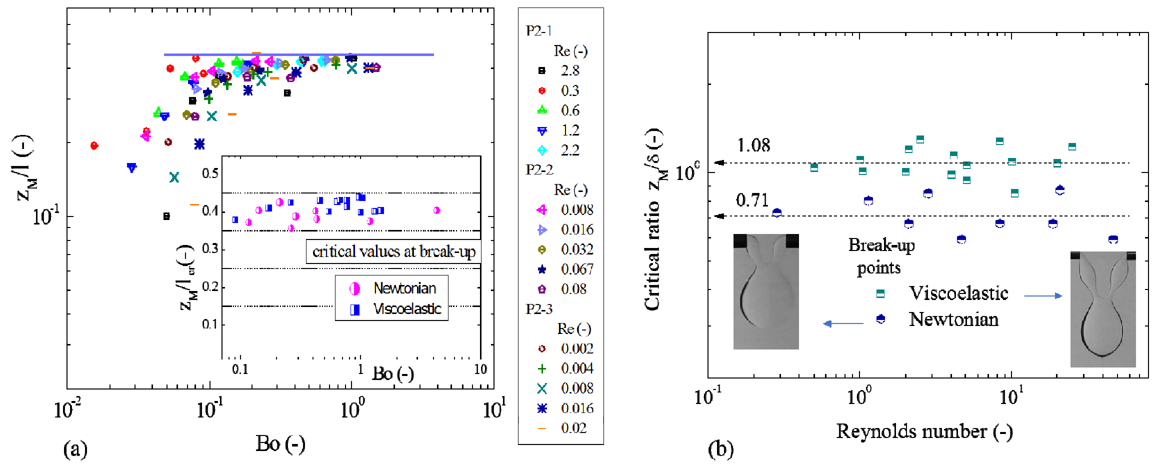

Fig. 5 – a) Maximum vertical displacement relative to interface length when increasing Bond number, at different Reynolds numbers. Critical values at break-up for viscoelastic and Newtonian samples (inset graph); b) average values of the critical ratio z_M/δ in the vicinity of break-up, viscoelastic and Newtonian upper limits being presented.

the distance between the nozzles. This is not the case when considering viscoelastic fluids, because the maximum vertical displacement can exceed δ for these ligaments.

The critical distance at which break-up occurs is increasing with both flow rate and fluid elasticity, higher flow rates being required for Newtonian ligaments to reach the same critical distance as viscoelastic ones. This can be attributed to the extra stresses that are present when elasticity is present. Since elasticity is a measure of storage of energy, the upper meniscus can withstand higher deformations, therefore a higher radius of curvature.

The boundary between a coalescent and a non-coalescent state is revealed by non-dimensional representations, such as Ca *vs.* Bo number for Newtonian fluids and δ/l_{EC} *vs.* Ca number for viscoelastic fluids, where $l_{EC} = \lambda\sigma/\eta$ defines the intrinsic visco-elasto-capillary length. Investigations of the length of the ligament, at its maximum values, were made by modifying the distance that separates the nozzles at 5 different flow rates for three different viscoelastic fluids. In order to preserve the dependence between δ and l shown by experimental data, when considering fluid properties, the values for the viscosity of the viscoelastic solutions were taken at a shear rate of 50 1/s. Figure 6a shows the boundary separating the coalescent state from that of non-coalescence in the case of Newtonian water and glycerol fluids, and Fig. 6b this boundary for viscoelastic polyacrylamide solution.

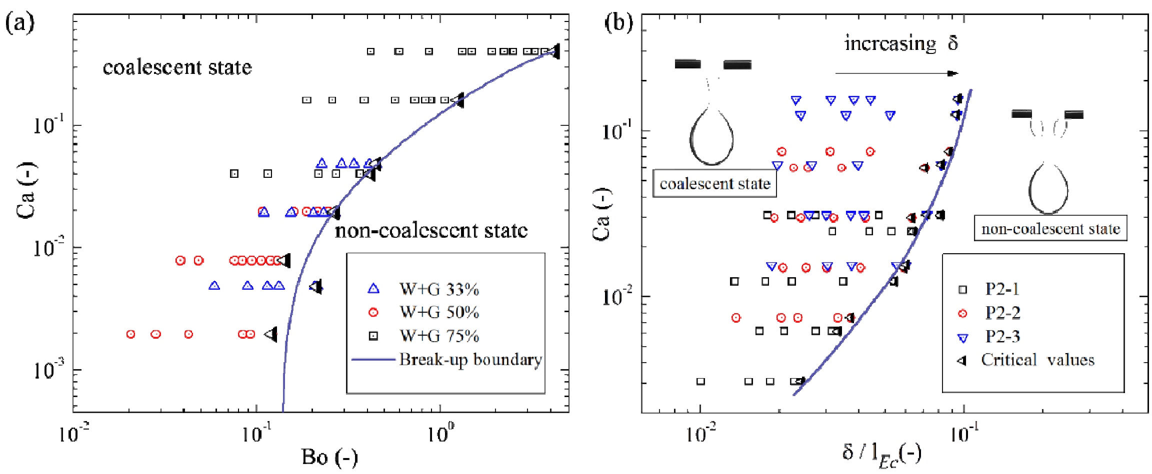

Fig. 6 – The boundary separating coalescent and non-coalescent states in terms of non-dimensional parameters in the case of Newtonian (a) and viscoelastic P2 samples (b).

5. CONCLUSIONS

The transition from a coalescent to a non-coalescent state, in the case of immersed fluid jets, is characterized by the irreversible rupture of the upper ligament that connects the nozzles. For Newtonian ligaments, the maximum vertical displacement cannot exceed the value of the distance that separates the nozzles. This is not the case when speaking of viscoelastic ligaments near break-up, the value of the vertical displacement exceeding that of the critical distance. Also, this critical distance at which break-up occurs increases with fluid elasticity. Near break-up, the ratio between the maximum radius of curvature the length of the meniscus tends to 0.5, regardless of the presence of elasticity.

The liquid mass that remains attached to the nozzles immediately after drop detachment is decreasing in value as Reynolds number increases. Increasing the distance that separates the nozzles does not affect the period of oscillation of the upper meniscus. Also, an increase in elasticity results in a slight increase in drop diameter. The influence of elasticity is observed in correlation with the behavior of both the coalescent bulk and the upper meniscus. The shear thinning effect of viscoelastic fluids can alter the state of the coalescent mass, when comparing a viscoelastic with a Newtonian fluid, both having the same zero-shear viscosity. Elasticity changes the jetting regime induced by the damping effect of viscosity into a prolongated dripping regime.The present study has implications both in understanding the fundamentals of fluid mechanics and in providing solutions for technical and commercial problems in engineering, for example: oil-water separation, mixing processes, drop-on-demand techniques. New methods of measuring material properties, such as opposed-jet rheometry, arise once the dynamics of the phenomenon is understood.

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