Dynamics of Immersed Coalescent Jets Under Viscoelastic Effects

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ABSTRACT

The paper investigates the elasticity influence on coalescent jets immersed in a pure viscous fluid and the time evolution of the meniscus which remains attached to the nozzles. Below a certain Reynolds number, at a fixed distance between the horizontal nozzles, the meniscus exhibits periodic oscillations due to downstream drop detachment. Increasing the elasticity of the injected fluid has a stabilizing effect on the meniscus, the flow dynamics between the nozzles subsequently reaching a quasi-steady state.

INTRODUCTION

Free surface flows always involve the existence of an interface that separates the bulk from the gaseous external medium. When the external medium is a viscous fluid, the interface that emerges has a different susceptibility to external perturbations due to interfacial stresses[1]. In return, if the fluids placed in contact are miscible then a coalescence phenomenon can occur at the interface-type boundaries that separates them[2]. Coalescence of immersed jets in a viscous surrounding medium received little attention and is still a fertile area of investigation. Understanding and modelling this phenomenon can lead to applications in the area of extensional and interfacial rheometry[3], particular mixing and transfer processes[4], and in understanding the fundamental aspects behind fluid-fluid interaction. The study presents the influence that elasticity has on the evolution of a coalescent mass of fluid, which connects two horizontally aligned nozzles immersed in a Newtonian mineral oil. Viscoelastic polymer solutions and water-glycerine mixtures were used in order to separate the elastic effects from those of viscosity. The curvature of the upper meniscus that is seen connecting the nozzles was also investigated. By varying the flow rate and keeping the distance between the nozzles fixed, one can change the behaviour of the coalescent mass. The latter can undergo dripping or jetting, depending upon the Reynolds and the Weissenberg number. The coalescent state of two horizontally aligned nozzles is presented in Fig. 1.

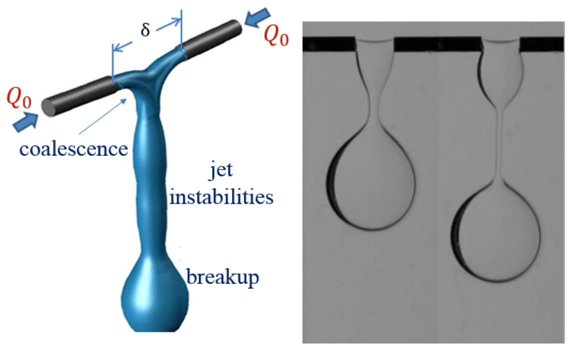

Figure 1. Schematic representation of the coalescent state in the case of a constant flow rate and a fixed distance between the nozzles (left). Dripping coalescent mass of a polyacrylamide solution at 5 ml/min (right); frames separated by 400 ms.

Drop formation causes the upper meniscus that connects the nozzles to curve and oscillate. The behaviour is periodic, the period being determined by the time it takes for a drop to detach from the liquid coalescent mass. At low flow rates the fluid's inertia is not sufficient to cause coalescence, in which case the latter needs to be achieved by an external factor, such as a short impulse or by considering initially a close to zero distance between the nozzles. After merging, the distance can be slowly increased up until the bridge experiences breakup due to downstream drop formation.

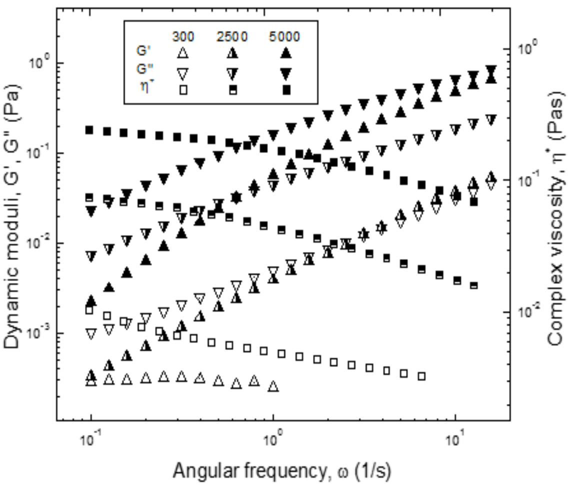

Figure 2. Dynamic moduli and complex viscosity curves for three PAM solutions.

EXPERIMENTAL DETAILS

The non-dimensional parameters used to describe the phenomenon are Reynolds, Weissenberg and Capillary numbers[5], as defined in Eq. 1.

$$Re = \rho V d/\eta,\ Wi = \lambda V/d,\ Ca = \eta V/\sigma \qquad (1)$$

where: V is the average velocity and ρ, η, σ, λ are density, viscosity, interfacial tension and relaxation time, respectively. The viscosity and the density ratios: η/η_{oil}, ρ/ρ_{oil} also need to be taken into consideration when the outer medium is represented by a viscous Newtonian fluid.

The experimental setup is composed of a glass tank filled with mineral oil and two horizontally aligned nozzles fixed at 4 mm apart. The fluid is being injected by two cylindrical nozzles with an inner diameter d=0.84 mm. A double syringe pump was used for the injection, identical flow rates Q_0 being discharged through both nozzles. A Nikon J5 camera recording at 400 frames/s was used to capture the phenomenon. The influence of elasticity on the coalescent mass is investigated by comparing viscoelastic fluids with purely viscous ones. The investigated samples are polyacrylamide solutions, in three different concentrations (0.03, 0.25, 0.5 wt.%, denoted therein PAM 300, 2500, 5000 ppm), and solutions of glycerol in water. Each water-glycerol solution was prepared such that its viscosity presented close value to the zero-shear viscosity of a viscoelastic sample. The viscosity curves and the dynamic moduli of the viscoelastic fluids in question (Fig. 2) were determined in oscillatory tests, using an Anton Paar rheometer, with a cone-plate geometry. The relaxation time was determined using data obtained in CaBER measurements of filament thinning[5]. The values of material properties are presented in Table 1.

Table 1. Material and interfacial properties for each sample at 25^0 C.

Sample	ρ [kg/m^3]	η [mPas]	σ [mN/m]
water	995	1	26.8
PAM 300 ppm, λ = 40 ms	999	6	26.5
Water-glycerol 47%	1150	≈6	25.2
PAM 2500 ppm, λ = 239 ms	1004	81	25.6
Water-glycerol 78%	1190	≈81	24.8
PAM 5000 ppm, λ = 316 ms	1035	250	24
Mineral oil	920	55	-

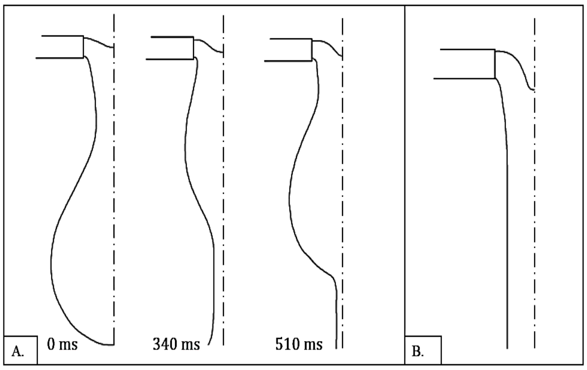

Figure 3. Coalescent fluid mass: comparison between PAM 2500 ppm (A) and a purely Newtonian water-78% glycerol solution (B) at 10 ml/min, both substances having the same zero-shear viscosity. The distance between the nozzles is δ = 4 mm in both cases.

RESULTS AND DISCUSSION

Experimental investigations show a completely different time evolution for the upper meniscus when comparison is made between a Newtonian coalescent mass and a viscoelastic one. Fig. 3 shows that, when elasticity is present, the bridge is able to deform and evolve in time as the fluid is being injected. The phenomenon is periodic, drops are seen detaching from the bridge and leaving behind viscoelastic threads. At the same distance between the nozzles and at the same flow rate, the water-glycerol solution with the same viscosity as PAM 2500 ppm does not experience oscillations at the interface between it and the surrounding viscous medium. It settles rapidly in a steady state characterised by a quasi-unperturbed fluid column from which drops are created further downstream due to Rayleigh instability.

Table 2. Drop volume and bridge volume for PAM solutions at a flow rate of 5 ml/min

Sample [ppm]	Period [s]	Drop volume [μl]	Bridge volume [μl]
PAM 300	1.26	160	30
PAM 2500	1.8	280	40
PAM 5000	1.5	250	75

As the fluid is being injected the liquid coalescent mass grows in volume and when gravitational forces overcome interfacial tension and buoyant forces, a drop detaches from the bulk. After detachment, a liquid bridge remains connecting the nozzles, Fig. 4A, the volume of which can be determined with Eq. 2, if one measures the period of the dripping process and the diameter of the drop D.

$$V_b = 2Q_0T - V_d, \quad (2)$$

where: $T$is the period of drop formation,V_b is the volume of the bridge and $V_d = \pi D^3/6$ the volume of the drop. Table 2 shows that increasing elasticity causes the volume of the bridge to grow. The upper interface of

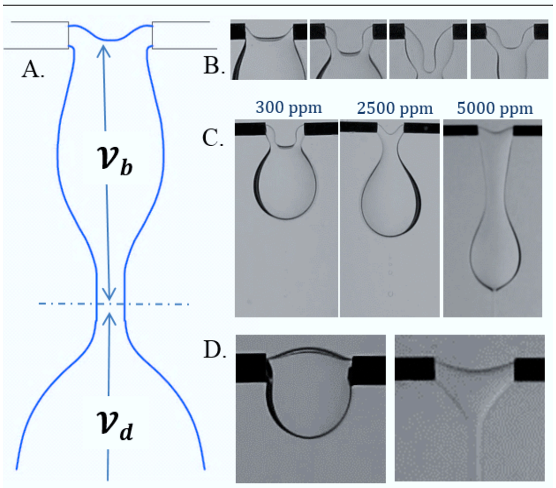

Figure 4. A) Schematic representation of the remaining mass of fluid after drop detachment; B) Time evolution of the upper meniscus for PAM 300 ppm at 5 ml/min; C) The influence of increasing elasticity on the liquid coalescent mass; D) Liquid bridges after drop breakup at 2 ml/min (PAM 300 ppm-left, PAM 5000 ppm-right)

the liquid bridge can undergo dramatic change in the case of weakly elastic solutions. Fig. 4B shows the time evolution of such an interface, the elasticity of the injected fluid preventing the meniscus to rupture. With increasing elasticity, the viscosity of the viscoelastic solution increases, which causes the upper meniscus to stabilize. The maximum radius of

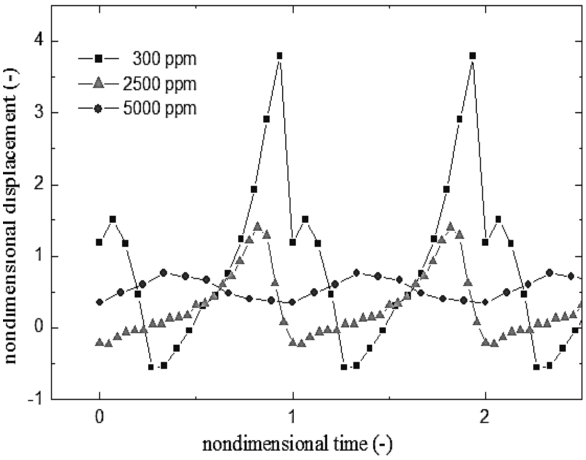

Figure 5. Time evolution of the maximum vertical displacement of the upper meniscus over two periods, vertical displacement and time being nondimensionalized with the inner diameter d of the nozzles and the period T of oscillation, respectively.

curvature is decreasing as the coalescent mass is stretched (Fig. 4C).

By measuring the maximum vertical displacement of the upper meniscus, at different moments in time, for the viscoelastic substances in question, one can observe that an increase in elasticity decreases the maximum radius of curvature, the interface being thus less sensitive to perturbations (Fig. 5).

CONCLUSIONS

The study presents the subsequent dynamics that follow after the coalescence of two horizontally opposed fluid jets. The dripping or jetting regime that settles depends upon the fluid's viscosity and elasticity. The presence of elasticity has an influence on the behaviour of the coalescent bulk, introducing instability and increasing it in volume. The viscosity of the fluid increases with elasticity and as a consequence the upper meniscus that connects the nozzles experiences less sensitivity to perturbations. As elasticity is increased the maximum radius of curvature decreases due to the fact that a fraction of the total load, produced by the growing bulk, is stored by elasticity. For a given fluid, increasing the flow rate results in a

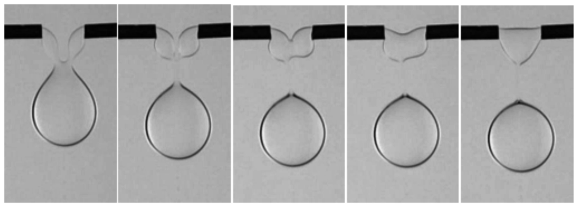

Figure 6. Breakup of the upper meniscus at the critical distance for PAM 300 ppm followed by a recoil of the interface that induces coalescence.

transition from dripping to jetting of the coalescent bulk. If the distance between the nozzles is increased, at some point the upper meniscus will rupture, sending the bulk in a non-coalescent state. Near this critical point the interface may coalescence even after breakup, as shown in Fig. 6, this being a consequence of the fact that a recoil of the interface is generated by the rapid breakup of the drop.

Future investigations will be focused upon determining the critical distance at which the coalescent state is stable, in the case of both Newtonian and viscoelastic substances.

ACKNOWLEDGMENTS

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