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# Viscoelastic liquid curtains

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## 1. Introduction :

Curtain coating has been intensively investigated on geometries and situations of increasing complexity (multilayer coating, inclined weirs, etc) [1]. We consider here the case of a viscoelastic liquid and focus on the simplest configuration, also investigated by Brown [2] and Aidun [3], of a vertical liquid curtain falling from a long thin slot and guided between two wires. To our knowledge, few works have investigated the incidence of viscoelasticity on curtain coating [4], and even elementary questions such as the flow structure and its stability remain unexplored. This situation is particularly surprising since the development of innovative processes, under the constraint of new environmental rules, frequently involves polymer solutions with unusual rheological behaviours. With the aim of filling this gap, we realized experiments with aqueous solutions of long chain polymers extruded across a long horizontal thin slot and investigated the flow structure and stability of the curtain downstream.

## 2. Experimental situation :

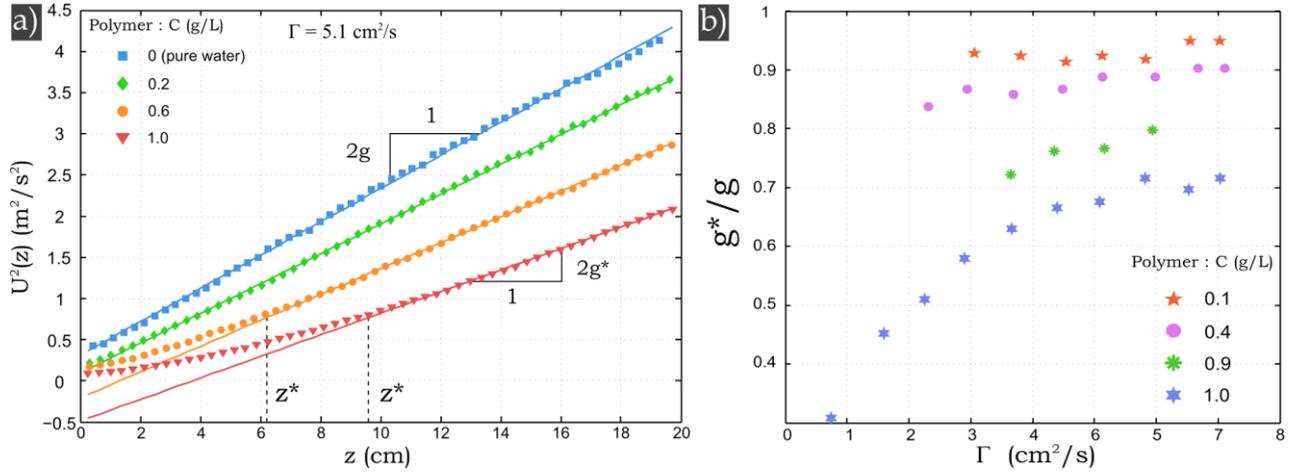
In our experiment, a long thin slot (length 14 cm, thickness  $a = 1$  mm) is drilled at the bottom of a horizontal hollow cylinder, which is kept filled with liquid and fed at constant flow rate by its two extremities. The liquid is extruded across the slot and then falls vertically under gravity, thus forming the curtain. Two vertical wires are placed on each side of the curtain to avoid lateral shrinking due to surface tension. We used aqueous solutions of polymer with concentrations  $C$  in the range 0.1 - 1.0 g/L. Shear rheology of such solutions was measured with a cone-and-plate rheometer, revealing a shear-thinning and viscoelastic behaviour, along with the development of a non-zero first normal stress difference  $N_1$ . The polymer concentration  $C$  and the linear flow rate  $\Gamma$  (volume of liquid crossing the slot per unit time per unit slot length) are the key parameters of the experiment.

## 3. Flow structure :

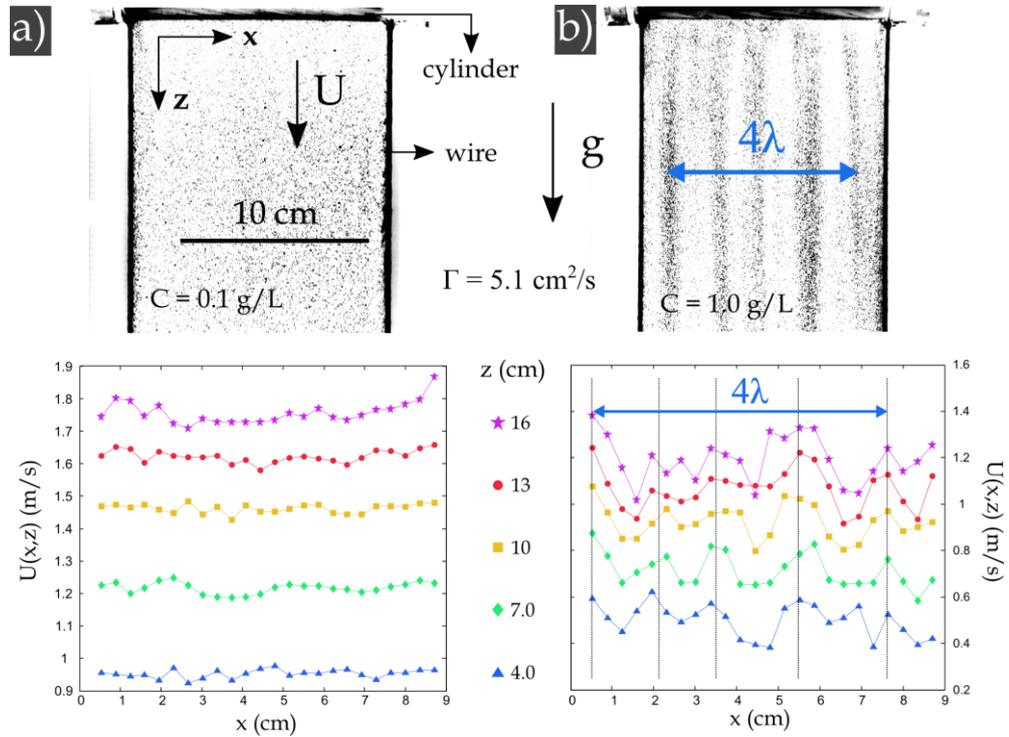
The bi-dimensional velocity field in the curtain was measured with Particle Image Velocimetry (PIV), using 50  $\mu\text{m}$  polyamide seeding particles and a high-speed camera. Surprisingly, and contrary to Newtonian liquids, the flow does not reduce to a free fall, even far downstream from the slot. We choose the vertical  $z$ -axis to point downstream,  $z = 0$  corresponding to the slot exit. Typical vertical velocity profiles in the  $z$ -direction are shown in Fig. 1-a for varied polymer concentrations. After a transition length  $z^*$ , we observe that the square  $U^2$  of the vertical velocity varies linearly with the distance  $z$  from the slot, i.e., for  $z > z^*$ :

$$U^2(z) = U_0^2 + 2g^*(z - z^*) \quad (1)$$

The parabolic shape of  $U(z)$  is preserved, but the acceleration  $g^*$  of the flow is actually reduced with respect to free fall. A viscoelastic curtain thus differs from a Newtonian curtain (with kinematic viscosity  $\nu$ ) which would relax to a free fall (with an acceleration  $g = 9.81 \text{ m.s}^{-2}$ ) at long distance  $z > (\nu^2/g)^{1/3}$  [2]. Here the presence of polymer slows down the liquid fall not only until  $z^*$ , but all over the curtain. As shown in Fig. 1-b, this effective acceleration  $g^*$  decreases with increasing polymer concentration  $C$  and decreasing flow rate  $\Gamma$ . The latter dependence suggests that the liquid keeps a memory of its shear deformation when passing through the slot. Moreover, the initial flow velocity  $U_0$  (at  $z = 0$ ) is found to decrease with  $C$  for a constant  $\Gamma$  and to be less than the expected  $\Gamma/a$  value corresponding to the mean velocity in the slot. This can be explained by a swelling of the curtain at the slot exit (see e.g. Tanner [5]). Indeed, the calculated values of the Weissenberg number, defined as the ratio  $Wi = N_1/\sigma$  between the first normal stress difference and the shear stress exerted on the slot wall, are larger than one and range between 10 and 50 in our experiment.

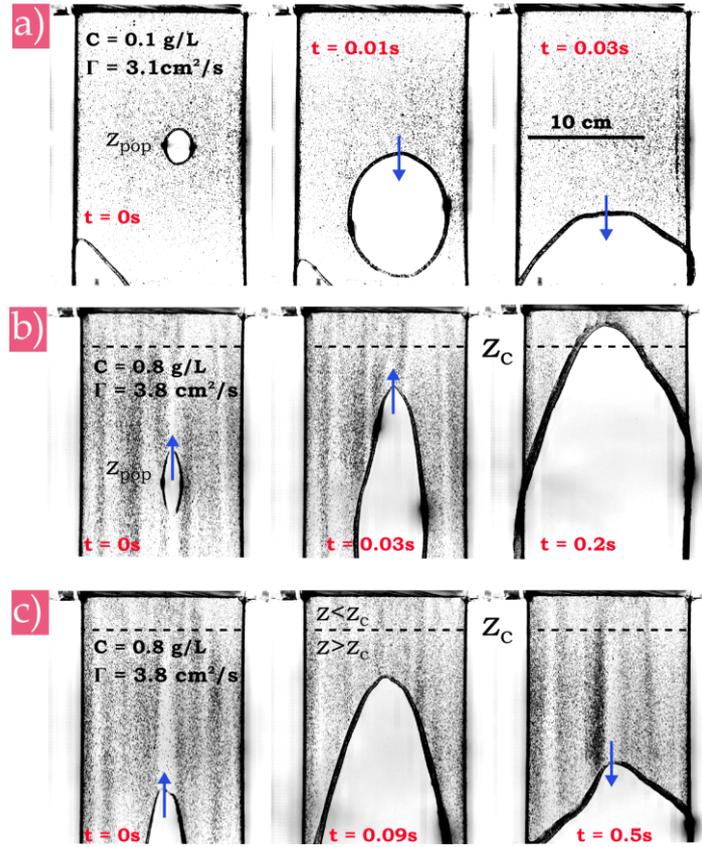


**Fig. 1:** (a): Vertical velocity profiles  $U^2$  versus  $z$  for a given linear flow rate  $\Gamma$  and different polymer concentrations  $C$ . The acceleration  $g^*$  of the flow at long distance decreases with increasing  $C$  (for pure water, a free fall with acceleration  $g$  is recovered). (b): Ratio  $g^*/g$  versus  $\Gamma$  for different polymer concentrations  $C$ . For large  $C$ ,  $g^*$  increases with  $\Gamma$ .



**Fig. 2:** PIV images (top) and velocity fields (bottom) of a curtain with low (a) and large (b) polymer concentration  $C$ . (top): Polyamide seeding particles appear as black dots. At large  $C$  (b), a horizontal modulation of the flow with wavelength  $\lambda$  appears. The thickness modulation is revealed by a non-homogeneous particles repartition (thin bands are poor in particles). Vertical velocity profiles  $U$  versus  $x$  for different altitudes  $z$  reveal the horizontal modulation in flow velocity. Correspondence between top and bottom shows that a concentrated curtain organizes in a succession of thick - fast vertical bands and thin - slow ones. (bottom): Averaging over  $x$  gives the mean  $U(z)$  values plotted in figure 1.

For large polymer concentrations, we also observed a spontaneous horizontal modulation of the flow. Indeed, PIV images show a modulation in particle repartition along the  $x$ -direction, thus suggesting a modulation of the curtain thickness leading to a succession of thick and thin vertical bands (Fig. 2 top). Velocity fields on the curtain reveal that this modulation in thickness is accompanied by a modulation in flow velocity: thick bands fall faster than thin ones (Fig. 2 bottom). The characteristic wavelength  $\lambda$  of this spatial modulation is centimetric and seems to be fairly independent of the polymer concentration as well as of the flow rate (although the modulation amplitude depends on both values).



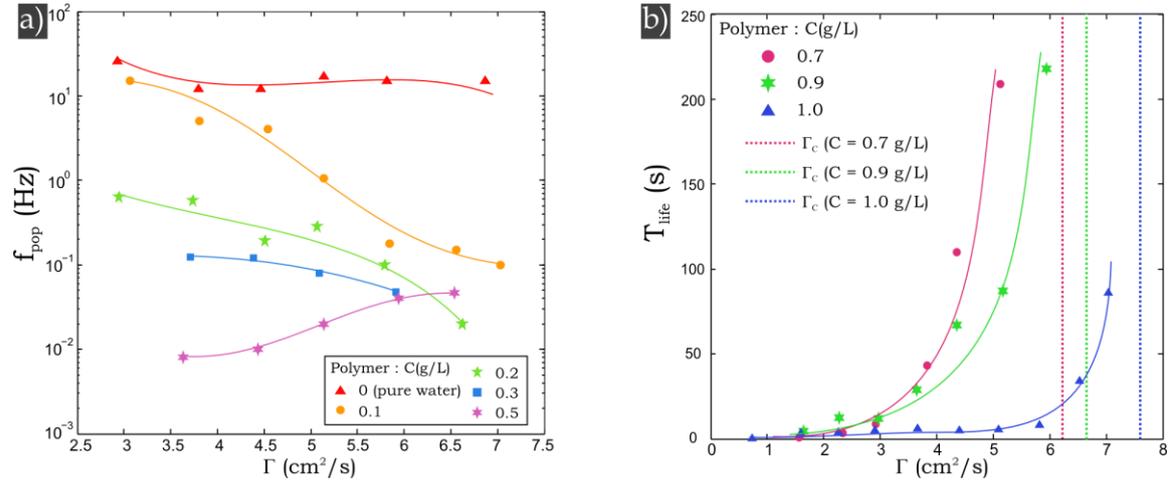
**Fig. 3:** Time sequences of hole opening in a low concentration (stable) curtain (a,  $\Gamma > \Gamma_C$ ) and a large concentration (unstable) one (b and c,  $\Gamma < \Gamma_C \Leftrightarrow z_c > 0$ ). (a): The hole is evacuated by the flow. (b and c): A bubble bursts in a thin band in which the local Taylor-Culick speed  $V_C$  is larger than the local flow velocity  $U$ . The upper edge of the hole thus propagates upward and eventually (b) reaches the unstable zone  $z < z_c$ , thus irreversibly breaking the curtain.

#### 4. Curtain stability :

The stability of a curtain is usually discussed in terms of a comparison between the liquid falling velocity  $U$  and the Taylor-Culick velocity  $V_C = (2\gamma/\rho h)^{1/2}$  at which a hole opens in the frame of reference of the moving liquid [2,6], where  $\gamma$  and  $\rho$  are the liquid surface tension and density and  $h = \Gamma/U$  is the local curtain thickness (without modulation) which decreases with  $z$  as  $U$  increases in order to respect flow rate conservation. Since, in the absence of modulation,  $U/V_C = (\rho\Gamma U/2\gamma)^{1/2}$  increases with increasing  $z$ , curtain stability is to be considered as a function of space. If a hole forms at an altitude  $z_{\text{pop}}$  where  $U > V_C$ , it will then be advected by the flow (Fig. 3-a). On the contrary, if  $U < V_C$ , the upper edge of the hole will propagate upward and finally reach the slot, thus irreversibly breaking the curtain. This defines a critical altitude  $z_c$  below which the curtain is stable ( $z > z_c \Leftrightarrow U > V_C \Leftrightarrow \text{Weber number } \text{We} = (U/V_C)^2 > 1$ ).

However, as shown in Fig. 3, holes (formed spontaneously by bubble bursting) formed at altitudes  $z_{\text{pop}} > z_c$  are able to propagate upward (b and c) and eventually reach the unstable zone  $z < z_c$  (b). This is in fact due to thickness and velocity modulation in the curtain. Indeed, bubbles (b and c) burst in thin bands ( $h$  small and  $U$  small) where  $V_C$  is increased and  $U$  is decreased, thus allowing  $V_C > U$  locally. As bubbles (inevitably formed during liquid circulation in the set-up) are more likely to burst in thin bands, the viscoelastic thickness modulation instability (observed for large polymer concentrations) destabilizes the curtain by allowing holes formed away from the slot to cause irreversible rupture.

On the other hand, for low polymer concentrations (negligible modulation), we measured that adding polymer strongly decreases the mean frequency  $f_{\text{pop}}$  of bubble bursting events in the curtain, as shown in Fig. 4-a. The frequency typically decreases from ten holes formed per second for pure water to one hole per minute for a moderate concentration  $C = 0.5 \text{ g/L}$ . This observation suggests that adding a moderate amount of polymer stabilizes the curtain. Indeed, besides the fate of a hole that has already formed, the stability of a curtain crucially depends on the occurrence of hole formation.



**Fig. 4:** (a): Frequency  $f_{pop}$  of bubble bursting events in the curtain as a function of the linear flow rate  $\Gamma$  for different (moderate) polymer concentrations  $C$ . Adding polymer decreases  $f_{pop}$  and thus stabilizes the curtain. (b): Curtain lifespan  $T_{life}$  (mean time during which a curtain remains entire before an irreversible rupture event occurs, like in Fig. 3-b).  $T_{life}$  increases with  $\Gamma$  and diverges at the critical flow rate  $\Gamma_C$  (above which  $T_{life}$  is infinite). Directly measured values of  $\Gamma_C$  are represented by vertical dotted lines for the corresponding polymer concentrations and seem to effectively match the singularity of experimental  $T_{life}(\Gamma)$  curves. Lines are traced to guide the eye.

In parallel, we measured the mean time  $T_{life}$  during which a curtain can remain entire before a hole reaches the slot (eventually using a thin band path) (Fig. 3-b). Other hole opening events (Fig. 3-a and c) are not taken into account so that  $T_{life}$  is not  $1/f_{pop}$  and represents the curtain lifespan. Our measurements (Fig. 4-b) show that  $T_{life}$  increases with  $\Gamma$  and diverges at a certain critical flow rate  $\Gamma_C$  that depends on the polymer concentration. Besides, for a given  $\Gamma$ ,  $T_{life}$  decreases with increasing  $C$ , which manifests the increasing influence of thickness modulation on stability.  $\Gamma_C$  is the critical linear flow rate above which no rupture event is possible, all holes being evacuated by the flow. For a Newtonian liquid, and assuming no swelling, one would expect  $\Gamma_C = (2\gamma a/\rho)^{1/2}$ , which corresponds to  $U_0 = V_C$ . Our measurements (Fig. 4-b) however show that  $\Gamma_C$  actually increases with increasing polymer concentration, which reveals an other destabilizing effect of the addition of polymers.

## 5. Conclusion :

We have investigated the flow and stability of a viscoelastic liquid curtain falling vertically from a thin slot. We have shown that both aspects are strongly modified compared to the standard behaviour of Newtonian liquids: the base flow, i.e. the velocity at which the liquid falls, is modified, and a specific instability is observed at the slot exit, which modulates the curtain thickness and velocity and influences the curtain stability. We believe that these effects result from the strong shear imposed to the liquid when flowing across the slot, the elastic stresses developed in the liquid being unable to completely relax in the sudden die-slot expansion [5]. This situation is reminiscent of a recent study by Lhuissier et al [7] on viscoelastic jet impact, in which unrelaxed stresses develop a faceting instability on impact. We are still investigating these unusual effects and are trying to develop models based on available theories of viscoelastic flows.

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