Particle Image Velocimetry of Film-Splitting Flows of Viscoelastic Liquids

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Roll coating is widely used to apply a thin liquid layer to a continuous flexible substrate. At low speeds the flow is two-dimensional and steady; as the roll speed is raised, the two-dimensional flow becomes unstable and is replaced by a steady three-dimensional flow which results in more or less regular stripes in the machine direction. This type of instability or rather the three-dimensional flow to which it may lead, is commonly called *ribbing*; it can limit the speed of the process if a smooth film is required as a final product.

The film-splitting flow of a Newtonian liquid exiting from two rotating rolls and the associated instability have been studied extensively. Pearson (1960) showed that the adverse pressure gradient near the film-split meniscus necessary to decelerate the flowing liquid destabilizes the free surface, whereas surface tension has a stabilizing effect. A critical value of the ratio between these two forces, i.e., the capillary number $Ca \equiv \mu V / \sigma$, marks the onset of the free surface nonuniformity. Here, μ is the liquid viscosity, σ its surface tension, and V is the mean roll speed.

In practice, coating liquids often contain polymers. Viscoelastic behavior can drastically change the nature of the flow near the free surfaces of coating beads. The extension-dominated deformation that occurs in these flow zones leads to changes in the force balance at the meniscus. In the particular case of forward roll coating, it has been shown experimentally that when minute amounts of flexible polymer are present, the onset of the three-dimensional instability that leads to regular stripes in the machine direction (ribbing) occurs at much lower speeds than in the Newtonian case, as shown in Fig.1. Bauman et al. (1982) experimentally tested the effect of certain polymer additives on the ribbing instability. They observed that the critical speed at which ribbing first appeared was lower than in the case of a Newtonian liquid. The formation of small liquid drops at the film split meniscus, a phenomenon known as spatter and misting, was studied by Glass (Glass 1978a-d). Their main conclusion was that paints with high apparent extensional viscosity produced large and stable filaments. Carvalho et al. (1994), and later Dontula (1999), with more details, analyzed experimentally the film splitting flow of aqueous solutions of PEG and PEO. They concluded that minute amounts of flexible polymer lowered drastically the critical speed at which the three-dimensional instability occurs. Grillet et al. (1999) and recently Lopez et al. (2002) studied experimentally the instability of non-Newtonian flow between two non-concentric cylinders. The latter used two aqueous polymer solutions with similar shear-thinning behavior but different elastic characteristics, i.e., Xanthan (inelastic) and Polyacrylamide (elastic). With the elastic (Polyacrylamide) solution, the critical capillary number for the instability dropped with growing polymer concentration by up to one order of magnitude compared to the Newtonian case. With the Xanthan solution, the critical capillary number decreased only slightly. The resulting three-dimensional pattern of the free surface is also a strong function of the liquid properties, which suggests that the instability mechanism may be different in the case of viscoelastic liquids. Owens et al. (2004) analyzed the effect of polymer additives on the stability of film splitting flows and on mist formation.

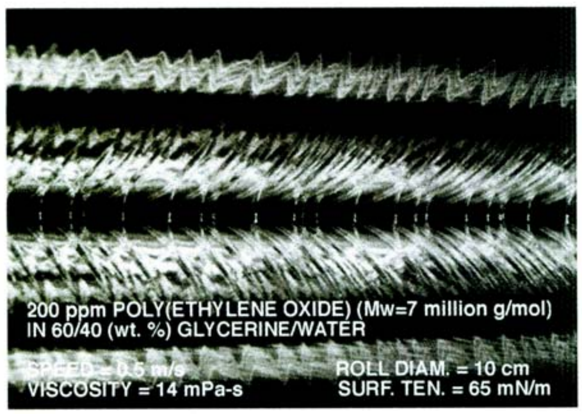

Fig. 1: Three-dimensional periodic flow in forward roll coating film splitting (from Carvalho et al., 1994).

Accurate theoretical predictions of the onset of ribbing when viscoelastic liquids are used is still not available. The mechanisms by which the liquid elasticity makes the flow unstable at Capillary numbers much lower than in the Newtonian case is not completely understood. Recent theoretical predictions (Zevallos et al.m 2004) have shown how the stress field changes with rising liquid elasticity (Weissenberg number), leading to the formation of an elastic stress boundary layer attached to the free surface. The high stress downstream of the flow splitting stagnation point pulls liquid away from the recirculation attatched to the free surface and completely changes the flow characteristic in that region. The evolution of the streamlines at $Ca = 0.2$ and normal stress along the streamlines as the liquid becomes more elastic predicted by Zevallos et al. (2004) is presented in Fig.2. At high Weissenberg number, the recirculation zone, present in the Newtonian flow completely dissapears.

In this work, film splitting flows between a stationary plate and rotating roll are analyzed experimentaly by visualizing the free surface configuration and measuring the velocity field using the Particle Image Velocimetry (PIV) technique. Various solutions of low molecular weight polyethylene glycol (PEG) and high molecular weight polyethylene oxide (PEO) in water were used in order to evaluate the effect of mildly viscoelastic behavior on the flow. The goal was to confirm the theoretical predictions of Zevallos et al. (2004) on the effect of liquid viscoelasticity on the streamline pattern and on the stability of the free surface with respect to three-dimensional disturbances.

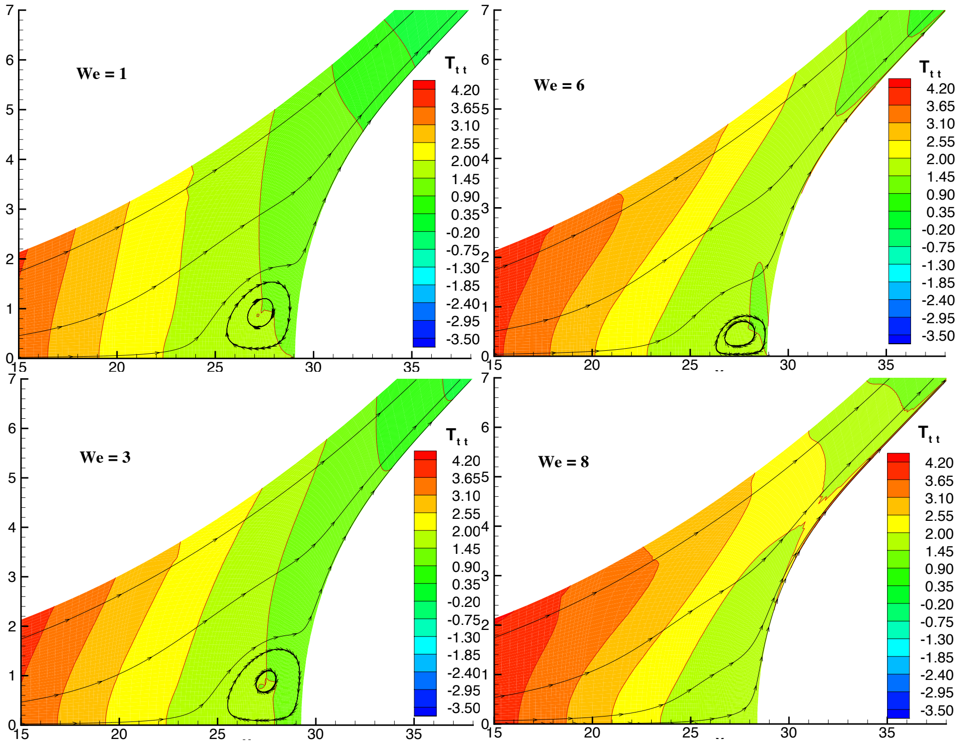

Figure 2: Evolution of the streamlines and normal stress component along the streamlines as Weissenberg number grows at *Ca = 0.2*.

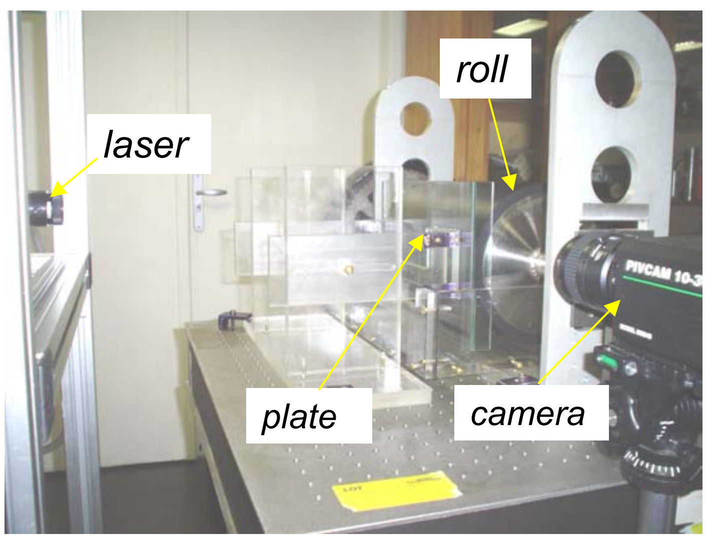

Figure 3: Experimental setup.

The experimental setup is shown in Fig.3. The coating bead was visualized using two view angles: a frontal view, through the glass plate, and a lateral view. The frontal view was used to determine the configuration of the meniscus in the transverse direction and to determine the onset of the instability. Example of such images is presented in Fig.4, which clearly shows the onset of ribbing at a gap-over-roll diameter ratio of $H_0 / R = 3\times10^{-3}$ at $Ca \approx 0.63$.

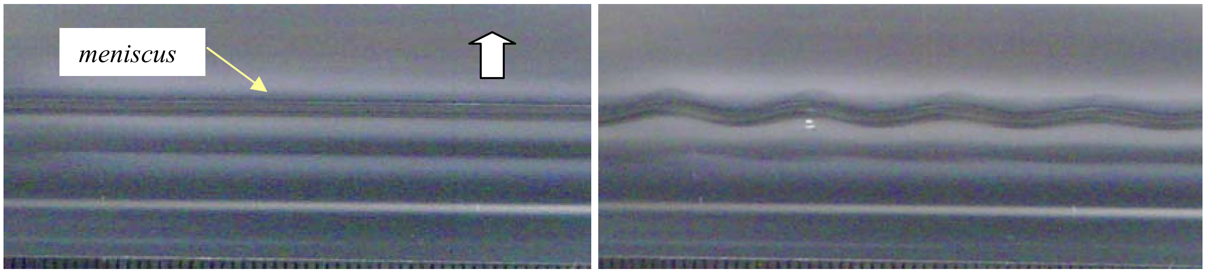

Figure 4: Frontal view of coating bead at $H_0 / R = 3\times10^{-3}$ and (a) $Ca = 0.6$ and (b) $Ca = 0.65$

The lateral view was used to visualize the flow pattern, and meniscus configuration, and to measure the velocity of the flow near the meniscus using the Particle Image Velocimetry (PIV) technique. In this method, a planar laser light sheet is pulsed twice and images of fine particles lying in the illuminated plane are recorded on a video camera. The displacement of the particle images is measured by dividing the image plane ito small interrogation spots and cross correlate the images from the two time exposures. The spatial displacement that produces the maximum cross-correlation statistically approximates the average displacement of the particles in the interrogation cell, as sketched in Fig.5. Velocity associated with each interrogation spot is just the displacement divided by the time between the laser pulses.

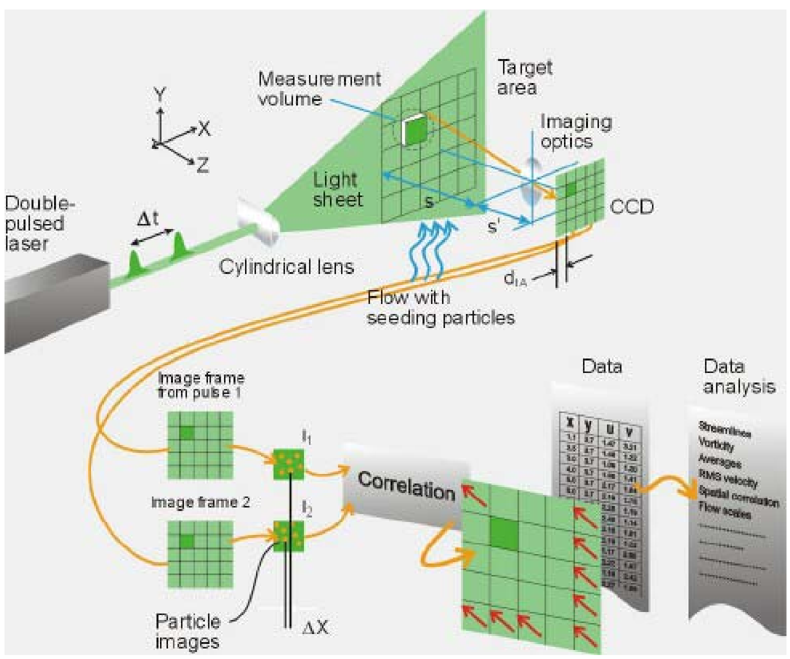

Figure 5: Particle Image Velocimetry Method.

Figure 6 shows the menicus configuration and velocity field near the free surface of a Newtonian flow. At this capillary number, the flow is stable and there is a large recirculation attached to the menicus. The experimental method is being improved by using smaller fluorescent particles ($\approx 1\mu m$) in order to improve the correlation of the images.

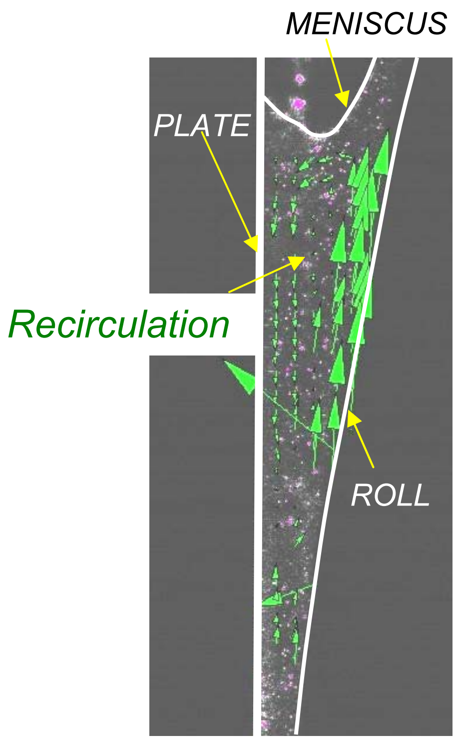

Figure 6: Lateral view with measurement of velocity field,

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