Measuring the velocity field in film-splitting flows of the Newtonian liquids

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Many different products are manufactured by depositing a thin liquid layer onto a moving substrate and subsequently solidifying it. Examples of products include premium papers, magnetic tapes and disks, printing materials, photosensitive coatings, membranes, films used in different types of displays, microelectronics circuits and many others. The region where the liquid first comes into contact with the substrate is called the *coating bead*.. It is usually bounded by two gas-liquid interfaces, or menisci, the solid walls of the coating applicator and the moving substrate. The competition among viscous, capillary and pressure forces, and in some cases inertial and elastic forces, sets the range of operating parameters at which the viscous free surface flow can be two-dimensional and steady – the conditions prerequisite for uniform coating.

Coating technology remained an art until the 1940's. Since then, rigorous mathematical analysis of viscous free surface flows started to be used to gain basic understanding of coating flows. Today, both industrial and academic coating flow research are based on comprehensive theoretical and experimental analysis. Theoretical analysis usually require advanced numerical methods to solve the mass and momentum conservation equations coupled with the appropriate boundary conditions for flows with gas-liquid interfaces. Most of the theoretical analysis can provide details and insights into the physics that control the two-dimensional flow in successful coating operations, stability limits of the flow states and, ultimately, stability limit maps of the process. However, the available theoretical models for coating flow analysis are not able to precisely describe some essential physical mechanisms, such as dynamic wetting and non-Newtonian behavior. Specially in these cases, it is essential to be able to compare the predicted flow states with experimental measurements of the flow field in order to validate the simplifying assumptions and to test the constitutive equations used to describe the mechanical behavior of the flowing liquid.

The first attempts to visualize a coating flow were limited to displaying the free surfaces or meniscii position and configurations, and were not able to resolve details of the flow inside the coating bead. Schweizer (1988) was the first to present streamlines with vortices in a coating flow. The pictures showed the flow pattern of two liquids merging on an incline plane and in the region between a slide coating applicator and the moving web. Optical access into the flow was gained through a side transparent window mounted such that it coincided with the side confinement of the flowing liquid. The plane of observation, at which the tracer particles were introduced, was sufficiently far from the side window to avoid edge effects and to guarantee a truly two-dimensional flow. Flow visualization techniques had a strong contribution on enhancing the fundamental understanding of different coating methods and have provided many new insights into the process. However, in order to understand the flow in more detail, a quantitative method capable of providing instantaneous measurements of the velocity field inside the coating bead is required. For example, if the instantaneous velocity at each point of the flow is known, the deformation rates to which the liquid is subjected inside the coating bead can be calculated. This information is vital to understand the role of liquid rheology on the process. Velocity measurement in coating flows is a challenging task. The main reasons are the small scales of the flow – the coating bead is usually in the order of 100 μm – the presence of the free surfaces, and the relatively high speed in some cases. Reports of velocity field measurements of coating flows are rare in the literature. Hens (1989) used Laser-Doppler Anemometry (LDA) to measure the liquid velocity in the vicinity of the dynamic contact line in a slide coating process. However, in that work, the velocity

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information was associated with high levels of uncertainty related to the spatial positioning of the measuring volume, since one of the laser beams was deflected by the meniscus, whose position and shape depend on operating conditions that were not known a priori. Clarke (1995) used Particle Tracking Velocimetry (PTV) to obtain the velocity field in a curtain coating flow. The liquid velocity was measured by obtaining the velocity of small bubbles as they travelled along streamlines within the curtain. PTV technique tracks individual particle images in consecutive image frames and the velocity field is obtained based on the displacement vector for each matched particle pair. This technique yields low resolution velocity measurements and the measured velocity vectors are unevenly distributed throughout the flow. Another widely used nonintrusive flow measuring technique is Particle Image Velocimetry (PIV). As in PTV, the flow is seeded with small tracer particles externally illuminated by a planar sheet of pulsating laser light, and the scattered light from the tracer particles is recorded. However, in PIV the velocity vectors are not obtained from the displacement vectors for each individual particle. Rather, the image is divided into small interrogation windows and an area-averaged displacement vector over each interrogation window is obtained by statistical evaluation of two consecutive images. The spatial resolution of the measured velocity field is a function of the size of the interrogation window an can be quite high. Moreover, the measured velocity vectors are evenly distributed over the flow domain, being obtained at pre-defined positions. Adrian (1996) presents an extensive discussion of several aspects of this technique. Although PIV has been widely used in several applications, to our knowledge, this method has not been applied to coating flows.

In this work, we apply the PIV technique and the numerical solution of the Navier-Stokes equation with the appropriate boundary conditions to describe the free surface to determine, experimentally and theoretically, the velocity field near the downstream free surface of a prototype forward roll coating flow. Roll coating is distinguished by the use of one or more gaps between rotating cylinders to meter and apply a liquid layer to a substrate. The position of the free surface is a strong function of the operating conditions, and a recirculation, attached to the meniscus, is present at low roll speeds. Above a critical roll speed, the two-dimensional film splitting flow that occurs in forward roll coating becomes unstable; a three-dimensional steady flow sets in, resulting in more or less regular stripes in the machine direction. The stability of the two-dimensional flow is determined by the competition of the different forces acting on the free surface – capillary, viscous and elastic, in the case of polymeric solutions. For Newtonian liquids, the onset of meniscus non-uniformity is marked by a critical value of the capillary number. Therefore, in order to fully understand this flow stability limit, it is very important to accurately measure the velocity field near the free surface to be able to estimate the different forces acting in that region of the flow. In the case of viscoelastic liquids, measuring the instantaneous velocity field near the free surface is even more important, since it will reveal the role of the liquid rheology on the flow pattern, what can be used to validate the different constitutive models used to describe viscoelastic behavior of polymer solutions.

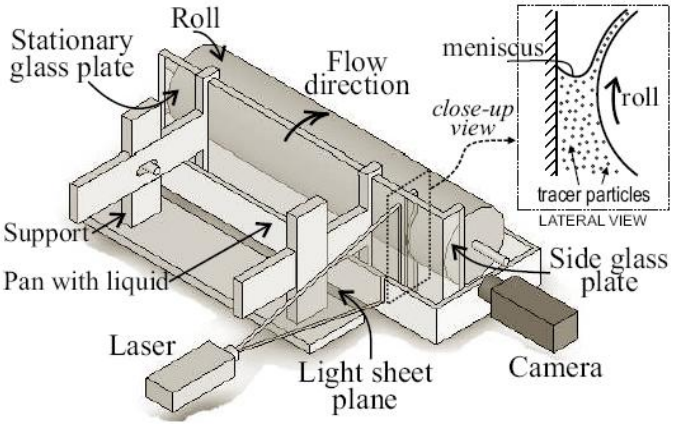

Fig.1: Schematic showing the main features of the experimental roll plate apparatus.

The experiments were conducted in the test section shown schematically in Fig. 1. It consisted of a stationary glass plate and a rotating roll. Liquid was picked out of a pan and a liquid bead was formed in the small space between the plate and the roll. A meniscus was formed in the region where the liquid detached from the plate, forming a film of liquid on the roll surface. The operating parameters that were controlled during the experiments were the gap between the roll and the stationary plate, H_0, the tangential roll speed, V , and the viscosity of the Newtonian liquid, μ. In the experiments presented in this work, the gap was kept approximately constant at $H_0 = 900\ \mu m$ (measured roll run-out of $20\mu m$), i.e. $H_0/R = 9 \times 10^{-3} \pm 0.5 \times 10^{-3}$. The transparent liquid used in the experiments was a Newtonian solution of low molecular weight polymer (PEG, poly-ethylene glycol, molecular weight 6000 g/mol) in

water. The concentration of the PEG was fixed at 30% by weight, which yielded a constant viscosity of approximately 30 cP. The density of the solution was ρ = 1047 kg/m3 and the surface tension was $\sigma = 52 \times 10^{-3}$ N/m.

The velocity field between the moving roll and the stationary plate in the neighborhood of the free surface was measured for different flow conditions using the Particle Image Velocimetry technique. In this technique a pulsed laser sheet illuminates small tracer particles previously distributed in the fluid. A digital camera mounted orthogonally to the laser sheet records the position of the tracer particles at two close instants. A synchronization circuit coordinates the laser pulse with the image capturing system, so that the two images are registered in consecutive frames. The particle displacements are determined by analyzing small sub-regions of the image (the interrogation windows) and cross-correlating the image intensity distribution of the two frames. The instantaneous velocity field is obtained by dividing the instantaneous displacement field by the time interval between laser pulses and by the magnification factor of the optical setup.

The major difficulty in applying the PIV technique to measure free surface flows in the vicinity of the free surface, arises from the light reflections originated at the gas-liquid interface. The light reflected at the gas-liquid interface is normally much more intense than the light scattered by the tracer particles, what precludes the registration of their images on the recording media. The proposed solution for this problem was to use a combination of fluorescent tracer particles and optical filters to avoid the undesired reflections.

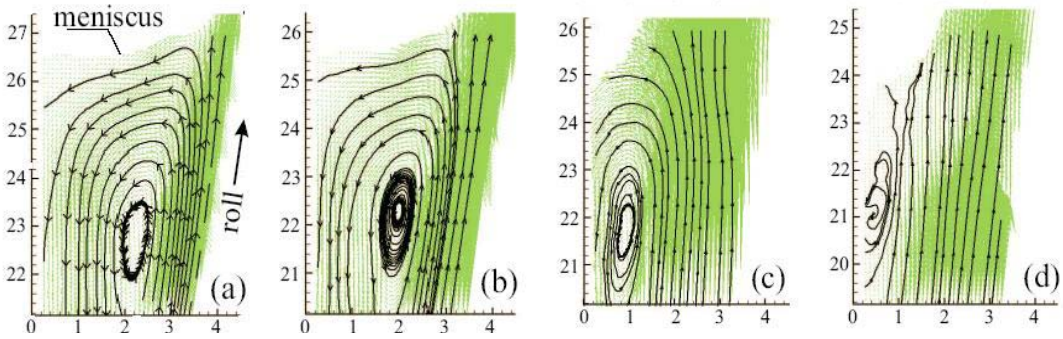

Fig.2: Lateral view of the °ow showing the average velocity ¯elds at di®erent capillary numbers: (a) Ca=0.1, (b) Ca=0.17, (c) Ca=0.57, (d) Ca=0.83 and H0=R = 9 x 10^{-3}. Horizontal and vertical axes values are in mm.

Although all the process conditions were constant, the actual flow oscilated periodically with time. The reason for that was the small variation of the actual radius along the circunference of the roll from its specified value of R = 100 *mm*. Because of the small clearance between the rotating roll and the plate, any small variation of the roll radius causes an appreciable variation on the gap. Consequentely, the meniscus position oscilated periodically and the flow was unsteady. In order to report the steady state values of the velocity field, a time-average of the velocity at each position was calculated. The sampling time was always larger than six revolution of the roll. What corresponded to between 200 and 400 velocity fields forming a typical sample.

The effect of the roll speed, represented in terms of the capillary number on the flow field is shown in Fig.2. As the capilary number rises, the recirculation region becomes smaller and smaller, until it almost vanishes at Ca = 0.83. The critical capillary number at this gap is approximately Ca ≈ 0.54, and the flow field at the two highest capillary number shown in the figure are three-dimensional and what is shown in actually a slice of a flow field at a meniscus valey.

The experimental results were compared to the theoretical predictions obtained by solving the governing equations using Galerkin's / finite element method. The predicted and measured streamlines at $H_0/R = 9 \times 10^{-3}$ and Ca = 0.17 are shown in Fig.3. The comparison of the steady-state solution with the measured time-averaged velocity field was done at an imposed contact angle that yielded the same vortex center position measured in the experiments, i.e. θ = 50° The predicted vortex center position is a function of the imposed contact angle and roll-plate distance. Except the meniscus configuration, the agreement on the flow pattern is good. As explained before, the time average used to represent the transient flow fields introduces uncertainties on the location of the free surface. The largest discrepancies are observed near the roll surface. The evaluation of the time-average introduces uncertainty on the location of the meniscus, but the agreement of the predicted and measured velocity profiles at different positions along the plate, far enough from the free surface, was very good.

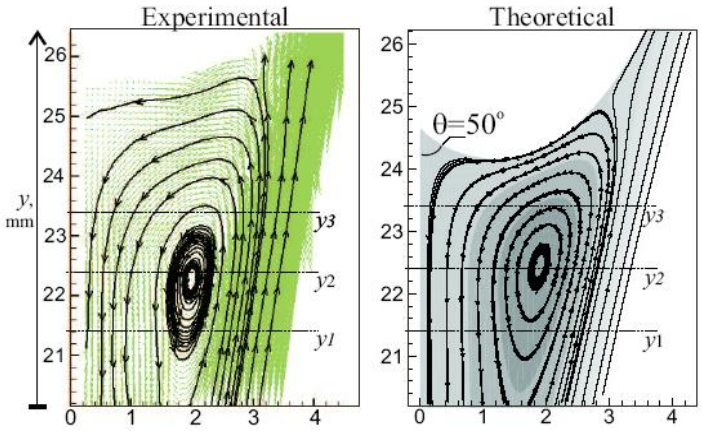

Fig.3: Predicted and measured flow field at Ca = 0,17 and H0/R = 9 x 10-3. Both results shows a large recirculation attached to the free surface.

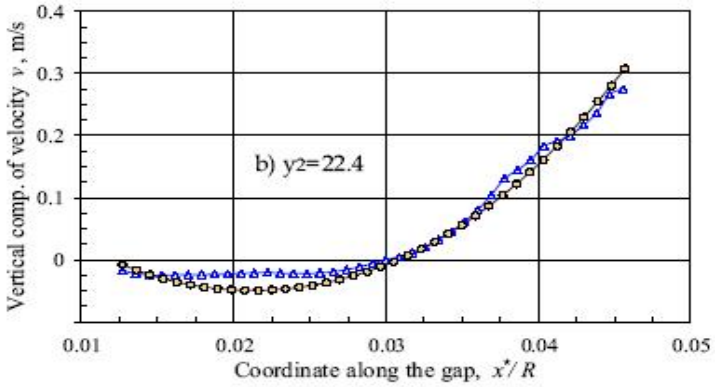

Fig.4: Comparisons of the vertical velocity along the gap v(x), y = 22.4 mm, obtained by experiments and theory at capillary number Ca = 0.17 and $H_0/R = 9 \times 10^{-3}$.

The measured and predicted vertical velocity profiles are compared at y = 22.4*cm* (at the vortex center), the results are shown in Fig.4. The agreement is very good.

The method proposed here to eliminate reflection from the free surface in combination with the PIV technique may be used to measure the velocity field in other coating methods. The quantitative knowledge of the velocity field inside the coating bead would certainly contribute to enhance the fundamental understanding of the process.

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