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Transient Slot Coating

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Introduction

An enormous range of manufactured products involves layers deposited as a liquid and then solidified on a solid surface. Frequently, the coating stage of a manufacturing process is significant in cost, time involved and the level of technology required for the production. To be competitive in the marketplace, all aspect of the manufacturing must be efficient and maintain an acceptable level of quality control. Products requiring precise control of coating thickness are usualy coated with a pre-metering coating techniques: the thickness of the coated liquid layer is set by the flow rate fed to the coating die and the speed of the moving substrate, and is independent of other process variables. Slot coating belongs to this class of coating methods, and is ideal for high precision coating. However, the nature of the flow in the coating bead and the uniformity of the liquid layer it delivers can be affected by the substrate speed, liquid properties, configuration of the die lips and cross-web uniformity of the contact lines position.

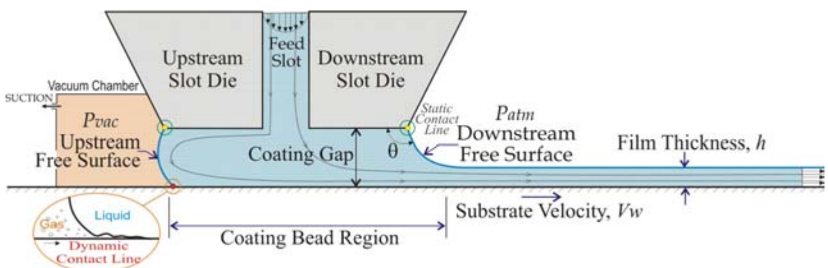

Figure 1 – Side profile of the single layer slot coating.

Slot coating is commonly used in the manufacturing of adhesive and magnetic tapes, specialty papers, imaging films, and many other products. In this process, the coating liquid is pumped to a coating die in which an elongated chamber distributes it across the width of a narrow slot through which the flow rate per unit width at the slot exit is made uniform. Exiting the slot, the liquid fills (wholly or partially) the precise narrow channel (coating gap in the figure) between the adjacent die lips and the substrate translating rapidly past them. The liquid in the gap, bounded upstream and downstream by gas-liquid interfaces, or menisci, forms the coating bead. Even the best designed coating operations are subjected to small oscillations on the process conditions, such as flow rate, vacuum pressure and gap fluctuations. The effect of these disturbances on the coated layer has to be minimized to assure a wet thickness as uniform as possible.

The two-dimensional, transient flow that occurs during the deposition of a Newtonian liquid onto a substrate with a slot die is examined. The effect of an imposed persistent periodic perturbation on the liquid flow rate in the coated layer thickness is explored at different process conditions and die configurations. The mathematical modeling of the transient slot coating flow involves solving an initial boundary value problem in which the location of the free surface is a part of the solution of the problem. The unknown flow domain (physical) is mapped into a fixed domain (computational). The system of equations, with appropriate boundary conditions, for a two-dimensional viscous liquid flow is solved in coupled form by the Galerkin / finite element methods, where the temporal discretization is done by a predictor-corrector algorithm. The set of non-linear algebraic equations for the finite element basis functions is solved by Newton's method.

The Physical Problem

The two-dimensional transient free surface flow depicted in Fig. (1) is defined by the governing Navier-Stokes and the continuity equations for a Newtonian liquid. Appropriate boundary and initial conditions are necessary to uniquely solve this system of equations.

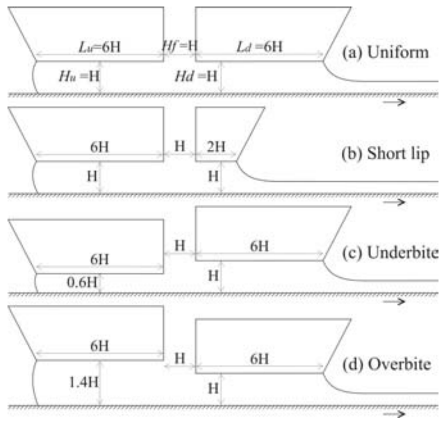

Figure 2 – Geometries used in this work.

The four different die configurations considered in the analysis are sketched in Fig. (2). Different lip length and underbite or overbite configurations were considered.

Solution Method

In a free surface problem, the physical domain is unknown a priori. Elliptic mesh equations must be added to the conservation equations to map the unknown physical domain into a convenient reference one wherein a simple mesh tessellation is effected (de Santos, 1991). The equations that describe the mapping between the two domains are solved simultaneously with the conservation equations.

In transient problems, the frame of reference lies across the space-time domain for which the physical grid points are constantly updated in time. Time derivatives at fixed Eulerian locations in space $\partial\Phi/\partial t$ are written in terms of time derivatives at a fixed iso-parametric coordinates, denoted by $\dot{\Phi}$ as $\partial\Phi/\partial t = \dot{\Phi} - \dot{\mathbf{x}} \cdot \nabla\Phi$, where $\dot{\mathbf{x}}$ is the mesh velocity (Christodoulou and Scriven, 1992).

The two-dimensional transient simulation was carried out using Galerkin / finite element method, with the primitive variable formulation and fully coupled solution methods (the position of the interface and the flow solution are computed simultaneously). The Galerkin weighted residuals form a set of nonlinear ordinary differential-algebraic equations. The temporal discretization of this set of equations is done by a predictor corrector algorithm. The predictor step consists of a forward Euler method and the corrector step consists of a first-order fully implicit Euler method, which is unconditionally stable in the sense that the time step is not restricted by any CFL-condition.

Results and Discussion

The flow in the coating bead as the flow rate fed into the die varies periodically is analyzed at different die configurations and frequencies of the imposed oscilation. Figure (3) displays contours of the transient streamfunction at three instants: $t_1 = 22\Delta t$, $t_1 = 38\Delta t$ and $t_1 = 55\Delta t$, which correspond to the maximum ($h_1 = h_0 + \Delta h_0$), average ($h_2 = h_0$) and minimum ($h_3 = h_0 - \Delta h_0$) film thickness, respectively. The upstream meniscus meets the web at the dynamic contact angle $\theta_{dyn} = 120^o$ and intersects the upstream slot lip at the static contact angle $\theta_{sca} = 70^o$. Under the downstream lip, where viscous and pressure forces balance each other, the flow is almost rectilinear until the liquid squeezes under the downstream meniscus and the liquid accelerates to reach the web speed. Over roughly three gaps downweb from the downstream lip edge, the meniscus configuration becomes flat and the velocity profile across the thin film is essentially plug flow.

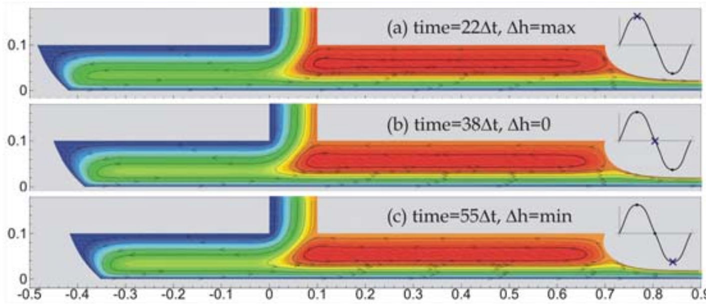

Figure 3 – Three time instant showing the flow field variation with time in a parallel coating gap.

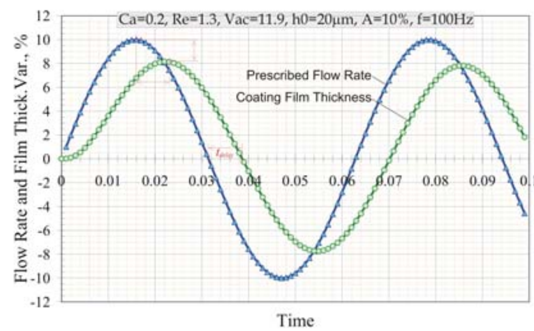

Figure 4 – Transient film thickness variation with amplitude.

The imposed flow rate variation and the corresponding film thickness variation with time is presented at Fig. (4) at a capillary number $Ca = 0.2$, Reynolds number $\mathrm{Re} = 1.3$ and frequency of the oscilation $f = 100Hz$. The amplitude of the imposed flow rate oscilation was $A = 10\%$. There is a time delay t_{delay} (phase shift) on the two periodic curves, which is a function of the operating parameters. At this set of operating conditions, the amplitude of the film thickness variation was of 8%.

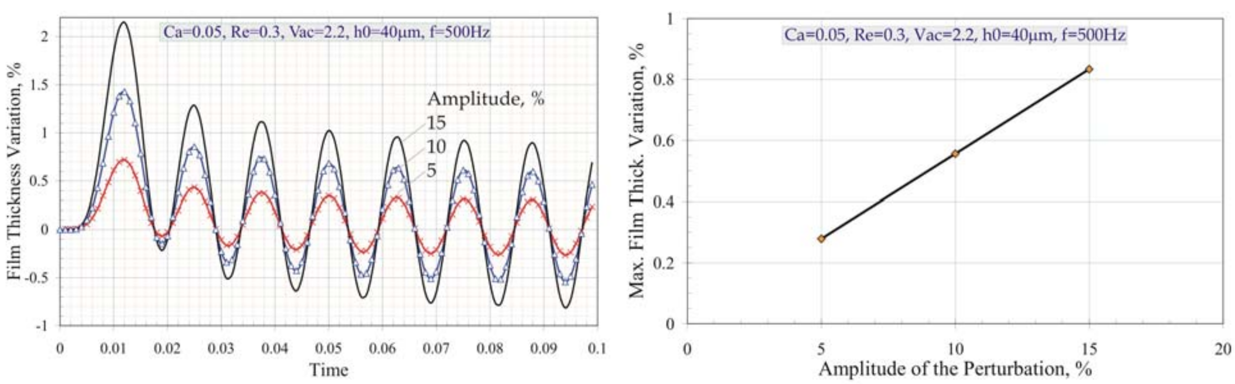

Figure 5 – Variation of the liquid layer thickness with the amplitude of the perturbation.

The influence of the amplitude of the perturbation on the amplitude of the film thickness variation is presented in Fig. (5). It shows that the higher the amplitude of the liquid flow rate oscilation, the higher the amplitude of the film thickness variation, and as is displayed in Fig. (5-b) this growth is linear. The results show that, at these conditions, the hypothesis of linear behavior that is embended in frequency response analysis is still valid up to a flow rate variation of 10%.

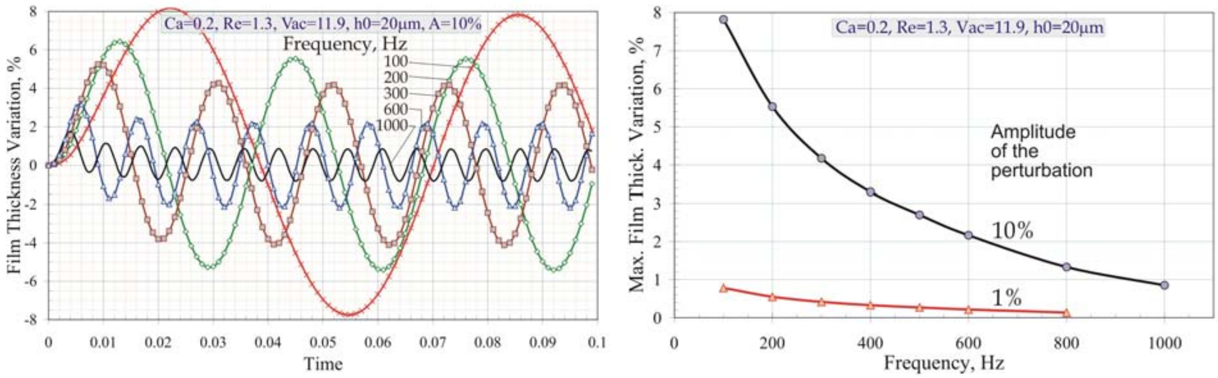

Figure 6 – Variation of the liquid layer thickness with the amplitude of the perturbation.

Figure (6) plots the variation of coating film thickness at frequencies ranging from 100 Hz to 1000 Hz. The results show that the higher the frequencies of the ongoing disturbances of flow rate, the lower the film thickness variation.

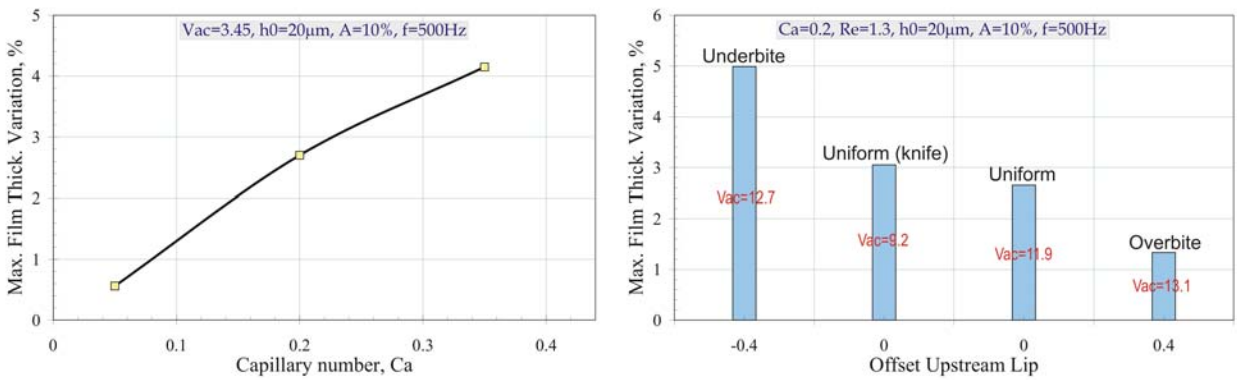

Figure 7 – Variation of the liquid layer thickness with the amplitude of the perturbation.

The influence of the capillary number in the amplitude of the film thickness variation is plotted in Fig. (7-a). The flow becomes more sensitive to flow rate oscilation as the capillary number rises. Similar analysis was performed with the different die configurations presented before. The amplitude of the film thickness oscilation as a function of the geometry is presented in Fig.(7-b). At this set of conditins, the overbite configuration was the least sensitive one.

References

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