Response of two-layer slot coating flows to periodic external disturbances

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1. Introduction

Multilayer slot coating is one of the different coating methods largely used in the manufacturing process of many different products. It reduces the production cost because different liquid layers are applied in a single pass and solidified together. Two-layer slot coating consists in depositing two thin uniform liquid layers onto a moving substrate through different feed slots. The two liquid phases are separated by an interlayer attached to the die surface, as shown in Fig. 1.

The flow into the coating bead is strongly affected by the operating conditions such as coating gap, flow rate of each layer, web speed, vacuum pressure, liquid properties and die configuration.

The region in the space of operating parameters of a coating process where the delivered liquid layer is adequately uniform is usually referred to as coating window. Knowledge of coating windows for different coating methods is needed in order to predict, in steady state regime, whether a particular method can be used to coat a given substrate at a prescribed production rate. There has been different analyses, both theory and experiments, trying to understand the boundary of this process to determine at which conditions is possible to have a two dimensional flow, steady state flow and stable flow.

A lot is known about steady-state operation and limits of operability of slot coating process but coating uniformity requirements is becoming more severe as new products come into the market. In optical films, for example, the film thickness variations should typically be less than 1% of the film thickness. Multi-layer slot coating has to be designed not only based on the steady state operation, but also taking into account how the flow responds to ongoing external disturbances. These disturbances may lead to thickness variation on each deposited liquid layer that may be unacceptable for product performance.

In a manufacturing plant, there are inherent periodic disturbances at different frequencies that influence the uniformity of the coated layer. In the particular case of slot coating process, the ongoing disturbances are usually periodic variations on the coating gap, web speed, vacuum pressure and flow rate fed. It is important to know how sensitive is the steady flow to these disturbances, even if the flow is stable with respect to them and to determine many different sets of operating conditions inside the coating window for a given product specification, which one will produce a more uniform final deposited layer. Once the flow response is known, the process may be designed and optimized to minimize the coating thickness oscillation.

The sensitivity of single-layer slot coating flows to periodic disturbance was analyzed experimentally by Joos (1999). The flow was excited by imposing an oscillatory variation on the flow rate and vacuum pressure at different frequencies and the downweb variation of the coating thickness was measured at each condition. The results show how the amplitude of the film thickness variation changes with the frequency of the imposed disturbance.

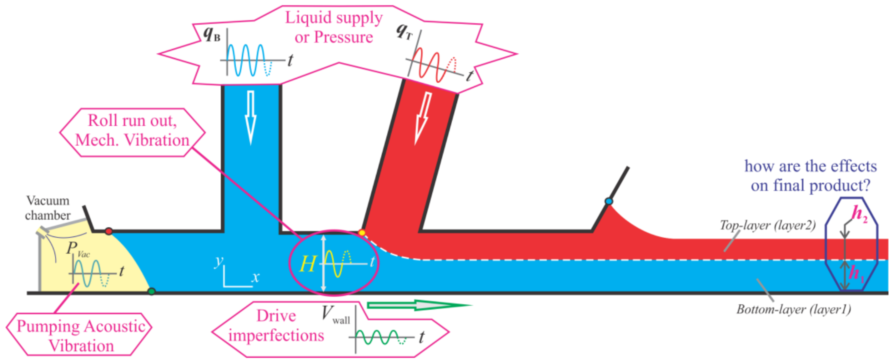

Figure 1. Simplified schematic of two-layer slot coating.

Romero and Carvalho (2008) solved the transient flow to analyze the film thickness oscillation in single layer coating process due to periodic variation on the flow rate fed into the coating die and on the coating gap. The analysis showed the most dangerous frequencies for each type of disturbance and the die configuration may be altered in order to reduce the sensitivity of the flow to periodic disturbances. Perez and Carvalho (2010) have used the predictions of the transient flow to evaluate the objective function of a bound-constrained optimization problem in order to determine the values of vacuum pressure and coating gap, the two easiest parameters to control in a coating line, that minimize the amplitude of the film thickness oscillation at a fixed web speed and flow rate.

Previous analyses did not discussed how external disturbances affect the final thickness of each layer in two-layer slot coating process and which die lip configuration minimizes the amplitude of the film thickness variation.

2. Mathematical Formulation

The mathematical formulation of transient slot coating flow was presented in detail by Romero and Carvalho (2008) and Nam and Carvalho (2010); it is only briefly summarized here.

The velocity v and pressure p fields of the transient, two-dimensional, incompressible flow are governed by the continuity and momentum equations for each layer:

$\nabla \cdot \mathrm{v} = 0$ and $\rho_i (\partial \mathrm{v} / \partial \mathrm{t} + \mathrm{v} \cdot \nabla \mathrm{v}) - \nabla \cdot \mathrm{T}_i = 0.$

Where ρ_i is the liquid density. The total stress tensor for Newtonian liquids is $\mathrm{T}_i = -\mathrm{p}\mathbf{I} + \mu_i[\nabla \mathrm{v} + (\nabla \mathrm{v})^{\mathrm{T}}]$, where μ_i is the liquid viscosity. Here, subscript *i* defines the two liquid phases, *i* =1 for the Bottom layer and 2 for the top layer. Because of the small dimensions of the flow, body forces are usually neglected in coating flows.

Boundary conditions are needed to solve the Navier-Stokes system. In a two-layer slot coating flow, the domain is bounded by inflow and outflow planes, solid walls and free surfaces (gas-liquid interfaces) and the surface that separates the two liquids, the inter-layer, as shown in figure 1.
In this analysis, the steady state solution of the flow was used as the initial condition for the transient analysis $\mathrm{v}(\mathrm{t}=0) = \mathrm{v}_0,\ \mathrm{p}(\mathrm{t}=0) = \mathrm{p}_0$. The initial condition had to be computed at each set of operating parameters. Periodic disturbances on the operating parameters lead to a transient response of the flow. The thickness of the each deposited liquid layer $\mathrm{h}_i(\mathrm{t})$ varies periodically around the steady state value $\mathrm{h}_i(0)$, leading to a non-uniform film along the downweb direction $\mathrm{h}_i = \mathrm{h}_i(0) + \mathrm{h}_{im}\sin(\omega \mathrm{t} + \phi_i)$. The amplitude of the oscillation h_{im} and the phase lag of the thickness response ϕ_i are unknown and need to be determined for each condition. The ratio of the relative amplitude of the film thickness oscillation to the imposed operating parameter disturbance (λ) is called the amplification factor α_{ij} defined as: $\alpha_{ij} = [\mathrm{h}_{im}/\mathrm{h}_{i0}]/\lambda_j$, where λ_j is associate with the source of the disturbances and represent the relative

amplitude of the disturbance parameter. Here, subscript *j* defines different disturbances, *j* = q for the flow rate, *j* = H for the gap and *j* = V for the web speed oscillation. For example: $\lambda_H = H_m/H_0$.

Flows with free surfaces and inter-layer give rise to a free-boundary problem. The flow domain is unknown a priori, and it is part of the solution. To solve a free-boundary problem by means of standard techniques for boundary value problems, the set of differential equations and boundary conditions posed in the unknown physical domain have to be transformed to an equivalent set defined in a known, fixed computational domain. This transformation is made by a mapping x = x(ξ) that connects the two domains. The physical domain is parameterized by the position vector x =(x, y) and the reference domain by ξ = (ξ, η). The mapping used here is the one described by de Santos (1991).

The system of governing equations together with the appropriate boundary conditions and initial condition was solved by Galerkin's method with quadrilateral finite elements. The temporal discretization of the set of ordinary differential-algebraic equations follows the first-order fully implicit Euler method. A mesh with 1,120 elements (22,228 degrees of freedom) was considered satisfactory and was used to obtain the solutions reported here. To keep the error less than 2%, a time step of $\Delta t \approx 70\omega$ was adopted in all computations, i.e. 140 time steps were used per cycle of the imposed periodic perturbation.

3. Results

Different die lip configurations are disclosed in the patent literature claiming to improve production rate and maintain a stable flow (Sartor et al.,1998). Transient response with the three die lip configurations shown in Fig.2a were obtained to determine the effect of die geometry on the film thickness oscillation.

Figure 2b shows how the amplification factor varies with the frequency of the imposed bottom flow rate oscillation. The results were obtained at $Ca \equiv \mu_i W_{vel}/\sigma = 0.42$, $Re \equiv \rho_i W_{vel} H_0/\mu_i = 12$, $Vac \equiv P_{Vac} H_0/\sigma = 6.25$, $G_1 \equiv H_0/h_1 = 2$ and $G_2 \equiv H_0/h_2 = 4$. The amplitude perturbation was $q_{1m} \equiv 0.1 q_{10}$ and $f =< 0.1 - 1000 >$ Hz.

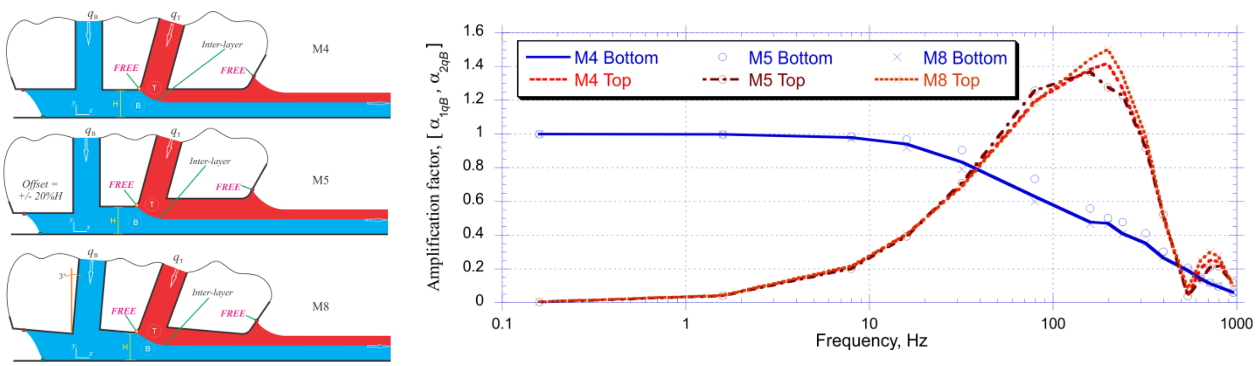

Figure 2. a) Different die lip configurations, as described in Sartor et al. (1998). b) Amplification factor as a function of the frequency of the bottom flow rate perturbation.

At low frequencies, i.e. $f \leq 1$ Hz, the quasi-steady limit is recovered. In this regime, the coated film thickness of the bottom layer h_1 is proportional to the imposed flow rate q_1 and consequently the amplification factor is equal to $\alpha_{1qB} \approx 1$ and the film thickness of the top layer h_2 remains virtually constant in the downweb direction, the oscillation is completely damped. At a frequency of $f \geq 10$ Hz, the diffusion of momentum occurs in a time scale comparable to the imposed perturbation and the amplification factor of the bottom layer decrease monotonically as the frequency rises. On the other hand, the film thickness of the top layer rises with frequency until reaching a maximum $\alpha_{2qB} \approx 1.42$ for M4 and $\alpha_{2qB} \approx 1.5$ for M8 at a frequency (natural frequency) approximately $f \sim 200$ Hz. The other hand the maximum gain obtained with M5 is $\alpha_{2qB} \approx 1.37$ at 170Hz. At the conditions reported here, the bottom flow rate oscillation leads to a variation of the top layer thickness along the downweb direction at those maximum gains, which may be unacceptable for many different products. However, above the natural frequency, the amplification factor

α_{2q} decrease as the frequency rises before a second resonance frequency (close to 750 Hz) that excites an amplitude of 0.25 for M4, 0.21 for M5 and 0.3 for M8. Results show that the frequency of the flow rate of the bottom layer should be kept below 40 Hz or above 300 Hz in order to avoid the resonance. For practical reason the selection of the pump size and pump rotation should be such that these critical frequencies should be avoided in operation. Comparing this prediction with single layer coating analysis obtained by Romero (2008) we can conclude the top layer behavior is similar to gap disturbance in single layer coating and the bottom layer behavior is similar to flow rate disturbance in single layer as well.

The viscosity ratio between the two layers and the steady state film thickness have strong effect on the pressure distribution in the coating bead and consequently on the transient response of the flow. Figure 3 presents the amplification factor for both layers related to oscillation on the bottom layer flow rate for different viscosity ratios and top layer film thickness. In the base case (lable M4), presented in Fig.2, both layers had the same viscosity and the top layer film thickness was ¼ of the coating gap (G2 = 4). Label M4m represents predictions at viscosity ratio $\mu B/\mu T = 5$ (G2 = 4), and lable M4t8 represents the predictions at top layer film thickness equal 1/8 of the coating gap (G2 = 8). Prediction shows that the top layer is less sensitive when the bottom layer is more viscous. The viscous forces damp the flow perturbation. The flow becomes more sensitive to bottom layer flow rate fluctuations as the top layer flow rate falls.

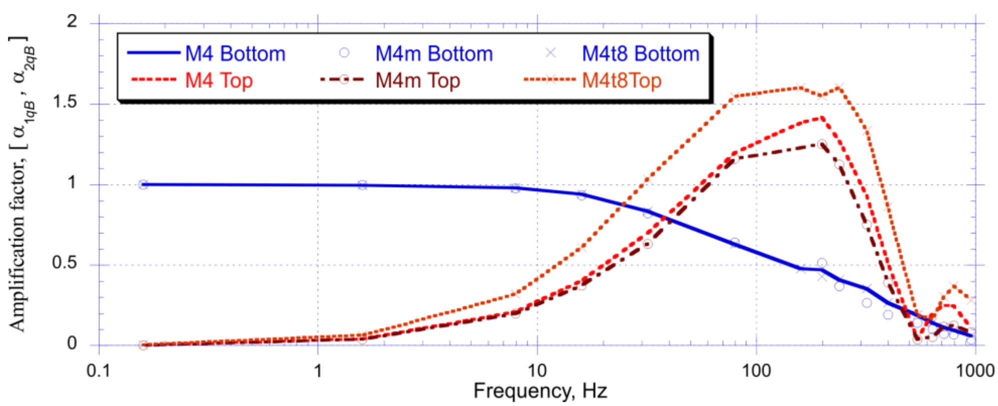

Figure 3. Comparison between M4, M4m and M4t8 in bottom flow rate perturbation.

4. Final Comments

The results show that the operating conditions can have a strong influence on the transient response of the flow to periodic perturbations. Therefore, two-layer slot coating process should be design based not only on the steady state operation, but also on how the flow responds to always present periodic oscillations on the different operating conditions.

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