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

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Abstract. Coating uniformity requirements is becoming more severe as new products come into the market. Multi-layer slot coating has to be designed and optimized not only based on the steady state operation, but also taking into account how the flow responds to ongoing disturbances, such as flow rate, gap or vacuum pressure oscillations. These disturbances may lead to thickness variation on each deposited liquid layer that may be unacceptable for product performance.

This study extends available transient analysis of single layer slot coating to determine the amplitude of the oscillation of each individual coated layer obtained by two layer slot coating in response to small periodic variation on the coating gap, web speed and flow rate as a function of process conditions and frequency of the perturbation.

The predictions are obtained by solving the complete transient Navier-Stokes equations for free surface flows. The results indicate how the process conditions can be optimized to minimize coating thickness variation of each individual layer.

Keywords: Multilayer coating, Periodic disturbances, Galerkin/FEM, Transient response, Free surface flow.

1. Introduction

Two-layer slot coating is one of different coating methods largely used in the manufacturing process of medical, optical and electronics products. The process consists in depositing two thin uniform liquid layers onto a moving substrate through different feed slots. The two liquid phases are separated by an inter-layer attached to the die surface as shown in Figure 1. When both liquids are immiscible they form an inter-layer inside the coating bead. But, when both layers are miscible, as in several coating applications, they form an inter-diffusion zone. Because of the small dimensions and large web speed, it can be considered as an inter-layer with zero interfacial tension.

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 whether a particular method can be used to coat a given substrate at a prescribed production rate.

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. Multi-layer slot coating has to be designed and optimized not only based on the steady state operation, but also taking into account how the flow responds to ongoing disturbances, such as flow rate, gap, vacuum pressure or web speed oscillations. 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

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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.

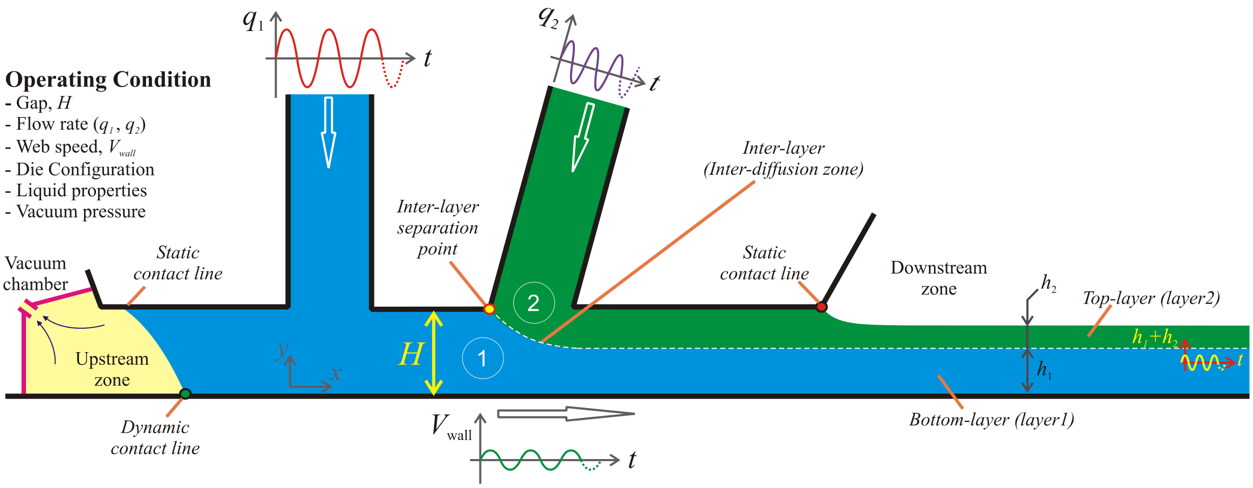

Figure 1. Simplified schematic of two-layer slot coating.

Initially 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.

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.

In this work, we extend available transient analysis of single layer slot coating to determine the amplitude of the oscillation of each individual coated layer obtained by two layer slot coating in response to small periodic variation on the coating gap, web speed and flow rate as a function of process conditions and frequency of the perturbation.

2. Mathematical Formulation

The mathematical formulation of the 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 $\mathbf{v}$ and pressure p fields of the transient, two-dimensional, incompressible flow are governed by the continuity $\nabla \cdot \mathbf{v} = 0$, and momentum, $\rho_i(\partial \mathbf{v}/\partial t + \mathbf{v} \cdot \nabla \mathbf{v}) - \nabla \cdot \boldsymbol{T}_i = \mathbf{0}$, equations for each layer. Where ρ_i is the liquid density. The total stress tensor for Newtonian liquids is $\mathbf{T}_i = -p\mathbf{I} + \mu_i[\nabla \mathbf{v} + (\nabla \mathbf{v})^{\mathrm{T}}]$, where μ_{i} is the liquid viscosity. Here, subscript i defines the two liquid phases, i =1 for the top layer and 2 for the bottom 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.

Initial condition is needed in order to solve the transient flow. In this work, the steady state solution of the flow was used as the initial condition for the transient analysis $\mathbf{v}(t = 0) = \mathbf{v_0}$, $p(t = 0) = p_0$, this initial condition had to be computed at each set of operating parameters. The periodic disturbance on the flow rate leads to a transient response of the flow. The thickness of the each deposited liquid layer $h_i(t)$ varies periodically around the steady state value $h_i(0) = q_i(0)/W_{vel}$, leading to a non uniform film along the downweb direction $h_i = h_i(0) + h_{im}\sin(\omega t + \phi_i)$. 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 parameters disturbance (λ) is called the amplification factor defined as: $\alpha_{ij} = [h_{im}/h_{i0}]/\lambda_j$, 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 $j = w$ 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 $\mathbf{x} = x(\boldsymbol{\xi})$ that connects the two domains. The physical domain is parameterized by the position vector $\mathbf{x}$ =(x, y) and the reference domain by $\boldsymbol{\xi} = (\xi, \eta)$. 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 $\Delta t \approx 60\omega$ was adopted in all computations, i.e. 120 time steps were used per cycle of the imposed periodic perturbation.

3. Results

As mentioned before, the initial condition for the transient analysis was the steady-state flow at a given set of parameters. Once a steady-state solution was obtained, a periodic variation on the flow rate with a prescribed amplitude and frequency was imposed. The results presented here show the flow response to these perturbations as a function of the film thickness.

Figure 2 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.

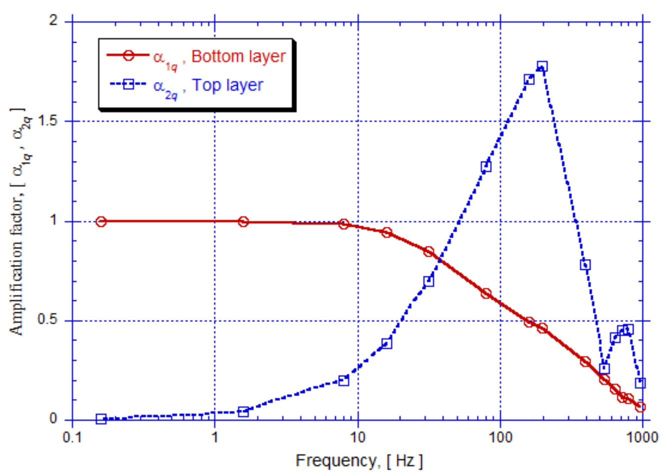

Figure 2. Amplification factor as a function of the frequency of the bottom flow rate perturbation.

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 $\alpha_{1q} \approx 1$ and the film thickness of the top layer h_2 keep going 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 it reaches a maximum $\alpha_{2q} \approx 1.8$ at a frequency (natural frequency) of approximately $f \sim 200$ Hz. At the conditions reported here, this oscillation would cause a variation of the top layer thickness along the downweb direction almost double of the flow rate oscillation, which may be unacceptable for many different products. However, after this natural frequency prediction shows the amplification factor α_{2q}decrease as the frequency rises. The result shows that the frequency of the flow rate of the bottom layer should be kept below 40 Hz or above 400 Hz in order to avoid the resonance.

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.

Figure 3 shows the sensitivity to flow rate of top layer. The amplitude perturbation was $q_{2m} \equiv 0.1q_{20}$. Fig. 3 clearly shows that the bottom layer flow is insensitive to this disturbance. The top layer decrease monotonically as the frequency rises and the bottom layer remain constant at different frequencies.

The results show that the flow response is a strong function of the frequency of the imposed flow rate perturbation. Disturbances at low frequencies are damped and there is a critical frequency at which they are amplified. The selection of the pump size and pump rotation should be such that these critical frequencies should be avoided in operation.

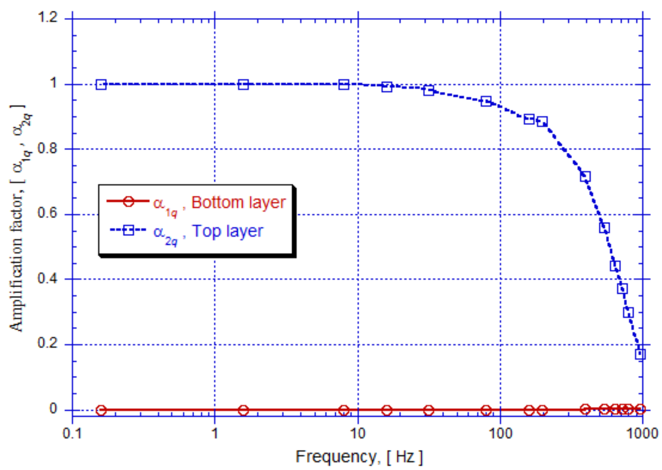

Figure 3. Amplification factor as a function of the frequency of the top flow rate perturbation. The predictions were at Ca= 0.42, Re=12, Vac=6.25, G_1=2, G_2=4, and q_{2m}=0.1q_{20}.

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