Adjusting the coating gap and vacuum pressure to minimize periodical thickness variation in the slot coating process

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Introduction

Slot coating is commonly used in the manufacturing of many different products. The coating liquid is precisely pumped to a coating die that has a narrow uniform slot from which the liquid is delivered. Exiting the slot, the liquid fills the gap between the die lips and the moving substrate. The liquid in the gap, bounded upstream and downstream by gas liquid interfaces, or menisci, forms the coating bead, as shown in Fig.1. In order to sustain the coating bead at higher substrate speeds and thinner films, the gas pressure upstream of the upstream meniscus is made lower than ambient, i.e. a slight vacuum P_{vac} is applied to the upstream meniscus. In stead-state slot coating, the thickness of the coated 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, therefore ideal for high precision coating.

Slot coating process needs to be designed and optimized not only based on the steady-state operation, but also based on the sensitivity of the flow to small ongoing disturbances. Coating gap oscillation is a souce of disturbance always present in the manufacturing operation.

Transient Slot Coating Flow

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, $\rho\left(\partial \mathbf{v}/\partial \mathbf{t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) - \nabla \cdot \mathbf{T} = 0$, equations. Where ρ is the liquid density. The total stress tensor for Newtonian liquids is $\mathbf{T} = -p\mathbf{I} + \mu[\nabla \mathbf{v} + (\nabla \mathbf{v})^{\mathrm{T}}]$, where μ is the liquid viscosity. Because of the small dimensions of the flow, body forces are usually neglected in coating flows.

The flow domain and its boundaries are shown in Fig. 1. The distance between the coating die and the moving substrate is called the coating gap. The imposed periodic oscillation of the gap $H(t)$ around the steady state value H_0 is taken to be sinusoidal, $H(t) = H_0 + H_m \, \sin(\omega \, t)$, where H_m is the amplitude of the imposed periodic disturbance and ω its angular frequency, which is related to the frequency f by $w = 2\pi f$.

At the inflow plane (1), a parabolic velocity profile with a prescribed flow rate q is imposed. The no-slip and no-penetration conditions are used along the solid surfaces; along the die lips and feed slot walls (2): $\mathbf{v} = \mathbf{0}$; and along the moving web (3): $u = V_w, \; v = H_m \omega cos(\omega \, t)$. V_w is the substrate velocity. The vertical component v of the substrate velocity is associated with the gap oscillation. For the cases at which the gap is constant, it is identically zero. Along the free surfaces (4), the traction in the liquid balances the capillary pressure, $\mathbf{n} \cdot \mathbf{T} = \frac{1}{Ca}\frac{d\mathbf{t}}{ds} - \mathbf{n}P_{atm}$ and there is no mass flow rate across the gas-liquid interface (kinematic condition). The downstream static contact line (5) is pinned to the sharp edge of the die. The upstream static contact line (6) is free to slide along the upstream die face with a specified upstream static contact angle $\theta_u = 110^0$. At the dynamic contact line (7), the Navier-slip is used to remove

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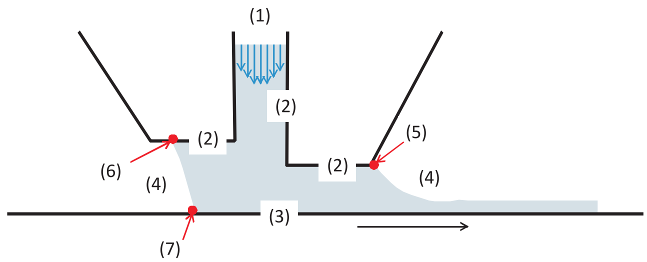

Figura 1: Boundaries of the flow domain.

the stress singularity and a prescribed dynamic contact angle $\theta_d = 60^0$ is imposed. The resulting thickness oscillation did not change significantly when assuming values of θ_u and θ_d around those prescribed above.

The steady state solution of the flow at the mean value of coating gap H_0 was used as the initial condition for the transient analysis.

The periodic disturbance on the coating gap leads to a transient response of the flow. The thickness of the deposited liquid layer $h(t)$ varies periodically around the steady state value $h_0 = q/V_w$, leading to a non uniform film along the downweb direction, $h(t) = h_0 + h_m \sin(\omega t + \Phi)$. The amplitude of the oscillation h_m and the phase lag of the thickness response Φ are unknown and need to be determined for each condition. The ratio of the amplitude of the film thickness oscillation to the amplitude of the imposed gap disturbance is called the *amplification factor* α_h, defined as $\alpha_h = h_m/H_m$.

The system of governing equations together with the appropriate boundary conditions was solved by Galerkin's method with quadrilateral finite elements. The temporal discretization of the set of ordinary differential-algebraic equations follows a predictor-corrector algorithm and the resulting set of nonlinear algebraic equations at each time is solved simultaneously by Newton's method.

Results

Dimensionless groups may be determined from the x-component of the momentum equation. They are: H_0/h_0; H_m/h_0; $Ca = \mu V_w/\sigma$; $Re = \rho V_w H_0/\mu$; $P_{vac} h_o/\mu V_w$ and $\omega H_0/V_w$.

When the dimensionless groups are kept constant and the frequency is replaced by the quantity $k = 2\pi f/V_w$ (wavenumber), which dimension is $[mm^{-1}]$, there is a good match among all curves of amplification factor against wavenumber for any process conditions and liquid properties. Besides providing the horizontal match of the curves with same dimensionless groups, the wavenumber provides a valuable reference to guide the process engineer on choosing the proper adjust of the process parameters in order to reduce the film thickness oscillation.

The frequency of the film thickness oscillation is exactly the same of the gap oscillation. This fact is of great pratical application, because measuring the wavelenght of the film thickness oscillation λ and knowing the web speed V_w, it is possible to determine the coating gap oscillation frequency by $f = V_w/\lambda$ [Hz] and in this way determine the wavenumber k of the coating gap oscillation.

The existing control parameters to dampen the effect of the gap oscillation are:

1. Geometric: lenght and angles of the die lips;
2. Liquid properties: Capillary and Reynold numbers;
3. Process: coating gap, upstream vacuum pressure and web speed.

Geometric parameters have significant impact on the amplification factor of the film thickness but this effect will not be shown here.

A sequency of contour plots of the amplification factor in a space of coating gap and vacuum pressure is shown on Fig. 3, for different wavenumbers. As the wavenumber increases, the region of optimum adjusts move to lower dimensionless gaps H_0/h_0. For wavenumbers greater than aproximately unit, the good adjusts are, most of the times, in the bottom left corner of the window (lowest gap and vacuum pressure).

The important result from the computer aided simulations made with several different die geometries is that the behavior of the contour plots with increasing wavenumbers follow the same trend of Fig. 3 for any geometry. More

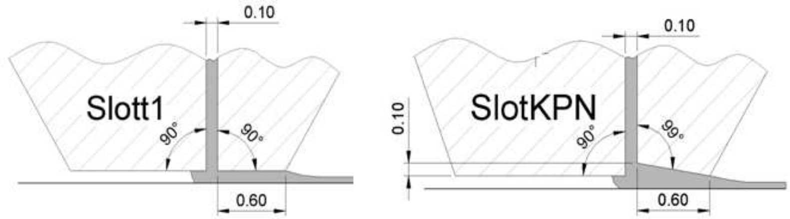

Figura 2: Die geometries used for drawing the contour plots of the Fig. 3 and Fig. 4

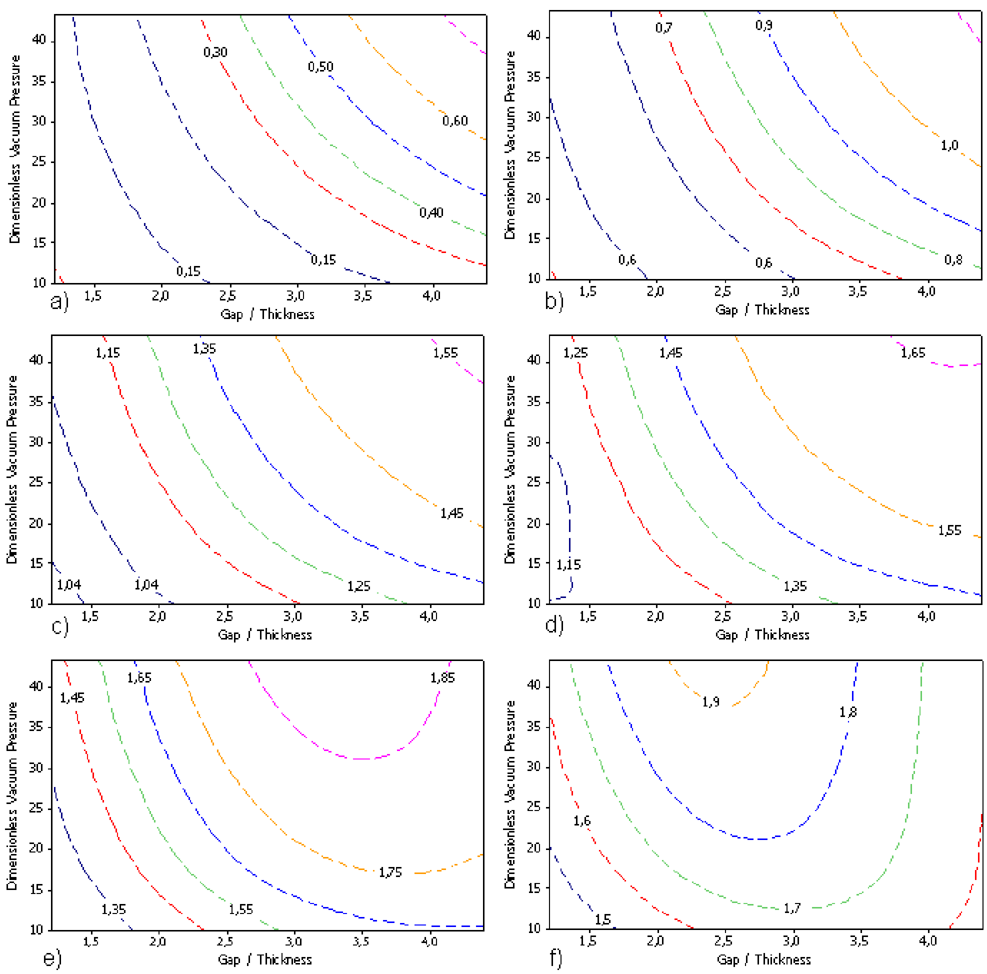

Figura 3: Sequency of contour plots of the amplification factor α_h showing the influence of the wavenumber. Die geometry is Slott1 from Fig. 2 and liquid properties $Ca = 0.20$ and $Re/H_0 = 3.33mm^{-1}$. a) $k = 0.19$ b) $k = 0.63$ c) $k = 0.94$ d) $k = 1.13$ e) $k = 1.88$ f) $k = 3.14$.

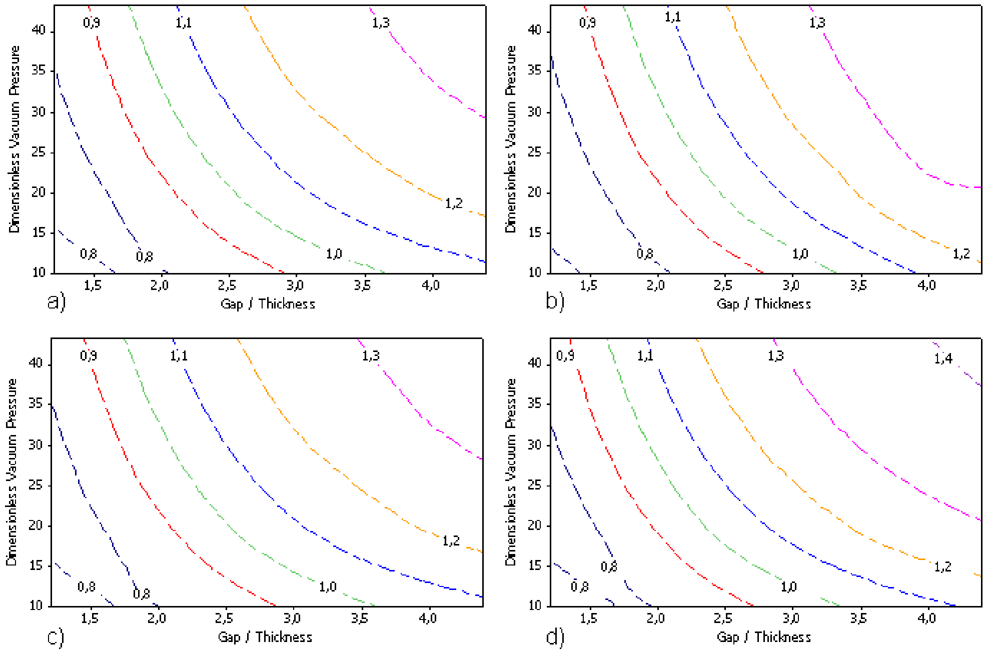

Figura 4: Contour plots of the amplification factor for the die geometry SlotKPN from Fig. 2, wavenumber $k = 0.94$. a) $Ca = 0.20$ and $Re/H_0 = 3.33mm^{-1}$ b) $Ca = 0.40$ and $Re/H_0 = 3.33mm^{-1}$ c) $Ca = 0.20$ and $Re/H_0 = 6.66mm^{-1}$ d) $Ca = 0.20$ and $Re/H_0 = 3.33mm^{-1}$, V_w is 2 times V_w of item a.

than this, the transition wavenumbers, where the window of optimum adjusts disapear from the contour plots are always around the unit. Absolute values of the amplification factor change depending on the geometry as is expected.

Changing liquid properties do not change much the contour plots of the amplification factor α_h since the wavenumber is kept constant, as shown in Fig. 4a, b and c. Finally, in Fig. 4d the web speed is two times the web speed in Fig. 4a but same wavenumber, capillary and Reynolds numbers.

A general guidance for adjusting the process parameters based on wavenumber k is given by:

- if $k < 1$ there is a range of optimum adjust for the coating gap and this range tends to lower values as k increases. After setting the coating gap, work on vacuum pressure to fine tune the adjust.
- if $k > 1$ set the coating gap and the vacuum pressure to the lower possible value.

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