Analysis of periodical thickness variation on slot coating

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Introduction

Products requiring high precision continuous coatings, such as optical films, are common in the coating industry. In most cases, final coating thickness variation higher than 2% is not acceptable. Slot coating is one of the preferred methods when high precision is required and several studies focusing on its steady state analysis were made to determine the operating window of the process. However, full understanding of coating flows requires not only the two-dimensional, steady state solution of the governing equations, but also the sensitivity of those flows to small upsets.

An effort to understand the impact of the coating gap periodic oscillation on down web thickness variation is made using computer aided simulation. Different slot die lip geometries and process conditions are tested and the respective amplification factors as a function of gap oscillation frequencies are reported. The liquid is assumed Newtonian and computations are made at low capillary and Reynolds numbers.

The transient free surface flow with appropriate boundary conditions is solved by the Galerkin / finite element methods, with time integration by a predictor-corrector algorithm. The set of non-linear algebraic equations for the finite element basis functions coefficients at each time step is solved by Newton's method.

Problem description

Periodical coating gap oscillation can be caused by back up roll run out or external sources of vibration not properly dampened by the die mounting structure. Coating gap oscillation ($H(t)$) is modeled as a sine function where H_0 (here 0.100mm) is the coating gap at steady state and H_m (here 0.010mm) is the oscillation amplitude.

$$H(t) = H_0 + H_m sin(\omega t) \qquad h(t) = h_0 + h_m sin(\omega t + \phi) \qquad \alpha(\omega) = \frac{h_m(\omega)}{H_m} \tag{1}$$

The final response of the flow to the gap oscillation is a down web coating thickness variation $h(t)$, at which the amplitude (h_m) depends on the gap oscillation frequency (ω). As shown by Romero and Carvalho (2007), the frequency of the thickness variation is the same of the coating gap oscillation, although a phase lag (ϕ) may exist. Coating thickness at steady state (h_0) is set to 0.050mm.

At each frequency the amplification factor $\alpha(\omega)$, which gives the ratio between the amplitude of the down web coating thickness variation to the coating gap oscillation, can be calculated from the transient response of the flow.

The goal is to find die lip designs and process conditions that reduce the amplification factor over the entire frequency range, or at least, in a small range of interest.

Computer Aided Analysis

A two-dimensional view of slot coating bead is depicted in Fig.1.

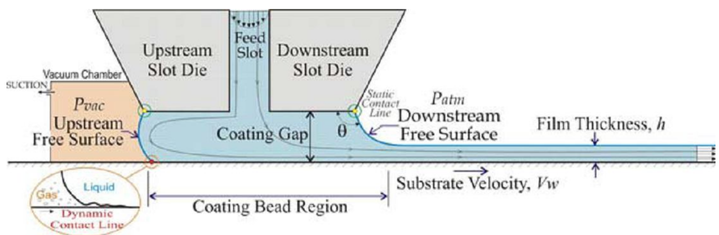

Figure 1 – Two-dimensional view of slot coating die (Romero, ISCST 2006)

Four different die designs (Figure 2) were considered. The geometric variables are the upstream coating gap (H_u), downstream coating gap (H_d), downstream lip length (L_d) and convergence angle of downstream lip (β_d). Downstream static contact line is assumed pinned at downstream corner of the die lip, while upstream static contact line is free to move under the upstream die lip, with a prescribed angle.

Die Code	H_u ***(mm)***	H_d ***(mm)***	L_d ***(mm)***	β_d ***(degree)***	H_f ***(mm)***	L_u ***(mm)***
Slott1	0.100	0.100	0.600	0.00	0.100	0.600
Slott2	0.150	0.100	0.600	0.00	0.100	0.600
Slott1D1	0.100	0.100	0.300	0.00	0.100	0.600
Slott1DC	0.100	0.100	0.600	18.43	0.100	0.600

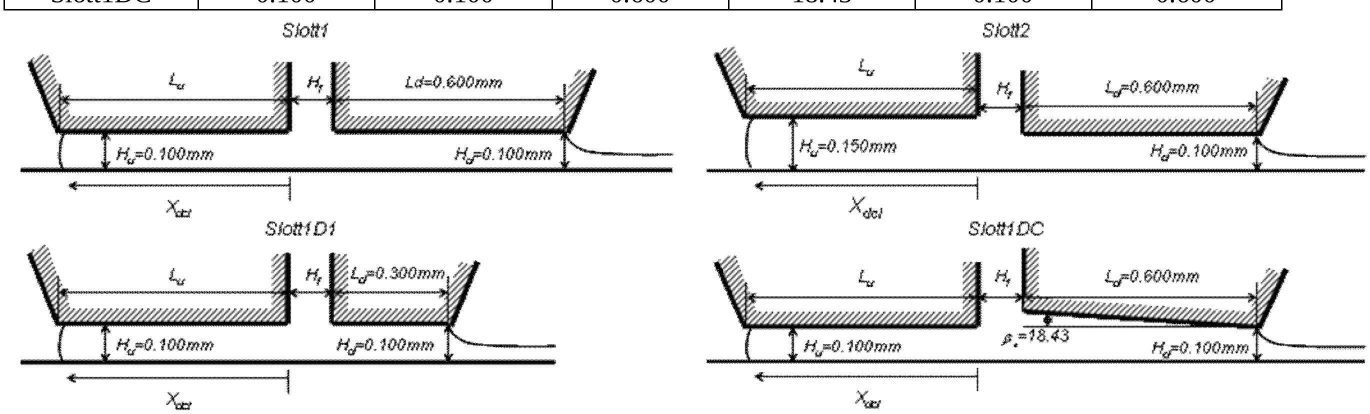

Figure 2 – Die lip design

The position of the dynamic contact line (dependent on vacuum level) and the capillary number are the two process parameters considered.

$Ca=\frac{\mu V}{\sigma}$	X_{dcl} (mm)	$Re=\frac{\rho V H_d}{\mu}$	$Vac=\frac{PvacH_d}{\sigma}$	*Pvac* (Pa)	V_w (m/min)	μ (cps)	ρ (Kg/l)	σ (dyn/cm)
0.05	0.6	0.33	2.33	-1380	6	30	1	60
0.05	0.2	0.33	1.17	-700	6	30	1	60
0.2	0.6	0.33	8.67	-1300	6	30	1	15
0.2	0.2	0.33	4.00	-600	6	30	1	15

Table 1 - Process parameters

Results and discussion

Figures 3 and 4 present the influence of the downstream and upstream die lip design on the amplification factor.

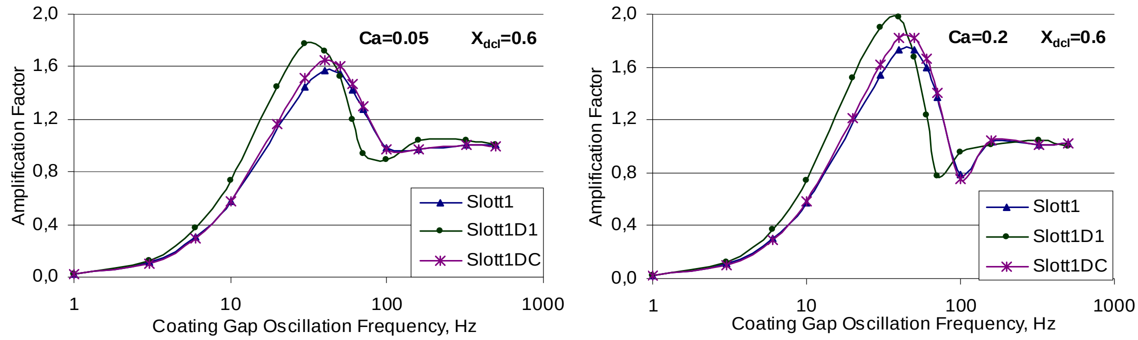

Figure 3- Influence of downstream coating gap on amplification factor

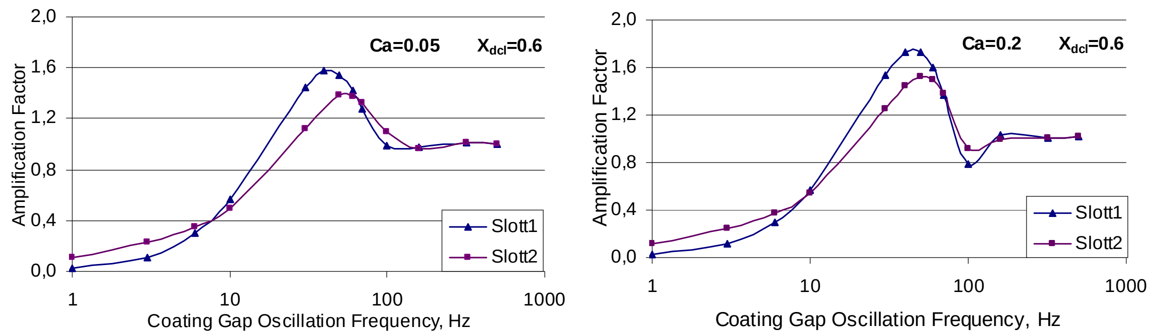

Figure 4- Influence of upstream coating gap on amplification factor

The results suggest that the downstream die lip shapes that promote higher pressure drop lead to smaller amplification factors. Downstream lip shapes with higher pressure drop reduce the impact of gap oscillation on downstream meniscus position, reducing thickness variation.

At low frequencies, the smaller upstream gap showed better results, while at intermediate frequencies the opposite is true. At low frequencies, there is a quasi static regime where the liquid bead responds promptly to gap oscillation and the Poiseuille flow variation under the downstream gap cancel a great part of the variation on Couette flow (which is proportional to gap variation). Higher pressure drop on upstream gap may help to focus the hydrodynamic flow response under the downstream lip.

As frequency rises, process time starts to approach the response time of the system and the thickness variation becomes more related to mass conservation issues. In this situation, lower pressure drop on upstream die lip helps the upstream meniscus to move and oscillate more freely reducing the impact on downstream meniscus. At even higher frequencies the amplification factor becomes approximate one and it is independent of die design and process variables.

Protection of the downstream meniscus from being disturbed seems to be a good design requirement. Figure 5 shows that pulling vacuum seems to be a good option to reduce the amplification factor when gap oscillation is at low frequency. Higher capillary number raises the maximum amplification factor.

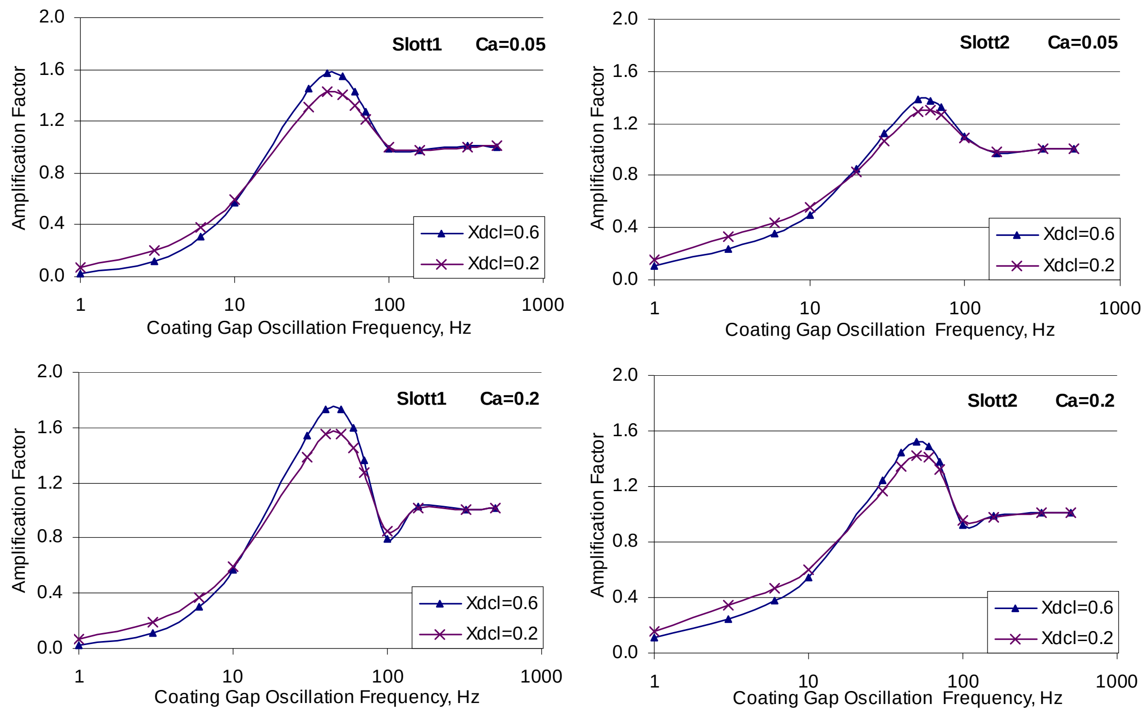

Figure 5- Influence of the position of the dynamic contact line on amplification factor

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