The instability in two-layer slot coating flows

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Introduction

Slot coating is one of the most versatile methods used in the coating industry, because it can precisely deposit a thin uniform liquid film on a flexible substrate at high speeds (Sartor, 1990). Exiting the slot, the liquid fills the gap between the adjacent die lips and the substrate translating rapidly past them. Slot coating can also be used to apply two liquid layers simultaneously (Musson, 2001). In this case, the slot die has two feed slots from which each liquid is fed to the coating bead.

The uniformity of the surface that separates the two liquids, the interlayer, plays a crucial role on the final product quality. The interlayer initiates at a point located on the mid die lip, usually called the separation point. In the ideal configuration, it is pinned at the downstream corner of the mid-lip, promoting cross-web uniformity. However, at some operating conditions, it can move upstream, in what is called mid-gap invasion. At these process conditions, the location of the separation point is usually not uniform in the cross web direction, leading to coating thickness variation. Moreover, the invasion induces microvortices under the mid-lip, mixing the two layers and causing different types of coating defects. Coating defects can also appear even at flow conditions at which the separation point is pinned at the downstream corner of the mid lip. Because of the small gap between the die and the substrate and the high web speed, the interlayer is subjected to enormous shearing. This may lead to flow instabilities in the interlayer that would ruin the final product quality.

Here we study the operating window of dual layer slot coating by determining the conditions at which the separating line is pinned and the two layer rectilinear flow under the downstream lip is stable.

Methodology and results

Mid-gap invasion is studied experimentally by visualizing the coating flow. Through a glass backing roll. The location of the interlayer separation point is marked by blue dye injected through a small port at the downstream shoulder of the mid lip. We found that only the bottom layer flow rate affects the location of the separation point, significantly. The plots of dimensionless bottom layer flow rate versus any operating condition show that the mid-gap invasion occur when the dimensionless bottom-layer flow rate, defined as $h^{*}=h_{w,2}/H_g$, see Fig. 1, is about 0.3. This critical value is supported by the simple lubrication model of parallel mid-lip flow, which yield 1/3.

The solution of Navier Stokes equation for free surface revealed that there are two mechanisms of mid-gap invasion: onset of turn-around flow in the top layer and onset of vortex in the bottom layer. This theoretical model, based on the method of Kistler and Scriven (1984), and de Santos (1991), predicts that the onset of turn-around flow occurs when the top layer is less viscous than bottom layer, and the onset of vortex occurs when the top layer is more viscous than bottom layer. In the onset of turn-around flow, the interlayer separation point moves along the mid-lip, until it reaches the upstream corner of the mid-lip. The location of the point is extremely sensitive to the bottom layer flow rate near the critical condition. In the other case, vortex occurs at the upstream corner of the mid lip near the critical condition, and the size of the vortex grows as the flow rate decreases. When the dimensionless flow rate is about 0.3, the separating streamline which defines the size of the vortex is very close to the interlayer, and leading to mixing of both layers.

Both mechanisms of mid-gap invasion occur near the critical condition, dimensionless bottom layer flow rate equal to 1/3. This condition can be re-written into a critical flow rate ratio condition when the total flow rate is fixed. The condition tells that mid-gap invasion will occur if the ratio of the top layer flow rate to the bottom layer flow rate is bigger than a critical value, which is a function of the total wet-layer thickness and the gap height.

$$h_{w,2} < \frac{H_g}{3} \longrightarrow f = \frac{q_1}{q_2} > \frac{3\,h_{w,t} - H_g}{H_g} \quad \text{When } h_{w,t} \text{ fixed.}$$

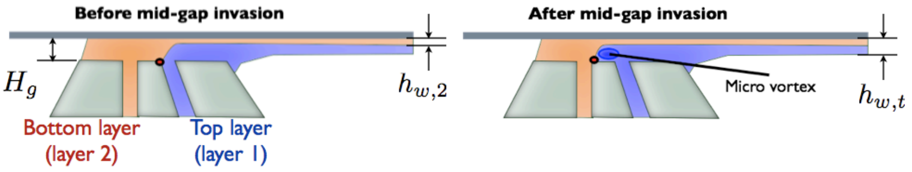


Figure 1. Critical flow rate ratio mid-gap invasion condition

In order to analyze the effect of high shear on the interlayer stability, the flow regime under the downstream die lip is modeled as a parallel channel flow. The interlayer stability of the two-layer rectilinear flow inside the coating bead is determined by following the fate of an infinitesimal disturbance of the flow and the interlayer configuration.

Typically, the interlayer location inside a channel is the independent parameter for the stability analysis (Yiantsios and Higgins, 1989). However, the location cannot be controlled directly. Here, we choose the flow rate ratio as the independent parameter, because it is an operating condition for the coating method. The effect of gravitational force on the flow is neglected and the second independent parameter is the viscosity ratio.

With these independent parameters, we perform linear stability analysis with the method of normal mode (Severtson and Aidun, 1996). For a numerical computation of the growth rate which governs the stability of the flow system, Galerkin finite element method is used to discretize the flow domain and construct a Jacobian matrix for the eigenvalue problem. To handle a large Jacobian matrix efficiently, we use a modified version of the matrix transformation method based on Valério and Carvalho (2007). By solving the eigenvalue problem and examining the eigenvectors, we confirm that a major source of flow instability comes from the interfacial disturbance, or so called the interfacial mode caused by the viscosity difference (Yih, 1967).

From the numerical analysis, we predict the neutral-stability curves that define the region of stable flow as a function of flow rate or viscosity ratio and wavenumber. High wavenumber mode stands for a disturbance with a short wavelength. With the curves, we confirm two effects that suppress unbounded growth of the interfacial mode: thin layer effect and action of interfacial tension. By putting less viscous liquid on relative thin layer, low wavenumber disturbances are effectively damped out (Renardy, 1987). The interfacial tension between the two layers will prevent amplifying high wavenumber disturbance.

According to thin-layer effect, there are two possible stable flow configurations: low flow rate ratio for low viscosity ratio and high flow rate ratio for low viscosity ratio, as in Fig. 2. However, the stable region at high flow rate ratio configuration coincides with the parameters at which mid-gap invasion occurs, i.e. high flow rate ratio above the critical value. Even though the interlayer is linearly stable for the infinitesimal periodic disturbance, coating defect can be introduced by the mid-gap invasion. Therefore top layer should be thin and less viscous to exploit thin-layer effect without invoking mid-gap invasion.

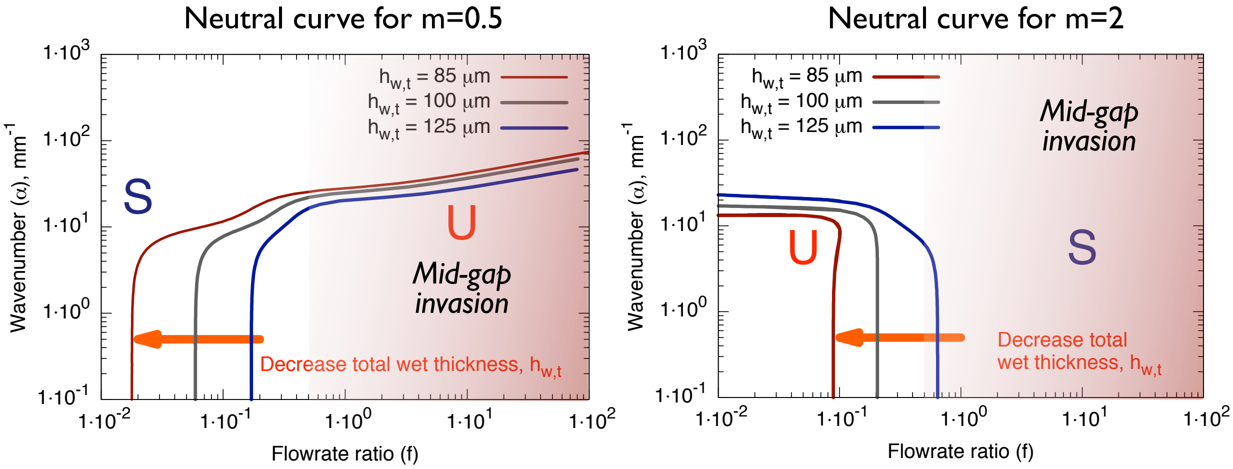
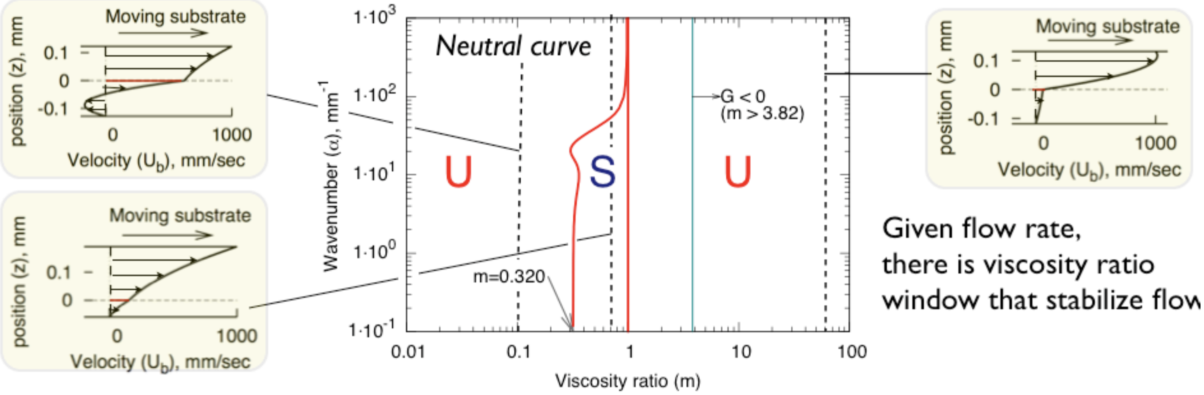


Figure 2. Neutral-stability curves for low and high viscosity ratio (m)

Furthermore, low viscosity ratio does not guarantee stable flow configuration for given flow rate. At fixed flow rate ratio, too low top layer viscosity introduces a turnaround flow at top layer which will increase layer thickness, i.e. top layer is not thin anymore. Hence, at fixed flow rate, there is narrow viscosity ratio window of stable flow.



Given flow rate,
there is viscosity ratio
window that stabilize flow

Figure 3. Neutral-stability curve for fixed flow rate ratio (f)

Reference

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