Two-Layer Coating on Tensioned Web over Slot Die

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Coating tensioned-web running over slot die is an efficient way of depositing thin and uniform layers on flexible web at high speed with a relatively simple set-up, a combination of slot die premetering and carefully controlled web transport. A particularly attractive feature of such tensioned-web coating is that two layers can be coated simultaneously, which makes it possible for one of the layers to be exceptionally thin, and for two layers to be created with less wastage than in tandem single layer operation. Successful two-layer coating from a two-slot die requires not only avoiding bead break-up, but also operating at conditions that fix the separation line of the interlayer zone at a proper position, which is generally the downstream corner of the mid-lip between the two feed slots; otherwise the layer becomes non-uniform [Cohen 1993, Sartor 1998] and microvortexes may be prompted in the coating bead.
Whereas one-dimensional elastoviscocapillary modeling accounts well for the web profile over the die, the gap between web and die lips, and the pressure profile along the gap, full two-dimensional Navier-Stokes theory is necessary to predict separation line location on the mid-lip and occurrence of microvortexes around the feed slots and downstream meniscus. To reduce computational cost, Navier-Stokes model for that region was hybridized with successful elastoviscocapillary model for the regions upstream of the bottom layer feed slot and downstream of the top layer feed slot; i.e. the regions were matched at two suitably positioned planes along the flow and all the governing equations were solved together. Effects of layer flow rate ratio, viscosity ratio, and slot exit shape were examined with the hybrid model.

Compound Foil Bearing Analogy

Coating a tensioned web passing over a slot die can be usefully related to combinations of simpler foil bearing flows [Park et al. ISCST 2004]. The upstream and downstream pressures on conventional foil bearings are both ambient. Those on the component parts of the compound foil bearing analogous to tensioned web-over-slot die are not. So we worked out as functions of bearing curvature, flow rate, and web tension number (elasticity number), the gap and pressure profiles and flow characteristics of back-pressured, forward-pressured, and blocked foil bearings [see poster, Park et al. 2006]. In the last configuration there is no net flow, as over the upstream lip in the coating bead. The results of elastoviscocapillary and hybrid modeling can be well understood in terms of a blocked foil bearing upstream of the first feed slot, a forward- or backward-pressured foil bearing over the mid-lip between the feed slots, and a forward-pressured foil bearing downstream of the second feed slot.

Effect of Feed Rate

As in compound foil bearings, feeding fluid through a slot between simple bearings in series raises the pressure above the feed point in order to drive the added fluid downstream by a steepened pressure gradient and widened clearance. A side effect is to steepen the adverse pressure gradient upstream and thereby widen the clearance in that direction, too. Examples from predictions of the 1D elastoviscocapillary model at different flow rates are shown in Figure 1. The gap over the feed slot is idealized as having constant liquid pressure.

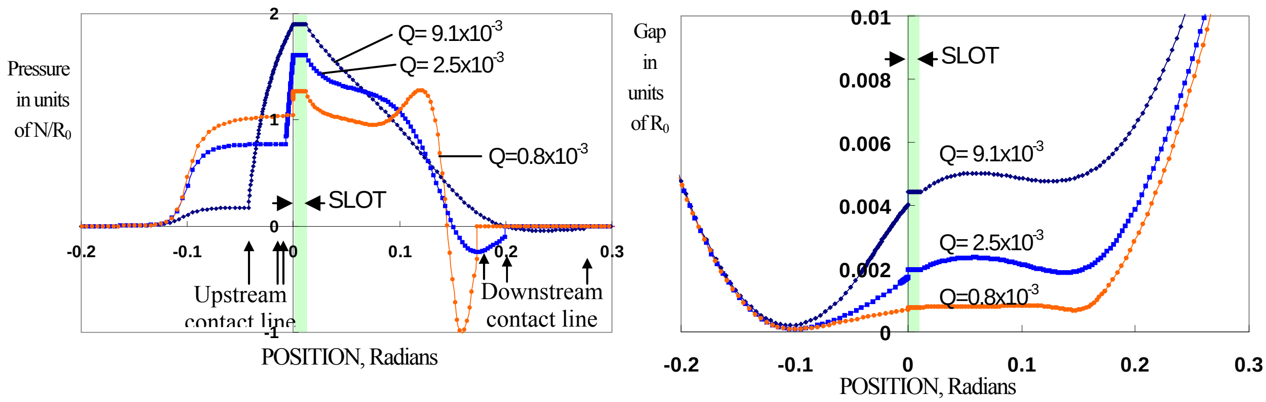


Figure 1. Effect of feed rate (in units of web velocity times half the radius of cylindrical die) on pressure profile and gap profile in single-layer coating of tensioned web over a constant-radius (R_0) slot die at elasticity ($\mu V/N$) = 5×10^{-5}, approach angle = 7°, and departure angle = 12°. N, V, and μ are web tension, web speed, and viscosity of coating liquid, respectively. The upstream and downstream contact lines shift with the operating parameters.

Theoretical Model

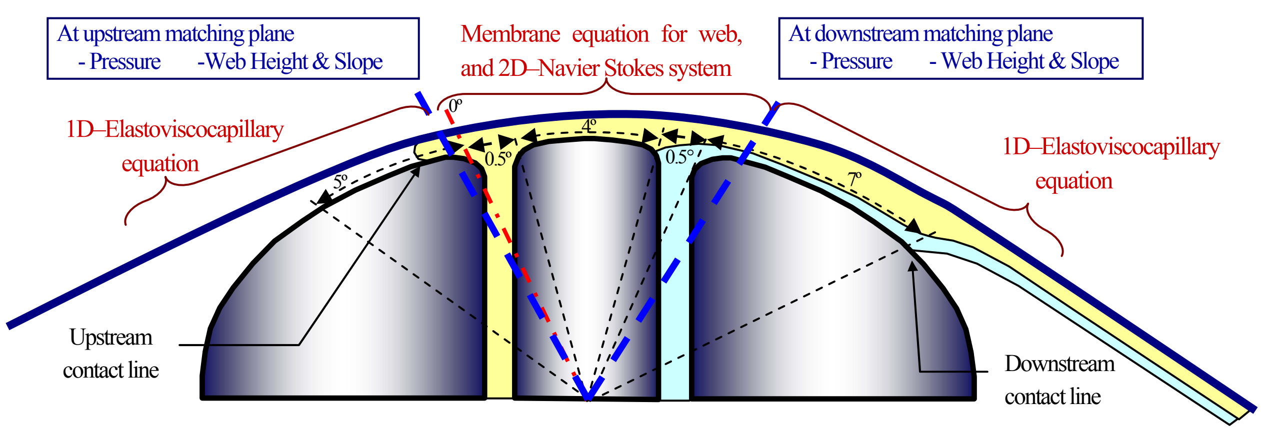
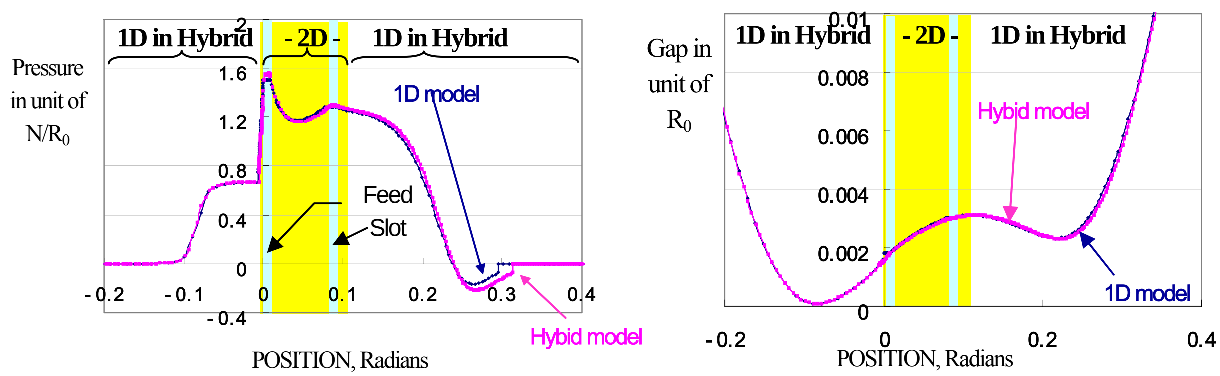


Figure 2. Structure of the hybrid model and matching conditions between its regions. The upstream and downstream contact lines are free to shift at set contact angles; the separation line is free to shift along the midlip.

Much of the gap between the web and the die lip is narrow and slowly varying, as is also the film flow beyond the downstream contact line. Hence the lubrication flow and membrane web approximations in the elastoviscocapillary model is apt and even bridges the turnaround flow at the upstream meniscus. The film-formation region downstream is well represented by the Landau-Levich approximation, another element of the model. But the model is intrinsically incapable of representing the two-dimensional flows around the feed slots, the configuration of the interlayer and the location of the separation line. Hence the full 2D Navier-Stokes system was used to describe the flow in these zones in combination with the elastoviscocapillary model elsewhere, as depicted in Figure 2. The matching planes were positioned adaptively so as not to affect the two-dimensional flows appreciably. All of the unknowns were represented by finite element basis functions and the complete equation system for their coefficients as given by Galerkin's method was solved by Newton iteration with continuation in parameters.

Comparison with Elastoviscocapillary Model

In the example of Figure 3—cylindrical die shape, approach angle of 5°, departure angles of 7°, top layer feed rate (Qt) = 0.76×10^{-3}, bottom layer feed rate (Qb) = 2.5×10^{-3}, and elasticity number ($\mu V/N$) = 4.6×10^{-5} — the pressure and gap profiles predicted by the cruder and the more accurate models are seen to agree closely except in a small zone near the downstream contact line. Evidently assuming uniform pressure opposite feed slot in the cruder model is reasonable.

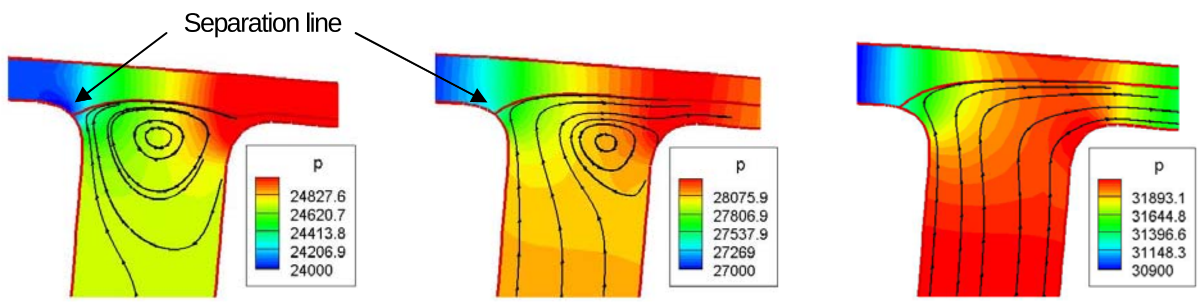


(a) Pressure profile (b) Gap profile

Figure 3. Comparision of 1D elastoviscocapillary model with the hybrid model that incorporates 2D Navier-Stokes flow in the slots and the region over midlip.

Separation Line Positioning and Microvortex

The utility of the hybrid model is illustrated by its predictions of separation line location on the rounded downstream corner of the mid lip, and of streamlines and pressure field around the downstream or top layer feed slot as feed rates were varied: see Figure 4 and 5 (viscosities of the two layers are equal). Interestingly, under the conditions chosen, no microvortex is present when the top layer feed rate (also final thickness) is high; but as it falls, a microvortex appears at the upstream corner of the downstream lip and grows to fill nearly the entire feed slot (Figuire 4). This is accompanied by expansion of pressure sidehill on the corner into a ridge across the gap that extends progressively downstream. It appears that this pressure gradient competes with those driving flow out of the feed slot and assisting flow out of the midgap to control the microvortex and the location of the separating streamsurface, which terminates in the separation line on the midlip.

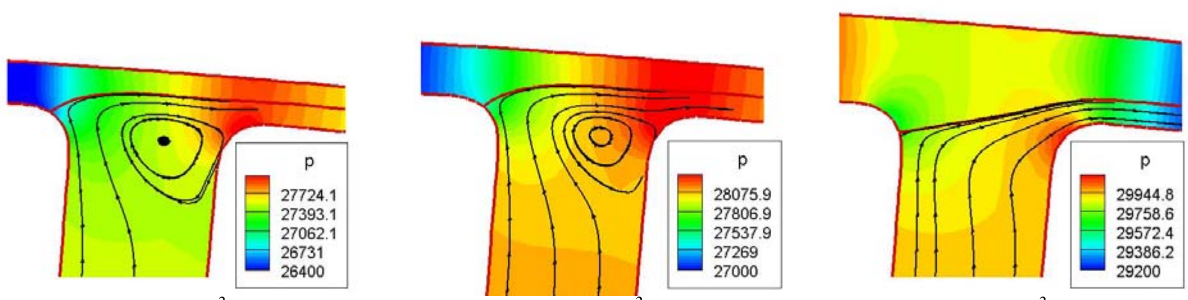


(a) Qt = 0.076×10^{-3} (b) Qt = 0.76×10^{-3} (c) Qt = 3.3×10^{-3}

Figure 4. Effect at downstream feed slot, of top layer feed rate(Qt) when other conditions are fixed: bottom layer feed rate(Qb) = 2.5 $\times 10^{-3}$ (in the units VR°/2), $\mu V/N = 4.6 \times 10^{-5}$, $L_f \rho V/\mu = 0.87$, cylindrical die shape. L_f is slot gap.

Thus at fixed top-layer feed rate, raising the bottom layer feed rate steepens the pressure gradient along the midlip and moves the separation line downstream on the corner of the midlip—and away from the unwanted state of midgap invasion: see Figure 5. The microvortex disappears as the bottom layer's feed rate (also final thickness) is raised.

Effect of layers' viscosity ratio and of die corner shapes have also been explored as a prelude to finding optimal lip shapes for given ranges of operating conditions.



(a) Qb = 2.0×10^{-3} (b) Qb = 2.5×10^{-3} (c) Qb = 6.3×10^{-3}

Figure 5. Effect at downstream feed slot, of top layer feed rate(Qb) when other conditions are fixed: bottom layer feed rate(Qt) = 0.76 $\times 10^{-3}$ (in the unit of VR/2), $\mu V/N = 4.6 \times 10^{-5}$, $L_f \rho V/\mu = 0.87$, cylindrical die shape.

Reference

Cohen, D. 1993 M. S. Thesis, University of Minnesota.
Sartor et al. 1998 US Patent 5728430.
Park, E., Carvalho, M.S., and Scriven, L. E. 2004 ISCST Symposium, Rochester, N.Y.