Effect of Radius of Curvature of Die Corners on Static Contact Line Pinning

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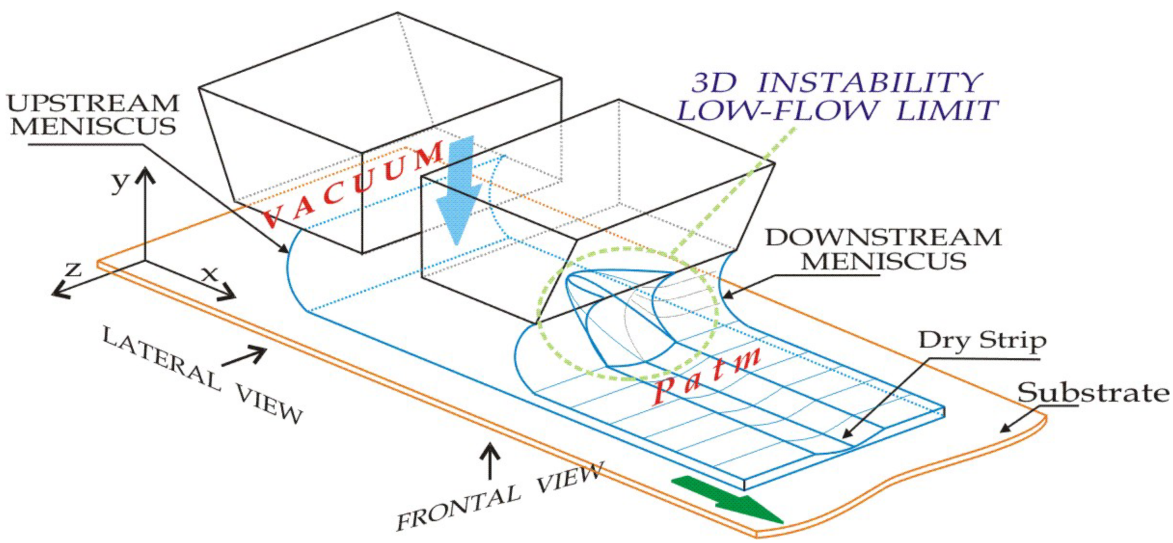

Figure 1: Sketch of the bead break-up from the upstream meniscus, which marks the onset of the low-flow limit in slot coating process.

Slot coating is commonly used in the manufacturing of many different products. The coating liquid is pumped to a coating die, is distributed across the width of a narrow slot in a distribution chamber and, as it exits the slot, the liquid fills the gap between the die and the moving substrate. The liquid in the gap, bounded upstream and downstream by gas-liquid interfaces, or menisci, forms the coating bead. The competition among viscous, capillary and pressure forces, and in some cases inertial and elastic forces, sets the range of operating parameters in which the viscous free surface flow of the liquid can be two-dimensional and steady. The region in the 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 of different coating methods in needed in order to predict whether a particular method can be used to coat a given substrate at a prescribed production rate. Romero et al. (2004) reviews the different analyses of slot coating flows and predictions of the coating window of the process for both Newtonian and non Newtonian liquids. The main contributions for Newtonian flows are by Ruschak (1976), Higgins and Scriven (1980), Sartor (1990), Gates and Scriven (1996) and Carvalho and Kheshgi (2000). They show that for low viscosity liquids, the most important limit in slot coating process occurs when, at a given substrate speed, too low a flow rate per unit width from the slot causes the downstream meniscus to curve so much that it cannot bridge the gap's clearance H_0. Consequently the meniscus becomes progressively more three-dimensional, alternate parts of it invading the gap until the bead takes a form that delivers separate rivulets or chains of droplets to the substrate moving past, as illustrated in Fig.1. This transition from a continuous coated liquid layer is what is called here the low-flow limit: the minimum thickness of liquid that can be deposited from a gap of specified clearance at a given substrate speed. It is independent of the vacuum applied, given that the vacuum is great enough to draw the upstream meniscus away from the feed slot.

Theoretical analysis of low-flow limit presented by Carvalho and Kheshgi (2000) and Romero et al. (2004) used the hypothesis that the downstream free surface was pinned at the corner between the downstream die lip and shoulder. However, corners are not mathematical and contact lines do not actually pin. The effects of rounding the downstream corner of slot dies on contact line location, effective contact angle, and the low-flow are examined by solving the Navier-Stokes system for Newtonian flow in the downstream part of the coating bead, as shown in Fig.2.

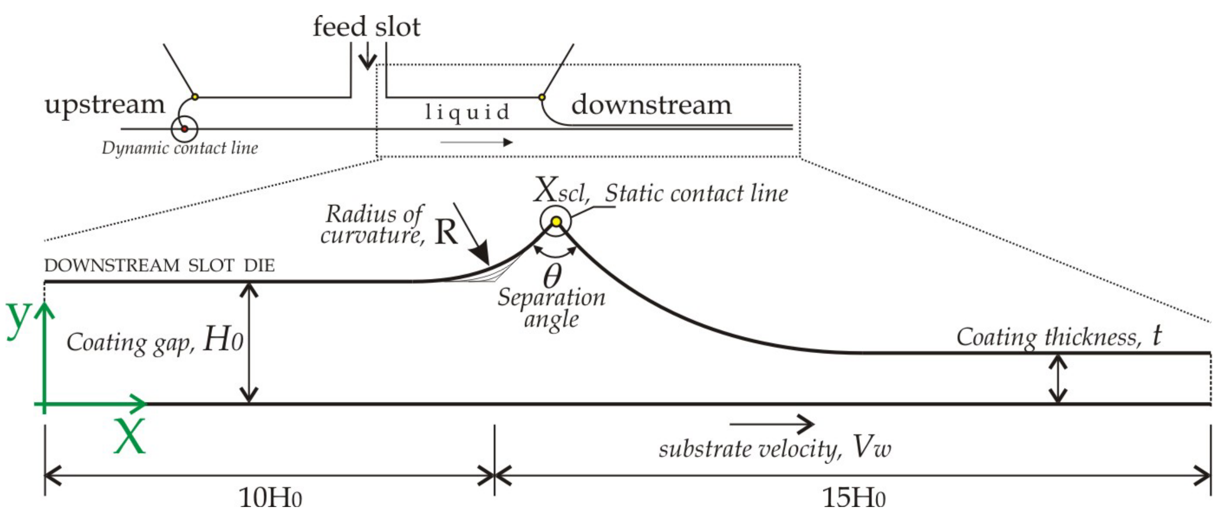

Figure 2: Sketch of the flow domain near the downstream free surface.

The local contact angle is treated as a specified equilibrium value and the static contact line position is free to move along the surface of the die (die shoulder and die lip). The systems are solved by Galerkin's method and finite element basis functions. A sample mesh is presented in Fig.3.

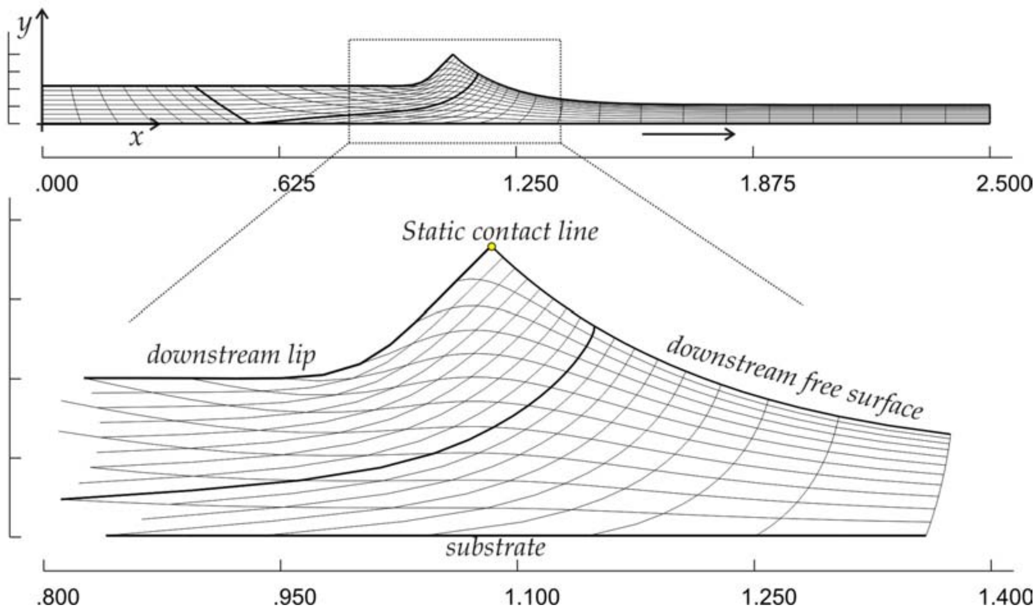

Figure 3: Sample mesh with 342 elements and 6854 degrees of freedom.

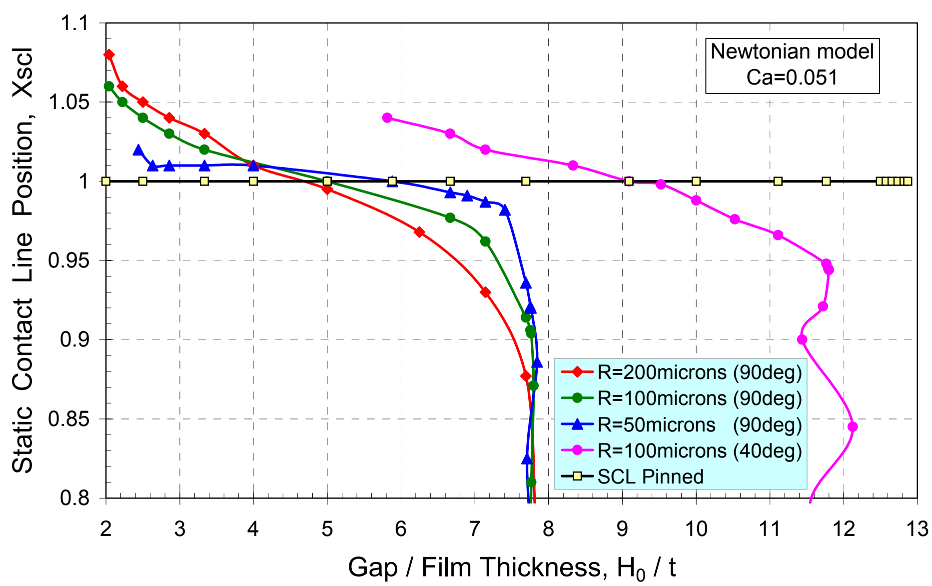

Figure 4: Static contact line position at different static contact angles and radius of curvature of the die corner.

Figure 4 shows the static contact line position as the flow rate falls, i.e. as the gap over film thickness ratio rises, at different static contact angles and corner radius of curvature. The predictions were obtained at $Ca = 0.051$. The position $X_{scl} = 1$ corresponds to the sharp corner position. If the contact line is pinned at the sharp die corner, a turning point on the solution path is obtained at $H_0 / t \approx 12.9$, i.e. the low-flow limit occurs at this condition. In the cases at which the radius of curvature of the die corner is large, e.g. $R > 100\mu m$, the sensitivity of the contact line position with respect to the film thickness is strong. At a static contact angle of $\theta = 90^0$, a turning point on the solution path could not be found, but a maximum gap-to-film thickness ratio is of approximately $H_0/t \approx 7.8$ is obtained assymptotically. This would indicate the onset of the low flow limit. At sharper die corners, e.g. $R = 50\mu m$, the sensitivity of the contact line position to changes in the flow rate is much weaker. The contact line virtually does not move as the gap-to-thickness ratio varies from $2.5 < H_0/t < 7$, i.e. it is a good hypothesis to consider the contact line pinned. The radius of curvature of the die corner does not affect the critical conditions at the onset of the low-flow limit. For all the radius of curvature tested, the low flow limit occurs at $H_0/t \approx 7.8$ when the static contact angle is $\theta = 90^0$.

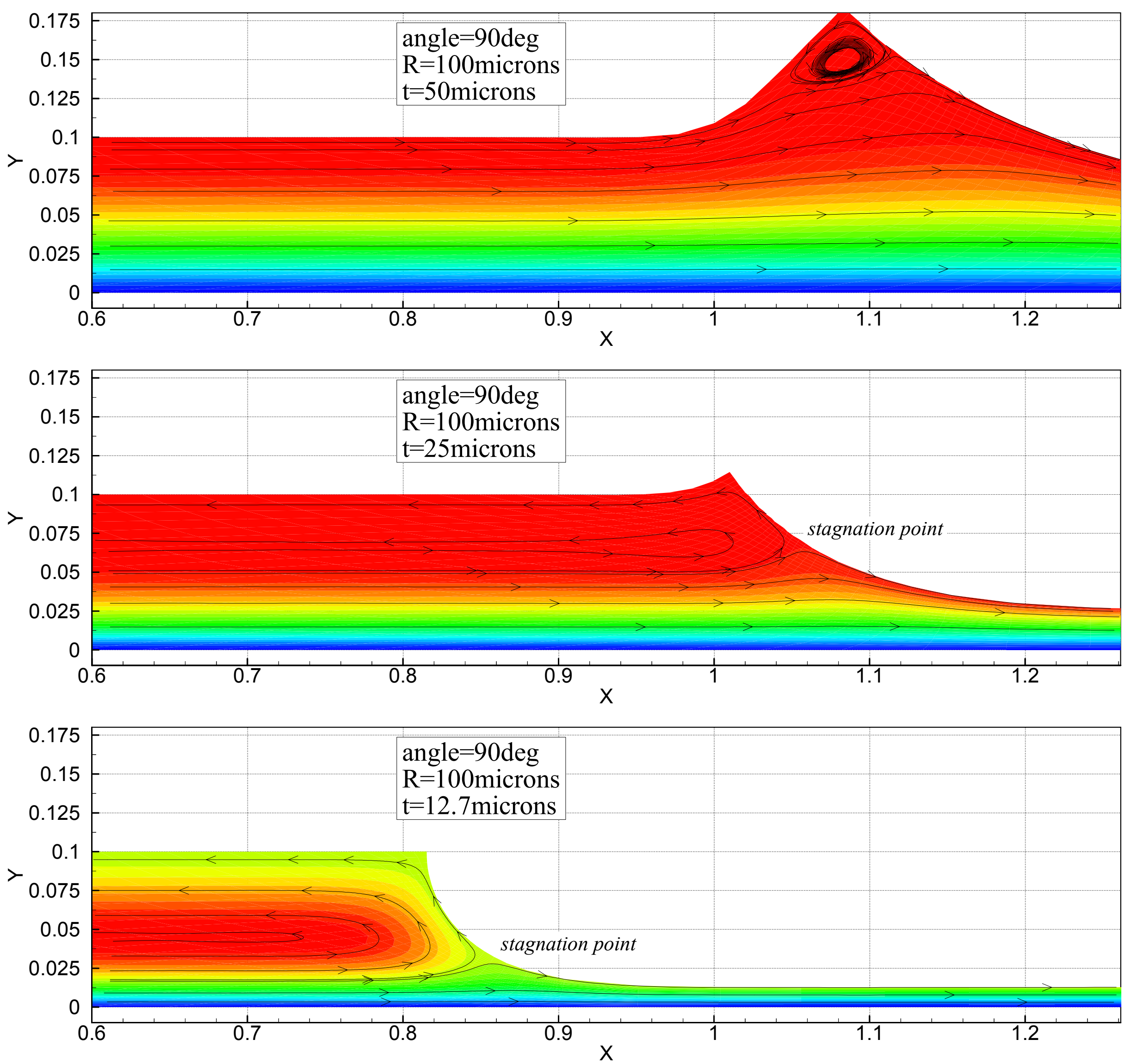

Figure 5: Evolution of the streamlines as the flow rate falls.

The effect of the static contact angle on the low flow limit is also presented in Fig.4, that shows the contact line position with a corner radius of curvature of $R = 100\mu m$ and static contact angle of $\theta = 40^0$. The sensitivity of the contact line position to the flow rate is not strongly affected by the contact angle, which has a large effect on the onset of the low flow limit. The critical condition at $\theta = 40^0$ is $H_0 / t \approx 11.8$. The evolution of the streamlines as the flow rate falls is presented in Fig.5 for $R = 100\mu m$ and $\theta = 90^0$.

The contact angle as the gap-to-film thickness rises for pinned contact line and for free moving contact line at $R = 100\mu m$, $\theta = 90^0$ and $\theta = 40^0$ is shown in Fig.6. The behavior of the contact angle for the pinned contact line is similar to that reported by Carvalho and Kheshgi (2000) and Romero et al. (2004), the angle between the free surface and the die lip falls as flow rate diminishes. The low flow limit for the cases at which the contact line was free to move along the die surface and the contact angle was prescribed occurred at the gap-to-thickness values that yielded this same angle in the case of pinned free surface.

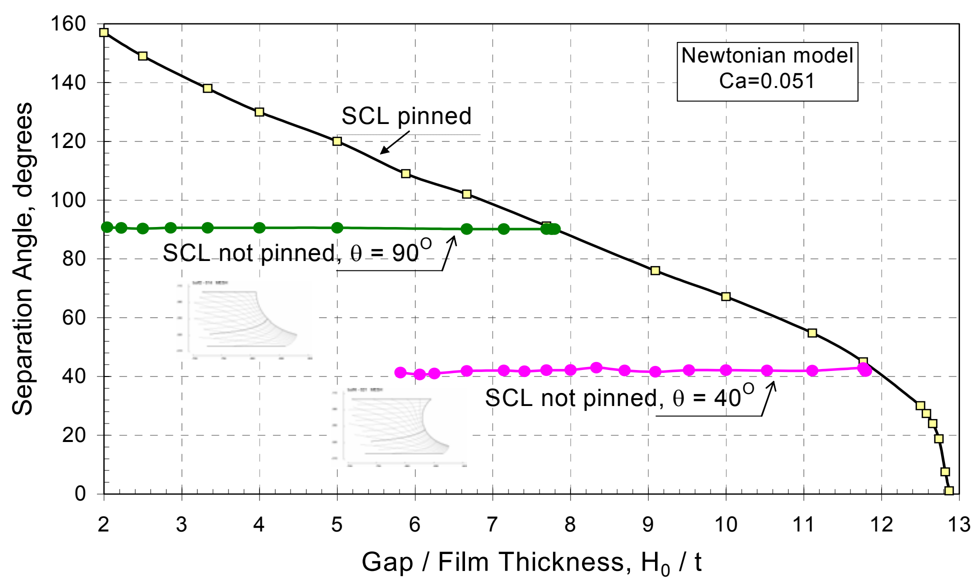

Figure 6: Contact angle as a function of gap-to-thickness ratio for pinned and free moving contact lines.

The theoretical predictions confirms that sharp corners promote contact line pinning, as it is well known, and show the minimum value of the radius of curvature of corners at which the variation of the contact line position becomes sufficientely small. The results also show that the critical conditions at the onset of the low flow limit is not affected by the corner radius, but only by the static contact angle of the coating liquid.

Acknowledgement

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