FUNDAMENTALS OF SLOT COATING PROCESS

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Introduction

Slot coating is commonly used in the manufacturing of adhesive and magnetic tapes, specialty papers, optical films, and many other products. In this process, the coating liquid is pumped to a coating die in which an elongated chamber distributes it across the width of a narrow slot through which the flow rate per unit width at the slot exit is made uniform. Exiting the slot, the liquid bridges the gap between the adjacent die lips and the substrate translating rapidly past them. The liquid in the gap bounded upstream and downstream by gas-liquid interfaces, or menisci, forms the coating bead, as sketched in Fig.1.

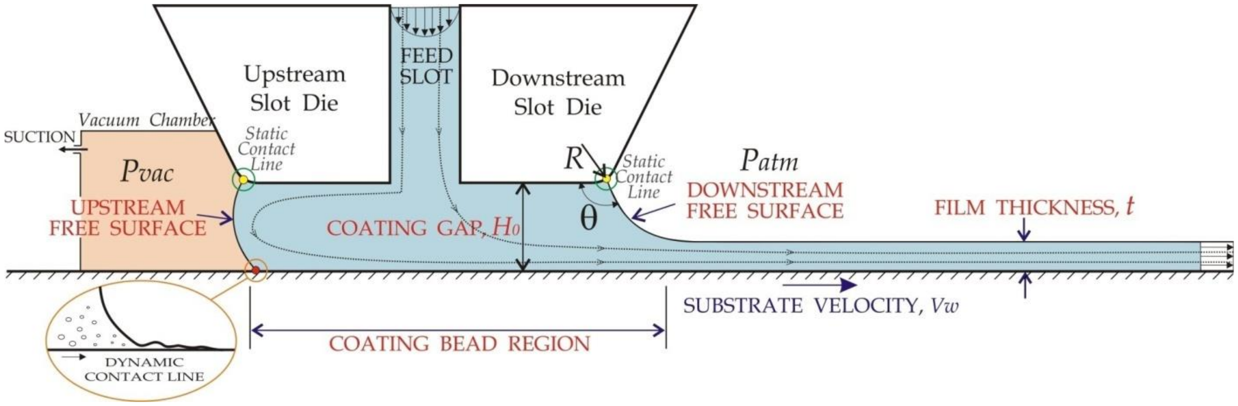


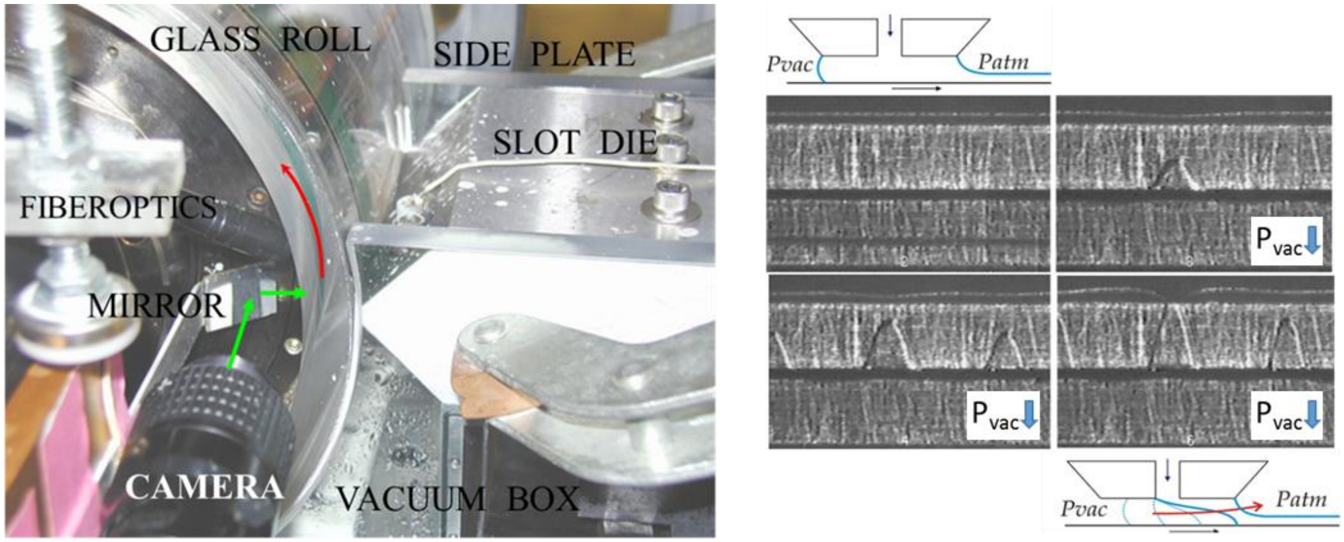
Figure 1: Sketch of slot coating flow.

Slot coating belongs to a class of coating methods known as pre-metered coating: the thickness of the coated liquid 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. Thus pre-metered methods are ideal for high precision coating. However, the nature of the flow in the coating bead, and therefore the uniformity of the liquid layer it delivers, can be affected by the substrate speed, the viscosity and any non-Newtonian properties of the liquid, and the configuration of the die lips immediately upstream and downstream of the slot exit. The region in the space of operating parameters of a coating process where the delivered liquid layer is adequately uniform is usually referred to as a coating window. Knowledge of coating windows of different coating methods is needed in order to predict whether a particular method can be used to coat a given substrate at a prescribed production rate.

Coating window can be determined by extensive production and pilot plant experiments. This approach is extremely expensive and time consuming. Coating process is a complex multidisciplinary science that involves wetting, adhesion, fluid mechanics, rheology, chemistry, interfacial science, and heat and mass transfer. Competitive pressure reduces the time available to bring new products into the market. Process development through extensive pilot plant trials may delay production. It is important to analyze the physical mechanisms responsible for the success or failure of manufacturing processes. Process engineers should pursue not only process *know-how*, but also the fundamental understanding of the process limits that will lead to process optimization, delaying or avoiding coating defects, i.e. the ultimate goal is the process *know-why*.

Modes of failure in slot coating flow

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, which is the desired state. In order to sustain the coating bead at higher substrate speeds, the gas pressure upstream of the upstream meniscus is made lower than ambient, i.e. a slight vacuum is applied to the upstream meniscus (Beguin, 1954).
Slot coating process has been deeply studied and understood. Despite all progress, there are still many industrial challenges that need to be addressed. Ruschak (1976) analyzed the coating window of a slot coating bead dominated by surface tension force (capillary pressure) in the upstream and downstream menisci; Higgins and Scriven (1980) took the viscous drag of the substrate and die lips into account.



(a) (b)

Figure 2: Visualization of slot coating flow failures through a transparent glass back up roll. (a) photograph of the experimental setup; (b) example of images obtained, showing the invasion of the upstream meniscus as the vacuum pressure is reduced leading to the formation of rivulets.

Refined flow visualization through a glass backup roll, illustrated in Fig.2, and finite element modeling, illustrated in Fig.3, of the flow were used to analyze the limits of operability and flow stability within those limits by Carvalho and Kheshgi (2000) and Romero, Scriven and Carvalho (2004; 2006).

The failure modes are sketched in Fig. 4. The figure shows that the coating window is bounded by three modes of failure:

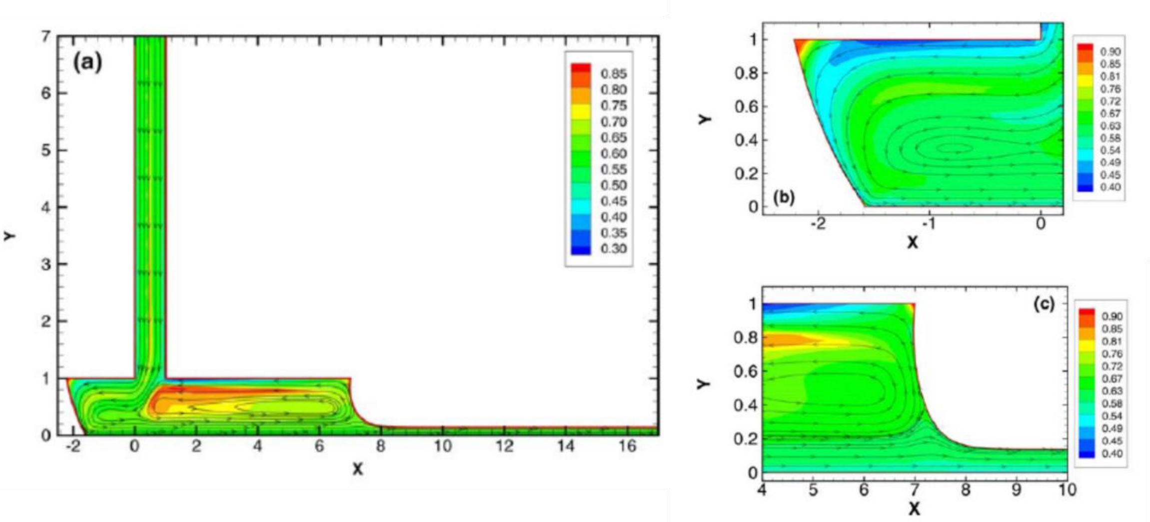


Figure 3: Example of slot coating flow prediction using finite element analysis. At these flow conditions, a large recirculation under the feed slot is formed.

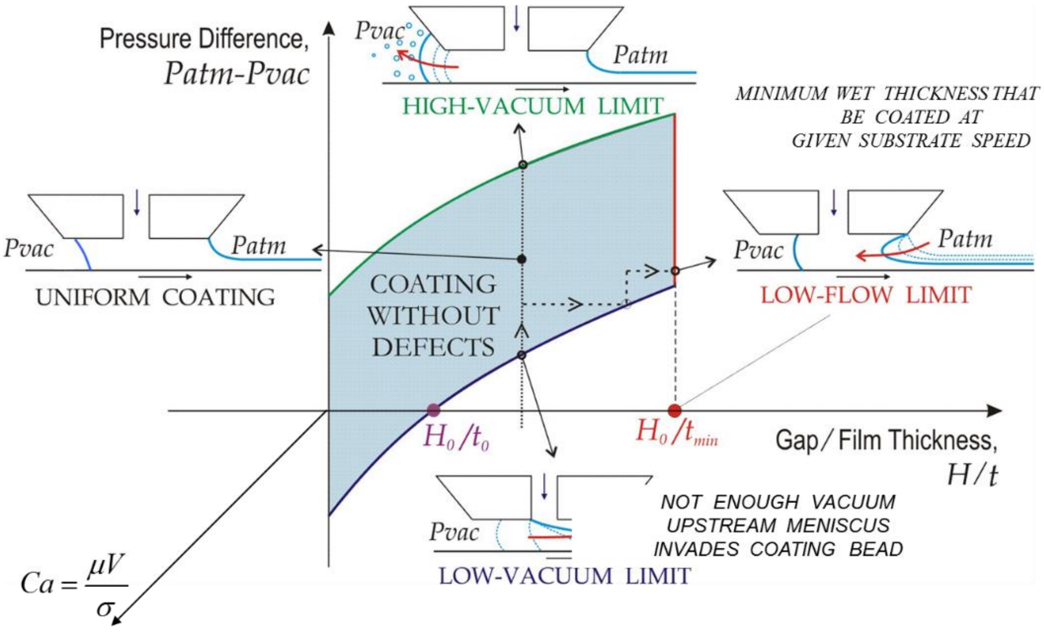


Figure 4: Sketch of slot coating process window as a function of coating thickness, gap and vacuum pressure.

(1) High-vacuum limit: When the coated layer is thicker than the thinnest that can be produced at a fixed gap and substrate speed, i.e. t > tmin in Fig. 4, too great a vacuum at the upstream free surface causes liquid to be drawn along the die surface into the vacuum chamber. This diversion of liquid destroys premetering.

(2) Low-vacuum limit: Too little vacuum at the upstream free surface leaves the net viscous drag force on the upstream part of the bead unbalanced by the pressure gradient that is imposed by capillary pressure forces in the menisci upstream and downstream and the difference in external pressure on those

menisci (i.e. vacuum). As a response, the upstream meniscus shifts toward the feed slot until the bead drastically rearranges into a three-dimensional form that delivers separate rivulets to the substrate. Between the rivulets are dry lanes that extend upstream through the bead. Along those lanes, air is sucked into the vacuum chamber. It is in this regime that, at given vacuum (ambient pressure downstream minus air pressure exerted on upstream meniscus), there is a lower limit to the thickness of continuous liquid layer that can be coated from a downstream gap of specified clearance. As Fig. 4 shows, the limit can be lowered by applying greater vacuum and thereby shifting the upstream meniscus away from the edge of the feed slot.

(3) Low-flow limit: At 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 clearance. 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. 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. And, as Fig. 4 makes plain, it is independent of the vacuum applied, given that the vacuum is great enough to draw the upstream meniscus away from the feed slot. The outcome is the same when at a given flow rate per unit width from the slot, the substrate speed is too high. In this case, the low-flow limit is sometimes referred to as the high-speed limit. The outcome is essentially the same when at a given flow rate per unit width from the slot and a given substrate speed, the clearance of the downstream gap is too great. In this case, the low-flow limit is referred to as the wide-gap limit: the maximum gap from which a given thickness of liquid coating can be deposited on a substrate moving at specified speed.

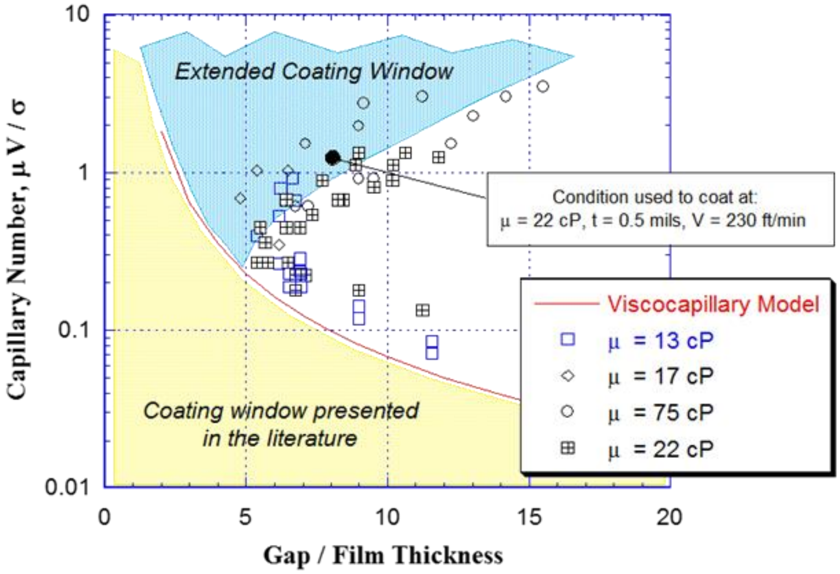


Figure 5: Onset of the low-flow limit at different conditions. The blue shaded area represents the augmented process window associated with inertial effects.

Industrial examples

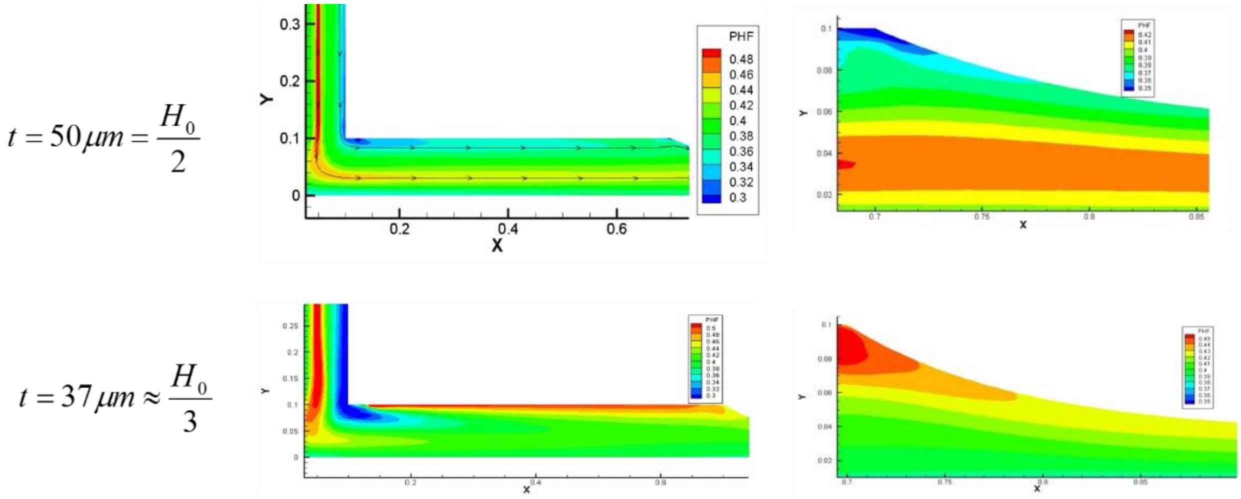
Coating thin films at high substrate speed

The low-flow limit is associated with the invasion of the downstream meniscus due to increasing capillary force needed to stabilize the free surface as the flow rate is lowered. By understanding the physical mechanisms related to the low-flow limit, Carvalho and Kheshgi (2000) were able to propose a way to delay the onset of this process failure, enabling coating thin films at high speeds. If the coating speed was high enough, liquid inertia pushes the downstream meniscus such that it does not invade the coating bead, delaying the breakup into rivulets. Fundamental understanding of the problem unveiled a new area of uniform coating, the blue area in Fig.5. Thin coating was obtained by raising the coating speed. The pilot-plant data together with the finite element simulation in the high-speed regime are shown in Fig. 5.

Slot coating of particle suspensions

The analysis presented considered the liquid as a Newtonian fluid. However, the liquids coated in practice are polymer solutions, particle suspensions, or a combination of both. The complex flow in a coating bead may create a non-uniform particle distribution in the flow, leading to strong viscosity changes within the coating bead, which may affect the process limits. Moreover, the flow may have a strong influence on the final particle distribution in the coated liquid that may be directly related to the microstructure and final product performance.

Campana et al. (2017) and Siqueira et al.(2017) have combined the solution of fluid flow equations that considers the liquid properties as a function the local particle concentration coupled with particle transport equation to study how the process parameters affects the particle distribution and alignment in the coated film. Figure 6 shows how the flow affects the particle concentration on the coated layer. Through the feed slot, the particles move from the high shear towards the low shear region of the flow, leading to a high particle concentration in the middle of the feed slot. When the coating thickness is equal half of the gap, the pressure gradient under the downstream die lip is negligible and the particle transport is weak, leading to a high particle concentration layer in the middle of the coated film. At lower values of the wet thickness, an adverse pressure gradient is created under the die lip. At a thickness close to 1/3 of the coating gap, the region of zero shear rate is located near the die lip. Particles move towards that area, leading to a high concentration neat the die lip surface and consequently on the top of the coated film.



$t = 50\mu m = \frac{H_0}{2}$

$t = 37\mu m \approx \frac{H_0}{3}$

Figure 6: Particle concentration under the downstream die lip and near the downstream meniscus for two different coating thickness.

Final Remarks

The examples discussed here show how fundamental understanding of coating flows and the physical mechanisms associated with the different failure modes lead to better designed processes and can drastically reduce the process development and production scale-up time required to bring new products into the market.

Fundamental understanding of coating processes is not easy. It requires collaboration between experts from different disciplines; it is a result of a continuous effort, and therefore requires time, investment and commitment.

Acknowledgments

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