

Prediction of the Minimum Wet Thickness of Slot Coating at Low Capillary Number

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Abstract

Theoretical prediction of coatability can often involve uncertainties, such as the assumption of boundary conditions or the constraints of theoretical model, when it is compared with experimental observations. In order to predict the low coating flow limit in slot coating process it is important to understand the major mechanism of maintaining a stable coating bead. In this study a theoretical method is applied[1] to analyze the feeding slot pressure upon the coating bead and correlate the prediction to the experimental slot coating at low capillary number (< 0.3). The theoretical analysis and experiments were carried out with Newtonian fluids. The computational calculation was performed using Nekton, a commercial finite element fluid dynamics software. The analysis indicates that the pressure drop of the feeding slot acts against the capillary pressure of the bead meniscus and provides the stability for the coating process. The pressure drop decreases as the coating thickness decreases until it reaches a certain minimum value. At this value the pressure drop is overcome by the capillary pressure and a stable process turns into a unstable process. The phenomenon has been correlated with the minimum wet coating thickness observed in the experiments. The correlation established in the study shows that the pressure drop of the feeding slot provides the major stability for the coating process at low capillary number.

Introduction

Thin film liquid slot coating method is an essential pre-metered coating technology applied in different industries. The coating process is operable only within certain stable and defect free range, which is well known as the operating window of coatability. The coating window is determined very often through an experimental approach in industry. How ever, not only the experiment is cost and time consuming but also it is difficult to obtain an optimized process control without an understanding of the internal coating flow field. Therefore, many efforts have been put into the theoretical prediction of the coating window, which include the analysis of the bounds set by the capillary pressure and viscous pressure drop[2]. It is also realized that the computational predictions can often involve uncertainties compared with experimental observations. The discrepancy could result from the constraints of theoretical analysis and the accuracy in experimental measurements.

In the current work, a finite element analysis of thin film slot coating window at low capillary number, where the capillary pressure is more dominant than the viscous pressure, was carried out. The pressure effect from the feeding slot upon the coating bead was analyzed through the pressure drop from the slot inlet to the coating bead at the slot exit near the dynamic contact line. By reducing the inlet total coating flow rate, a disturbance from the capillary pressure of the bead upstream meniscus was analyzed. The low flow limit of the coating window was predicted through the pressure drop disturbance.

The slot coating experiments were set up to obtain a thin liquid film coating window and to compare with the numerical predictions. The minimum wet thickness limitation of the slot coating at certain web speeds, zero bead vacuum, and well-controlled coating gaps was investigated. The minimum wet thickness of the experimental coating has been well correlated with the computational results at each low capillary number, and the mechanism of the coating instability has been discussed.

Theoretical

The slot coating flow pattern of mixed Poiseuille-Couette flow in the bead between die surface and moving web has been discussed in several reference papers[1,2,3]. The flow pattern separates the coating bead as two regions at the exit of the slot die. The Poiseuille flow in the down stream region has the same direction with Couette flow. However, the Poiseuille flow in the upstream region is opposite to the Couette flow which maintains the stable coating bead. The total flow rate consisting Poiseuille component and Couette components in the down stream bead region is described as follows

$$Q = \frac{vH}{2} + \frac{H^3}{12\mu}\left(\frac{-\Delta P}{L}\right) . \qquad (1)$$

As shown in Figure 1, μ is the viscosity of the fluids. v and H is web line speed and coating gap respectively. The total flow rate of coating fluids is defined as Q. The ΔP in the down stream bead region is determined by the ambient pressure P_o and bead pressure at slot exit P_{exit}, which can be affected by the capillary pressure of upstream meniscus at thin film coating. The L is the relevant length scale of the pressure drop.

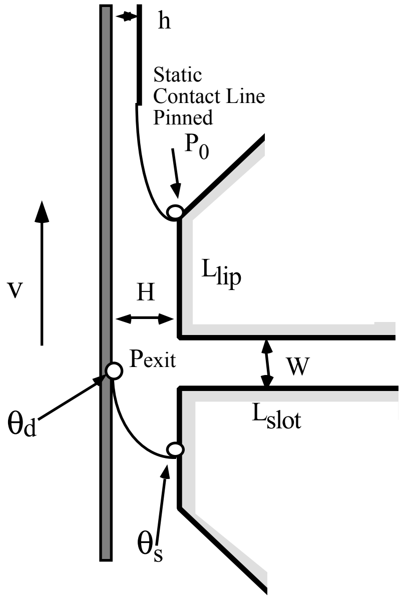

Figure 1. Single Slot Coating Bead Computational Domain H coating gap, W. slot height , v web velocity, Q inlet flow rate, h wet thickness. Pin slot inlet pressure, Pexit bead pressure at slot exit, Po ambient pressure, θ_d dynamic contact angle, θ_s static contact angle.

The cause of the Couette flow is the drag of the moving web, while the driving force of the Poiseuille flow is the pressure drop through feeding slot, i.e.,

$$\Delta P_{slot} = P_{in} - P_{exit} \, , \qquad (2)$$

where P_{in} is the slot inlet pressure, and P_{exit} is the bead pressure at slot exit.

The slot pressure drop ΔP_{slot} has the following linear relationship with the total flow rate Q

$$Q = -\frac{W^3}{12\mu}\frac{\Delta P_{slot}}{L_{slot}} \, , \qquad (3)$$

or with the equivalent coating wet thickness h, i.e. $h = \frac{Q}{v}$, where W and L_{slot} is the slot height and length respectively.

At thin film coating situations the linear relationship between ΔP_{slot} and h can be disturbed, since the dynamic contact line can move downward along the stream, and the capillary pressure of up stream meniscus can affect the bead pressure P_{exit} at slot exit. The capillary pressure of the up stream meniscus is described by Young-Laplace equation

$$\Delta P_{Y-L} = -\frac{2\sigma}{R} \qquad (4)$$

where σ is the fluid surface tension and 1/R is the curvature of the meniscus shape.

A 2-dimensional flow model has been established to analyze the thin film coating with a finite element method. The steady state flow is governed by the Navier-Stokes equation

$$\rho(\partial_t u + (u \cdot \nabla)u) = -\nabla p + \nabla \cdot [\mu(\nabla u + (\nabla u)^T)] + \rho g \, , \qquad (5)$$

with the continuity of fluids $\nabla \cdot u = 0$. Here ρ is the density of coating fluids, g is the gravity, p is pressure, and u is the velocity vector. The boundary conditions involve inlet, outlet flow planes, wall boundaries of slot, moving web, and down stream and upstream free surfaces. The free surface condition is described as follows:

$$\tau_{ij} n_j = \sigma k n_i + \nabla_i \sigma \text{ , and} \qquad (6)$$

$$u_j n_j = 0 \, . \qquad (7)$$

where n_i is norm of the free surface, τ_{ij} is stress tensor, σ is surface tension, and k is curvature of the surface. Figure 1 illustrates the computational domain of the finite element model. The numerical simulation was carried out using Nekton software, a finite spectral element technique with Arbitrary Lagrangian Eulerian for handling free surfaces fluid dynamics.

Experimental

The experimental slot applicator is schematically described in Figure 2. A single slot applicator with a flat die lip length was used to deposit the coating liquid from the slot exit to a moving substrate supported by a 25.4 cm diameter back roll. The slot height W inside the applicator can be adjusted by inserting U-shaped shims of certain thickness to form the liquid dispensing chamber. The slot was set up horizontally such that the axis of the slot would always pass through the center of the back roll. The coating gap between the slot applicator lips and the web can be accurately adjusted and monitored by a digital gauge. The vacuum can be applied to the upstream meniscus through a sealed chamber. In the present study there is no bead vacuum applied.

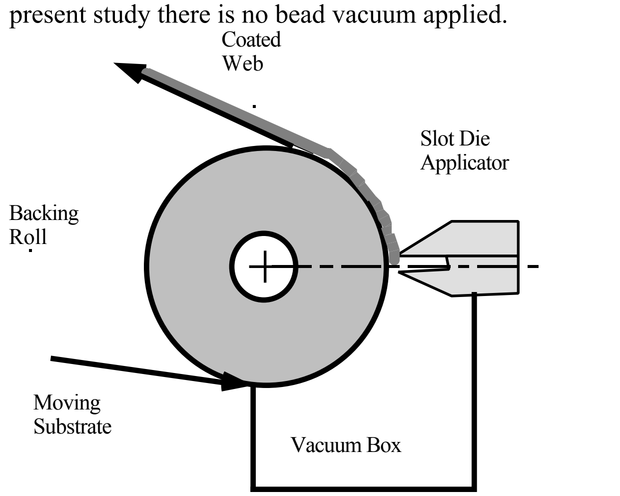

Figure 2. Experimental Slot Die Applicator and Parameters.

The slot coater provides a sophisticated web transport system and an accurate control of operation parameters. During the experiment the web was transported past the slot applicator where the liquid coating would be applied, and then into a scrape off station. The deposited liquid was then removed from the web at the scrape off station before being rewound. A gel sub-coated polyester base was employed as a coating substrate for all the coating experiments.

The glycerol-water solutions were used in the coating experiments, in order to compare the low flow coating limit of Newtonian fluids with the finite element model prediction. The coating fluid physical properties are listed in Table 1.

Table 1. Coating Fluid Physical Properties

Liquid at 20 C	Density [g/cm3]	Surface Tenson [dyne/cm]	Viscosity [cp]
95% Glycerol-H2O	1.250	65	515
88% Glycerol-H2O	1.232	65	125
62% Glycerol-H2O	1.160	65	10

The coating experimental method is similar to the method applied by Gutoff and Kendrick[3], and also by Lee and Liu[4]. All the experiments were performed at ambient temperature approximately 20^{o}C. During each experiment, at a given gap of H. The tested fluid was dispensed to the web at a fixed flow rate of Q and the coating speed v was adjusted to obtain a defect-free uniform coating surface. Then the coating speed was increased to a maximum value at which the bead was still stable. Above this coating speed the bead became unstable and ribbing and /or air entrainment defects started appearing. This value was recorded as a critical coating speed and the relevant wet thickness was estimated as minimum wet thickness, h_{min}. The relationship is also reported in a form of dimensionless minimum wet thickness t and capillary number Ca in the following discussions, where $t = \frac{h_{min}}{H}$ and $Ca = \frac{\mu v}{\sigma}$.

Results and Discussions

The slot coating minimum wet thickness of the glycerol-water solutions of various viscosities were examined at coating gap of 0.127 to 0.254 mm, respectively. The results are shown in Figure 3. The observed capillary number dependence and coating gap dependence of the minimum wet thickness are similar to the published studies[3,4]. The slight difference might attribute to the criteria chosen for accepting defect-free coating uniformity. The bead vacuum P_b is not applied. For the low viscosity solutions, i.e. most likely in lower capillary number situations, the ribbing and air entrainment arises as the coating speed increases. The higher viscosity solution shows more weeping or dripping than the air entrainment when the coating speed increases.

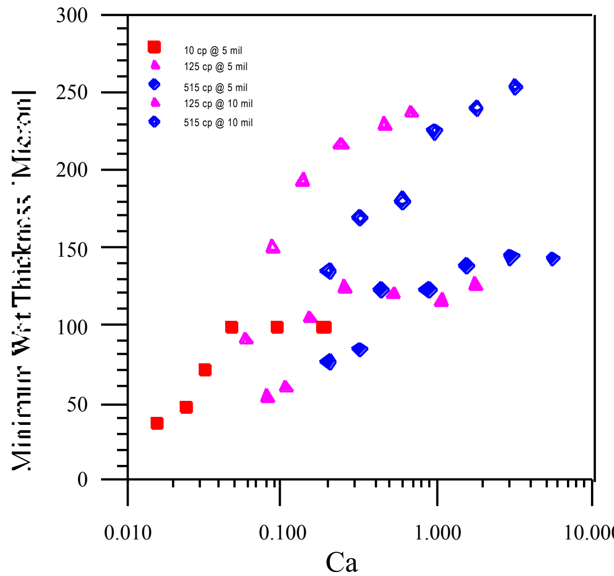

Figure 3. Low Flow Limits of Coatability on Slot Coating withGlycerol-Water Liquids

The minimum wet thickness can be reached to a very small value when the capillary number is low. As the capillary number increases the minimum wet thickness increases. Once the capillary number is higher than a critical value the minimum wet thickness levels off and becomes independent of capillary number. For the case of a 0.13 mm coating gap, the minimum wet thickness of all three fluids reaches a critical value about 125 micron. In the case of 0.26 mm coating gap, the critical value of the minimum wet thickness is about 250 micron. The results illustrates the coating gap effect on the slot coating minimum wet thickness. At the higher capillary number situation the two minimum wet thickness curves differ from each other significantly.

The slot coating minimum wet thickness is also predicted with finite element analysis method by using Nekton commercial software. The geometry and coating conditions applied in the simulation are summarized in Table 2. The dynamic contact angle under the coating condition is estimated with Gutoff and Kendrick[4] or Hans and Mues[5] formula.

Table 2. Geometry and Coating Conditions of Single Slot Simulation

Slot Height:	0.025 cm	Inlet Flow Rate:	0.05 to 0.15 cm3/cm-s
Slot Lip Length:	0.1 cm	Wet Thickness:	50 -150 micron
Coating Gap:	0.02 cm	Static Contact Angle:	90 degree
Applied Vacuum:	0	Dynamic contact Angle:	107 degree
Web Speed:	10 cm/s	Capillary Number Ca:	0.028 to 0.286

As described in the computational domain, the static contact point of the upstream meniscus slides along the slot die lip rather than pinned. The down stream meniscus was pinned on the upper lip end. Given a certain liquid inlet flow rate and a coating web speed, a stable coating flow structure and an uniform wet thickness can be simulated and the pressure drop from the slot feeding point across the coating bead, ΔP_{slot} can be calculated. As the inlet flow rate was decreased gradually, the corresponding wet thickness decreases until it reaches a minimum value at which the flow becomes unstable.

The finite element analysis result of ΔP_{slot} vs. coating wet thickness h is plotted in Figure 4 at each capillary number case. The linear function of ΔP_{slot} vs. h at high flow rate can be seen as is expected from Equation 3. However, when the coating thickness continuously decreases the ΔP_{slot} shows a change from downward direction to an upward direction. The direction turning point reflects the minimum wet thickness h_{min}. This phenomenon can be interpreted due to the capillary pressure influence from the upstream meniscus, since the shape of up stream meniscus becomes concave with relative large curvature at the point. This might be described in Young-Laplace equation (Eqn. 4) where the surface tension of the free surface can be significant. All four low capillary cases are showing the same phenomenon. The ΔP_{slot} eventually increases as coating thickness continuously decreases to certain value of h. This situation implicates the possible bead break because of the too low bead pressure at slot exit P_{exit}. By using the "turning point" from the curve of ΔP_{slot} vs. h, the minimum wet thickness has been predicted. The predicted minimum wet thickness at each capillary number is listed in Table 3.

Table 3. Predicted Slot Coating Minimum Wet Thickness

Capillary Number Ca	Minimum Wet Thickness hmin [micron]	Dimensionless Thickness t h_{min} / H
0.028	60	0.30
0.040	70	0.35
0.057	100	0.50
0.286	110	0.55

The minimum wet thickness determined by the ΔP_{slot} "turning point" is compared with experimental results as shown in Figure 5. The experimental data is plotted as dimensionless minimum wet thickness h_{min} vs. capillary number Ca. The predictions agree quite well with the experimental results in low capillary number region. In high capillary number region the dimensionless minimum wet thickness levels off, which is consistent with the results of Lee et al.[3]. In this region, the viscous force becomes more dominate than the capillary force. The capillary pressure disturbance on the ΔP_{slot} is relatively small comparing to the viscous force contribution. Therefore, the low flow limit can no longer be predicted simply by Δp_{slot}.

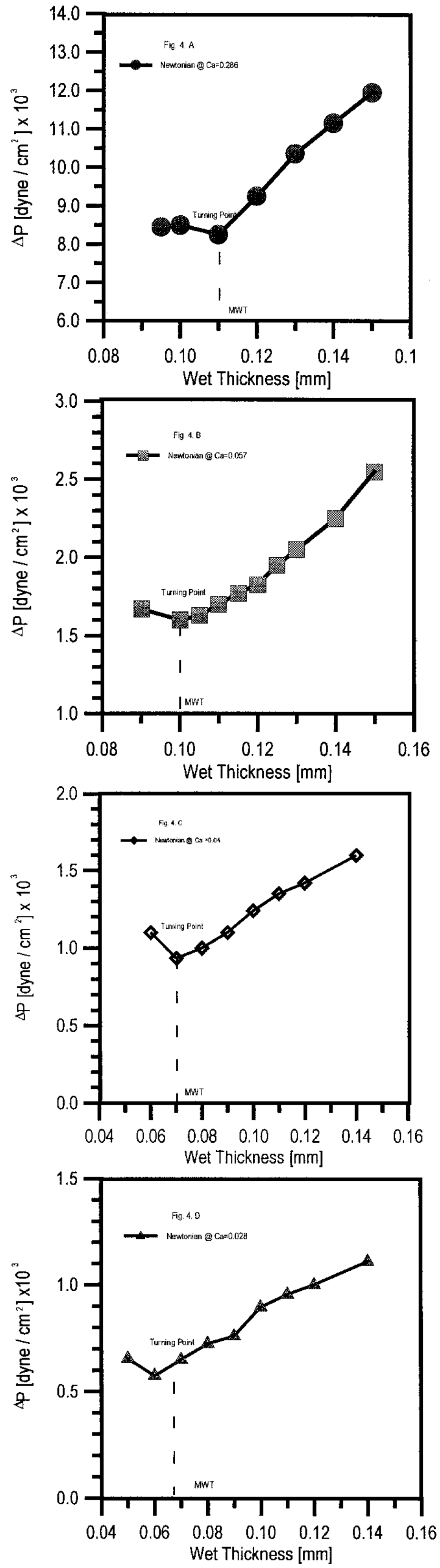

Figure 4. Slot Coating Minimum Wet Thickness Prediction by ΔP_{slot} (= P_{in} - P_{exit}) A. Ca = 0.286, B. Ca = 0.057, Ca = 0.040, Ca = 0.028

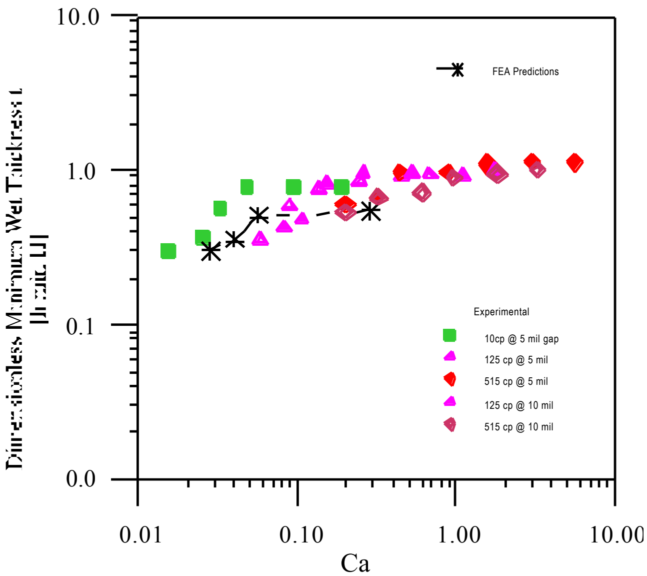

Figure 5. Comparison of FEA Predictions and Experimental of Slot Coating Low Flow Limits of Coatablility with Glycerol-Water Newtonian Fluids.

The finite element analysis also provides some phenomena that are hardly observed in the experiments. The numerical simulation is performed at fixed θ_s and θ_d, allowing wetting line slip to compensate the flow rate change. It has been reported that by tracking the wetting contact line point slipping during the flow rate reduction, there exists a "turning point" as the flow moves from a stable status to an unstable status[6]. This phenomenon was demonstrated by Fluent Inc.[7] as well. Another important phenomenon that should be emphasized here is the change of the up stream meniscus shape. As the coating thickness decreases the shape of the up stream meniscus changes from convex to straight, then to concave, which will eventually break the coating bead. This is because that the contribution of capillary pressure $\Delta P_{Y\text{-}L}$ becomes more and more important as the coating thickness decreases. This phenomenon was also observed from slide coating experiments by Schweizer[8].

Conclusions

The low flow limit of liquid film slot coating has been studied numerically with the finite element method. The analysis indicates that the capillary pressure of upstream meniscus has significant influence on the pressure drop of maintaining Poiseuille flow. As long as the Poiseuille flow can be maintained the pressure drop shows a linear function of the coating thickness. When the pressure drop changes from a decreasing to an increasing direction through a "turning point" the wet thickness reaches a minimum value. Therefore, the minimum wet coating thickness has been predicted from the turning point of the pressure drop ΔP_{slot} at low capillary numbers.

The minimum wet thickness by a slot coating has also been examined experimentally. At low capillary number, i.e. the meniscus surface tension dominate situations, the low flow coating limit shows strong capillary number dependence. The observed minimum wet thickness agree quite well with numerical predictions.

The current study has demonstrated that both finite element analysis and experimental results are consistent with the observations from the previously published work by others.

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