FLOW LIMITS IN SINGLE LAYER TENSIONED-WEB COATING:

NUMERICAL AND EXPERIMENTAL ANALYSES

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INTRODUCTION

When a fluid is in contact with a solid flexible material, the interaction between the two phases plays an important role in controlling the location of the interface between the fluid and the solid material. This is called elastohydrodynamic interaction. Tensioned-web-over-slot die (TWOSD) coating exploits the interaction to deposit an ultra-thin layer of liquid on top of a flexible substrate. Unlike conventional slot coating, the TWOSD coating method does not have a rigid backup roll to support the substrate, and hence the gap height, the distance between the coating die and the substrate, is regulated by the elastohydrodynamic interaction between the coating liquid and the curved substrate under tension. In general, the method can maintain an extremely small gap height, up to few microns, without scratching the die lip surface. Hence, the minimum possible wet thickness can be significantly reduced by the method (Nam and Carvalho, 2010a).

Since the method was developed from industrial needs, scientific literature is scarce. Most of it was computational or simple mathematical analysis of the method (Nam and Carvalho 2010a, Park 2008, Feng 1998, Lin *et.al.* 2008). There was an attempt to visualize the TWOSD flow (Lin *et. al.* 2007, Park 2008) but the scope of the analysis was limited focusing only on the bead breakup that occurs when the flow rate is smaller than a critical minimum value.

As discussed in (Romero et. al. 2004), the range of operating conditions of the tensioned web over slot coating method surrounded by different modes of failure, which are closely related to downstream meniscus configuration (ribbing), upstream meniscus location (bead breakup and weeping), and microvortex inside the coating flow (feed slot vortex). These different failure modes are summarized in Fig. 1 and a detail description of each of them can be found in Nam and Carvalho (2010a, 2010b).

The goal of the present work is to explore and examine the limit flow states that define the operating limits of TWOSD coating process by visualizing the flow. The critical parameter values for coating failure obtained from the visualizations are compared to the predictions from the computational model presented by Nam and Carvalho (2010a). Flow state evolution beyond the critical parameter values are explored. These flow states cannot be predicted by the two-dimensional computational model.

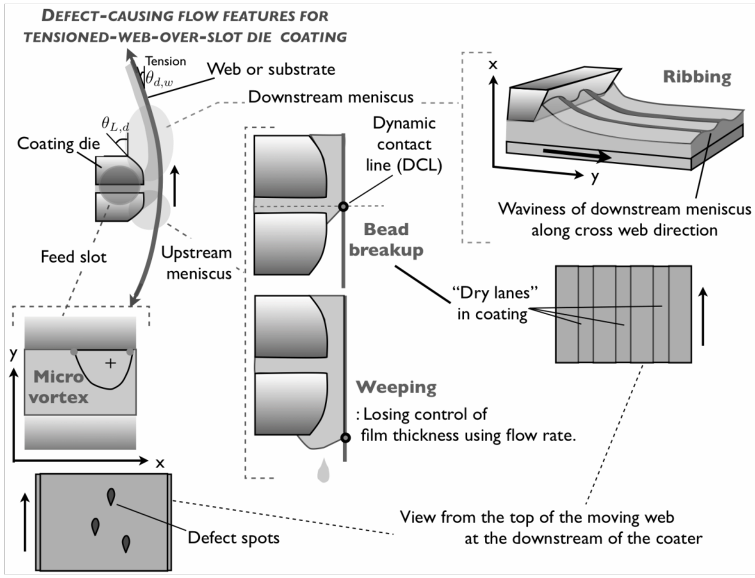

Figure 1 Flow features that lead to coating defects in tensioned-web-over-slot-die coating

FLOW VISUALIZATION

Flow visualization was done in a laboratory-scale coating apparatus with built-in tension controllers. The coating die was designed by Wieslaw Suszynski at the University of Minnesota and manufactured by PREMIER die Co., Chippewa Falls, WI. The web transport machine was designed and made by IMATION Co., St. Paul, MN. Schematic details of the apparatus setup are shown in Fig. 2.

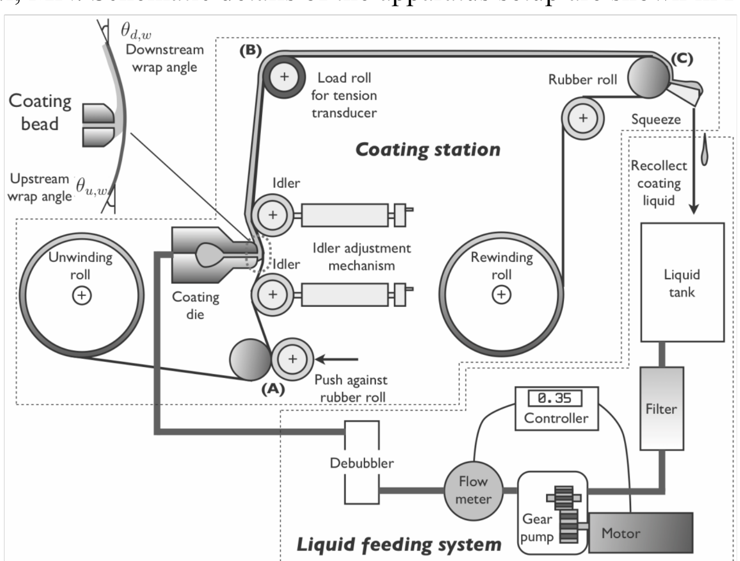

Figure 2 Tensioned-web-over-slot die coating apparatus setup

The camera installed in the middle of the setup was used to visualize the coating bead through the transparent moving substrate. It recorded the configuration of the downstream meniscus and the upstream meniscus location. The presence of microvortex in the feed slot was verified by injecting tracer particles inside the coating flow, as shown in Fig.3.

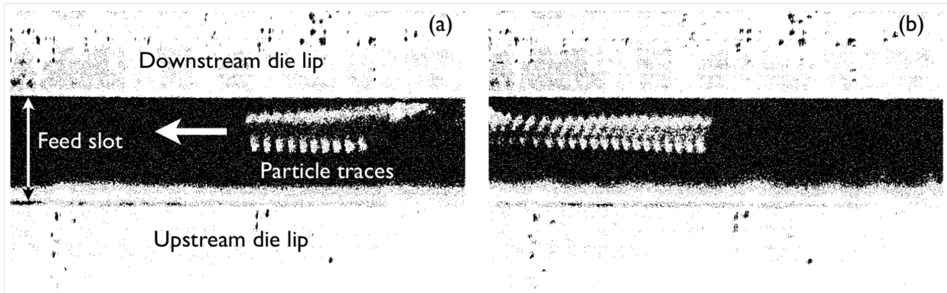

Figure 3 Flow visualization of feed slot vortex

COMPARISON: COMPUTATIONAL MODEL VS. EXPERIMENT

Throughout the visualizations of the TWOSD coating flow, we collected data points for onset of bead breakup, weeping and feed slot vortex in the parameter space of dimensionless wet thickness $h^*_w = h_w/R_d$ (R_d is the radius of curvature of the downstream die lip) and tension number N_T . All data points were found by fixing the web speed U_w and increasing or decreasing h_w through controlling the flow rate. When the flow rate was adjusted, we waited at least 2 minutes to ensure a steady-state flow.

Figure 3 shows the comparison between predictions from the computational model and results from the flow visualization. The bead breakup and weeping data shows that the upstream meniscus location predictions from the computational model are extremely accurate even though the model assumed a two-dimensional flow. And it also proves that the successful coating flow is truly two dimensional.

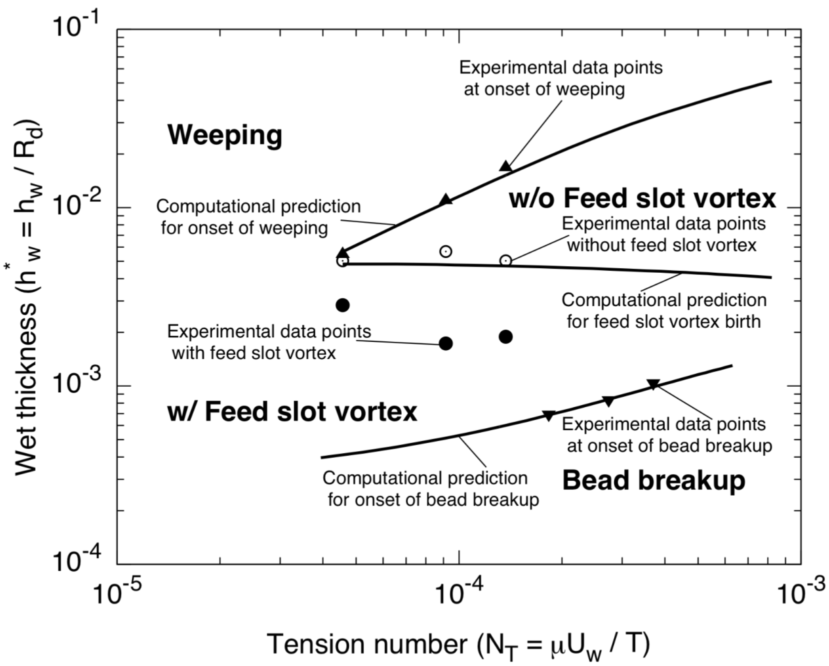

Figure 4 Comparison between predictions from the computational model and results

According to Nam and Carvalho (2010a), the critical wet thickness for the onset of the vortex is nearly a function of the gap height when Reynolds number is moderately small $N_{Re} = \rho q/\mu \sim O(1)$, which is the case for our study. Open and closed circle data points in Fig. 9 support the computational predictions. This microvortex is usually linked to defect coating Nam et. al. (2009). In TWOSD coating flows, the existence of feed slot vortex was only shown theoretically or computationally (Nam and Carvalho, 2010a). Unlike roll coating or slide coating (Schweizer 1988) that has relative large vortices, the size of the vortex is in the order of ten microns.

CONCLUSION

Flow visualization is powerful tool to examine the different flow states in a coating flow. The images and experimental data should be used to validate computational predictions, to explore the effect of flow parameters beyond the limits at which the model is valid and to ultimately help the fundamental understanding of the physical mechanisms. However, capturing different flow states in micro-sized coating flows is extremely challenging. In this study, the ribbing instability, the rivulet, and the dripping phenomena were visualized, and the three-dimensional nodular structure of the feed slot vortex was examined. Those flow states could not be described by the two-dimensional computational model proposed by Nam and Carvalho (2010a).

Not only qualitative, but also quantitative comparisons between the flow visualizations and the computational predictions were performed. The critical wet thickness data were collected with properly chosen limit flow states during the visualizations. The data were plotted in terms of two chosen dimensionless parameters, namely dimensionless wet thickness and tension number, and compared with the computational predictions. The agreement was excellent.

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REFERENCES

Nam, J. & Carvalho, M. S. 2010a Flow in tensioned-web-over-slot die coating: Effect of die lip design, *Chemical Engineering Science* **65**, 3957—3971

Nam, J. & Carvalho, M. S. 2010b Flow visualization and operating limits of tensioned-web-over slot die coating process, *Chemical Engineering and Processing: Process Intensification (accepted)*

Nam, J., Scriven, L. E., & Carvalho, M.S. 2009 Tracking birth of vortex in flows, *Journal of Computational Physics* **228**, 4549—4567

Feng, J. Q. 1998 Computational analysis of slot coating on a tensioned web, *AIChE Journal* **44** 2137—2143

Park, E. 2008 *Physics of coating tensioned-web over slot die*, Ph. D. Thesis, University of Minnesota Published by University Microfilms International, Ann Arbor, MI.

Lin, F-H, Liu, C-M, Liu, T-J, & Wu, P-Y 2007 Experimental study on tensioned-web slot coating, *Polymer Engineering Science* **47**, 841—851

Lin, F-H, Liu, C-M, Liu, T-J, & Wu, P-Y 2008 A macroscopic mathematical model for tensioned-web slot coating, *Polymer Engineering Science* **48** 307—315

Romero, O. J., Suszynski, W. S., Scriven, L. E. & Carvalho, M. S. 2004 Low-flow limit in slot coating of dilute solutions of high molecular weight polymer, *Journal of Non-Newtonian Fluid Mechanics* **118** 137—156

Shibata, N. & Chino, N. 1993 Method of application and device for application, U. S. patent 5,206,056

Schweizer, P. M. 1988 Visualization of coating flows, *Journal of fluid mechanics* **193** 285—302