Sensitivity Analysis of Slot Coating Flow using Frequency Response

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Abstract

Slot coating process is mainly applied for the manufacture of flat panel displays and long life batteries. In slot coating process, as in other coating process, producing very thin uniform coating film is a difficult task because of the occurrence of unexpected disturbances that causes defects during coating operations. The sensitivity of slot coating flow has been experimentally and theoretically analyzed in this study using frequency response method. Sinusoidal variations of the wet film thickness with respect to sinusoidal disturbances at flow rate, web speed, coating gap, bead pressure, etc. have been estimated from both 1D and 2D models. Also, sensitivity results of the wet film thickness and upstream meniscus position on sinusoidal web speed condition have been obtained from slot coating experiments and compared with those by simulations.

Introduction

The final goal of slot coating process is to manufacture uniform coating products through optimal internal and external die designs. However, such thin and uniform coating products are not always obtained at high speeds because of the occurrence of various flow instabilities and defects. Theoretically, it is important to examine the coating flow dynamics in coating bead region and establish the coating windows which are defined in the range of operating parameters for maintaining the uniform coated liquid layer (Ruschak, 1976; Higgins and Scriven, 1980;

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Kistler and Schweizer, 1997; Gates, 1999). Also, it is essential to scrutinize the sensitivity of coating system since the occurrence of unexpected disturbances in even stable region of process condition inevitably causes coating defects (Romero and Carvalho, 2008). This study has experimentally and theoretically focused the sensitivity of slot coating system using frequency response method, which measures the amplitude of state variables with respect to the sinusoidal disturbances at flow rate, web speed, bead pressure, etc. This analysis can provide the crucial information to control the coating process under various operating conditions.

Simulation for slot coating flow

The sensitivity of slot coating systems for Newtonian and shear thinning liquids has been investigated in this study, using both the 1D viscocapillary model and 2D model by Flow-3D. Viscocapillary model (Gates, 1999), which was derived using the lubrication approximation at laminar flow and incorporated with Young-Laplace and Landau-Levich approximations (Probstein, 1994) for upstream/downstream menisci, has been extended to non-Newtonian case.

The viscocapillary model for non-Newtonian liquid (Power-law model) is expressed as follows.

$$x_u = x_f - \frac{1}{\mu a}\left[P_d - P_v - 1.34Ca^{2/3}\frac{\sigma}{h_\infty} - (x_d - x_f)\mu b + \frac{\sigma}{h_u}(\cos\phi + \cos\theta)\right] \quad (1)$$

where, $a = \left[-\frac{U_{web}(n+1)(2n+1)}{n}\right]^n h_u^{-n-1}$, $b = \left[\frac{U_{web}(2h_\infty - h_d)(n+1)(2n+1)}{n}\right]^n h_d^{-(2n+1)}$.

Global mass balance in coating bead region was also employed for the sensitivity analysis (Gates, 1999).

$$\frac{dx_u}{dt} = \frac{1}{h_u(t)}\left(U(t)h_{00} - Q_f(t) + \int_{x_u}^{x_f}\frac{\partial h_u(t)}{\partial t}dx + \int_{x_f}^{x_d}\frac{\partial h_d(t)}{\partial t}dx\right) \quad (2)$$

Above equation set has been solved by 4th-order Runge-Kutta method. Also, the two-dimensional flow behavior in coating bead region has been obtained by Flow-3D, which is the commercial computational fluid dynamics software package specialized in free surface flow calculation.

A sustained oscillatory perturbation is introduced into the governing equations to analyze the sensitivity of system by comparing with amplitude ratios of input and output in frequency domain. In this study, a sinusoidal perturbation in bead pressure, web speed, flow rate, and coating gap is considered.

Experiment for slot coating flow

Glycerin-water solution was used as a Newtonian liquid and xanthane was added to the Newtonian liquid for non-Newtonian nature. We measured the sinusoidal change of wet coating thickness with respect to sinusoidal variation of web speed under different frequency conditions, using our lab coater equipment and visualization devices (Fig. 1).

Result and discussion

Fig. 2(a) exhibits the transient behavior of the wet coating thickness of a Newtonian liquid at far downstream position under sinusoidal web speed conditions with different frequencies. It has been found that the amplitude ratio of wet coating thickness with respect to web speed disturbance is decreasing in frequency regime. Disturbances changing the mass flow rate, e.g., web speed or flow rate – give unity amplitude at low frequency, because the change of the mass flow rate directly alters the final wet coating thickness, meaning that the 10% change of perturbation produces the 10% change of output variable. Whereas, disturbances not influencing the mass flow rate, e.g, bead pressure, will start from almost zero amplitude at low frequency (Jung et al., 2004). Also, the sensitivity of Newtonian liquid on various disturbances is portrayed in Fig. 2(b). It has been substantiated that amplitude ratio data of the wet coating thickness of Newtonian liquid obtained from 1D viscocapillary model, 2D model, and experiments give good agreement one another. More detailed sensitivity results for both Newtonian and Non-Newtonian liquids will be presented in ISCST 2008.

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References

I. A. Gates, *Slot Coating Flows: Feasibility, Quality*. PhD Thesis, University of Minnesota (1999).

B. G. Higgins and L. E. Scriven, *Chem. Eng. Sci.*, **35**, 673 (1980).

H. W. Jung, J. S. Lee, L. E. Scriven and J. C. Hyun, *Korean J. Chem. Eng.*, **21**, 20 (2004).

S. F. Kistler and P. M. Schweizer, *Liquid Film Coating*, Chapman & Hall, New York (1997).

R. F. Probstein, *Physicochemical Hydrodynamics*, John Wiley & Sons, Inc., New York (1994).
O. J. Romero and M. S. Carvalho, *Chem. Eng. Sci.*, **63**, 2161 (2008).
K. J. Ruschak, *Chem. Eng. Sci.*, **31**, 1057 (1976).

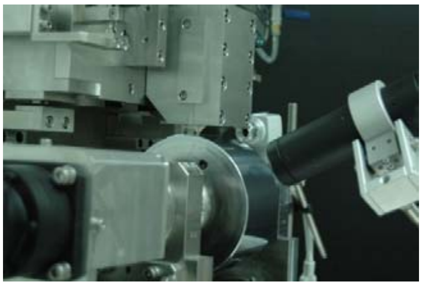
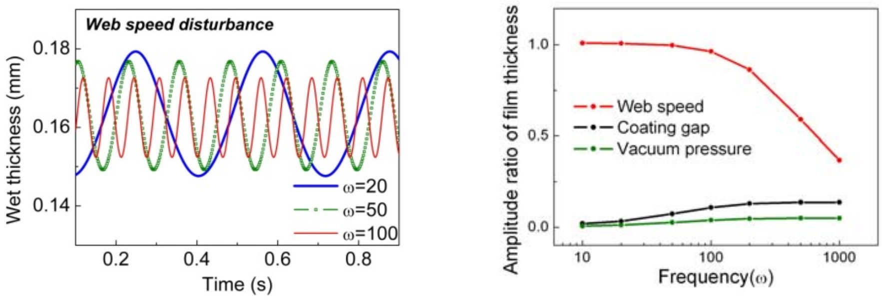


Fig.1. Slot coater equipment and thickness measurement device.



(a) (b)

Fig. 2. (a) Sinusoidal change of wet coating thickness of Newtonian liquid and (b) Amplitude ratio of wet coating thickness of Newtonian liquid with respect to various sinusoidal disturbances.

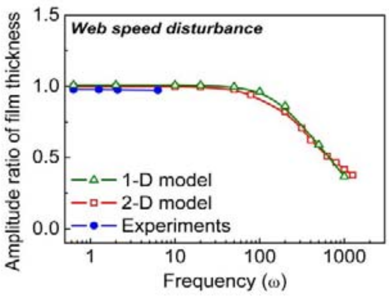


Fig. 3. Amplitude ratio of wet coating thickness by simulations and experiments.