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RAPID COMMUNICATIONS

Effect of flow rate variation on the frequency response in slot coating process with different upstream sloped die geometries

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Abstract−The sensitivity of slot coating process with different sloped upstream die configurations has been investigated using the viscocapillary model for a coating liquid with constant viscosity (Newtonian) through frequency response technique. Amplitude ratios of coating thickness with respect to a sinusoidal disturbance at flow rate are compared under different input frequency and upstream die lip angle conditions. Amplitude ratio values decrease as the upstream die lip angle increases, implying that the coating system is less sensitive to the given disturbance due to the larger space condition in the upstream die region. Amplitude ratio curves obtained from various conditions can be usefully unified in a single one with the help of new dimensionless time between fluid time scale in upstream region and perturbed time scale by input frequency.

Keywords: Sloped Slot Die, Frequency Response, Sensitivity, Operability Coating Window, Slot Coating

INTRODUCTION

Slot coating, which is one of pre-metered coating processes, has been extensively studied for uniformly depositing coating liquids onto the web or substrate with a high speed [1,2]. As in other coating processes, the control of process conditions for reliable stable coating operations is of utmost importance in this system. For example, related critical issues on this process are the development of operability windows for uniform coating [3-9], the physical understanding of coating bead flow regime [10-14], the sensitivity by ongoing disturbances introduced in this process [5,6,15-17], etc.

Coating defects such as leaking and bead breakup (e.g., ribbing, rivulets, barring, and air entrainment) can be frequently observed in coating bead flow regime bounded by the surfaces of die lips, moving web, and upstream and downstream menisci (Fig. 1). The representative operating conditions in constructing the operability window of this process are bead pressure (pressure difference between the ambient pressure beyond free surfaces located at downstream and upstream die regions, $\Delta P=P_d-P_v$), web speed, flow rate, and upstream/downstream die lip geometries. Various operability windows have been developed from simple and fuller theories [3-7] and experiments by flow visualizations [8,9]. From the previous research results, it turns out that the position of upstream meniscus in coating bead could be regarded as a useful indicator to determine coating limits like leaking (when the position of upstream meniscus is located at the far upstream die lip) and bead breakup (when its position lies at the slit exit). Koh et al. [3] and Lee et al. [6] compared operability windows by changing rheological properties of non-Newtonian liquids using the viscocapillary model. And, Lee et al. [4] clarified the effect of die lip geometries on the coating stability using both viscocapillary and two-dimensional Navier-Stokes models for a Newtonian liquid.

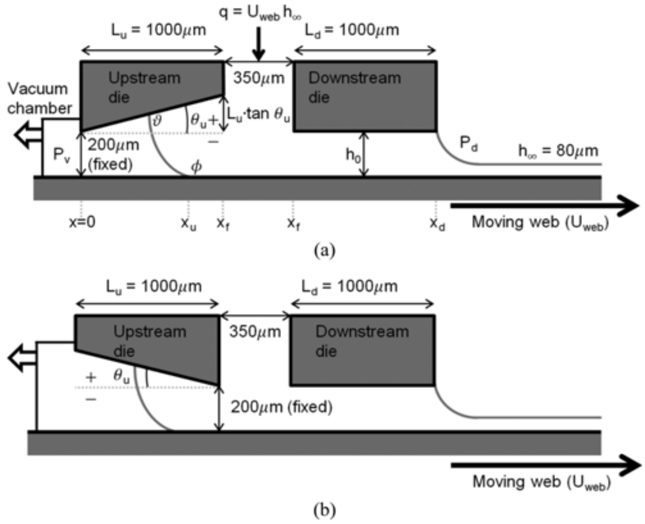

Fig. 1. Schematic diagrams for sloped slot die lip geometries under the fixed upstream angle at (a) outer corner (case 1) and (b) inner corner (case 2) of the upstream die lip.

It should be emphasized here that the flow state in the coating process can be aggravated by unexpected disturbances, even under stable operation. Therefore, predicting how the disturbances inevitably imposed during the operation can affect the coating system

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is the key to ensure the good productivity and processing capability. For instance, the final coating thickness can be periodically varied with respect to the ongoing disturbance at flow rate caused by the subtle pumping oscillation, depending on the oscillation frequency. Such sensitivity problem is typically scrutinized via the frequency response method [5,6,15-17], measuring the amplitude of sinusoidal state variables with respect to the given sinusoidal disturbance in frequency domain.

In this study, the frequency response analysis was further carried out using the viscocapillary model for a Newtonian coating liquid with constant viscosity to investigate the sensitivity of slot coating with changeable sloped upstream die lip geometry which can exert a decisive influence on coating dynamics. Based on results by Lee et al. [4] on the operability windows for different sloped die designs, amplitude ratios of final coating thickness corresponding to the ongoing disturbance at flow rate were newly plotted along with input frequency (i.e., Bode plot) and upstream die shape. Interestingly, the amplitude ratios obtained here under different conditions could be uniquely estimated from a single master curve of Bode plot by defining the dimensionless time.

EQUATIONS FOR FREQUENCY RESPONSE ANALYSIS

1. Viscocapillary Model Considering Sloped Upstream Die Geometry

Viscocapillary model for a Newtonian liquid in coating bead region with linear sloped die lip designs was derived in detail by Lee et al. [4] using the lubrication approximation. Note that operability windows established by this simple model remarkably agreed with those by 2-D Navier-Stokes model under different die lip geometries. Relation for the cases with linear sloped upstream die lip configurations in Figs. 1(a) and 1(b) is expressed as follows:

$$\Delta P = 1.34Ca^{2/3}\frac{\sigma}{h_\infty} + \frac{\sigma}{h_u(x_u)}(\cos\phi + \cos\vartheta) + a + L_d\frac{6\eta U_{web}(h_d - 2h_\infty)}{h_d^3}. \tag{1}$$

Parameter a is redefined for the following cases with different upstream die lip geometries.

For case 1: angles from the fixed outer corner of the upstream die lip (Fig. 1(a)),

$$a = \frac{6\eta U_{web}}{\tan\theta_u}\left(\frac{1}{\tan\theta_u \cdot x_u + h_0} - \frac{1}{\tan\theta_u \cdot L_u + h_0}\right) \tag{2}$$

For case 2: angles from the fixed inner corner of the upstream die lip (Fig. 1(b)),

$$a = \frac{6\eta U_{web}}{\tan\theta_u}\left(\frac{1}{h_0} - \frac{1}{\tan\theta_u \cdot (L_u - x_u) + h_0}\right). \tag{3}$$

In the case of θ_u=0, parameter a can be more simplified below [5,6].

$$a = (x_f - x_u)\frac{6\eta U_{web}}{h_u^2} \tag{4}$$

Above equations to determine coating limits or onsets were slightly modified for only focusing on the upstream die lip change, in comparison with those in Lee et al. [4]. Definitions, units, and numeric values for variables and parameters in above equations are fully described in the Nomenclature.

2. Transient Mass Balance for the Frequency Response

Time-dependent global mass balance of a liquid in the coating bead should be considered together with the above viscocapillary model for evaluating the transient change of a coating thickness (h_∞) along with time when an ongoing disturbance at flow rate (Q_f in Eq. (5)) is introduced in the system. This is obtained by combining changes of liquid mass in the upstream and downstream die regions [5,6]:

$$\frac{dx_u}{dt} = \frac{1}{h_u(x_u)}(U_{web}h_\infty(t) - Q_f(t)) \tag{5}$$

The amplitude ratio of coating thickness (i.e., AR=$(h_{\infty,max} - h_{\infty,min})/(2h_{\infty,s}A)$) with respect to the sinusoidal disturbance around the steady flow rate (i.e., $Q_f(t)=Q_{f,s}(1+A\sin(\omega t))$ with 5% input amplitude, A=0.05) has been solved by 4th-order Runge-Kutta method for time integration and Secant's method for calculating the coating thickness (h_∞) and the position of upstream meniscus (x_u) in Eqs. (1) and (5). Newtonian liquid (i.e., a mixture of glycerin and water (80 : 20 wt%) [4,6]) adopted in this simulation has the following properties: viscosity (η) of 0.045 Pa·s, surface tension (σ) of 66 mN/m, density (ρ) of 1,210 kg/m^3, static contact angle (ϑ) of 60^o, and dynamic contact angle (ϕ) of 120^o.

RESULTS AND DISCUSSION

Frequency response test is usually conducted by introducing the tiny sinusoidal perturbation with a specified frequency around uniform stable states. From the operability window as reproduced in Fig. 2 [4], conditions of bead pressure and web speed for stable coating operations, free from leaking and bead breakup defects, were decided for two cases of Fig. 1. Note that marginal curves for two cases are identical from the viscocapillary model; however, these are slightly different each other from 2-D full model. Bead

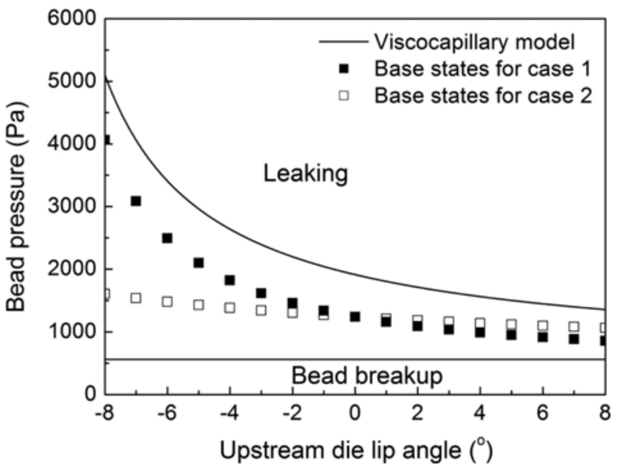

Fig. 2. Operability window for two cases in Fig. 1 along with bead pressure and upstream die lip angle. Closed and open symbols denote base states when the upstream meniscus is located at the middle of upstream die lip for case 1 and case 2 in Fig. 1, respectively.

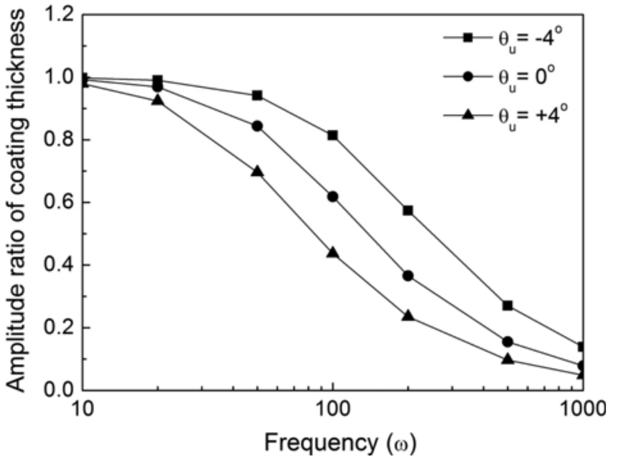

Fig. 3. Amplitude ratios of sinusoidal coating thickness for case 1 under different upstream die lip angles with respect to sinusoidal disturbance at flow rate in frequency domain.

pressure values for leaking onsets generally increase as the upstream angle decreases. This implies that the strong bead pressure is required to pull the coating liquid toward the upstream region when the upstream coating gap becomes narrow. This trend is quite similar to the cases with the overbite and underbite slot die geometries [5,6].

First, we compared amplitude ratios of final coating thickness with respect to sinusoidal flow rate disturbances with different frequencies when the upstream menisci in base states under different upstream lip angles were located at the middle of upstream die region. These base states are marked in symbols in Fig. 2. As depicted in Fig. 3, all amplitude ratio values for the case 1 of Fig. 1(a) decreased with the input frequency, starting from almost 1 at low frequency, for a flow rate disturbance directly changing mass balance [6]. It was found that the transient response of final coating thickness in the case with sloped angle of +4° was less sensitive to a sinusoidal disturbance in contrast to other cases. This would be directly linked with the previous results [6,15], reporting that the overbite die design gave lower amplitude ratio than standard or underbite die designs, owing to the damping effect by larger space in the upstream die region. Fig. 4 displays changes of amplitude ratio of coating thickness along with upstream die lip angle at several frequencies for two cases of Fig. 1. Amplitude ratios decreased with upstream lip angle when the space for a coating liquid in the upstream die lip region changed from underbite-like (smaller space) to overbite-like (larger space) under the given frequency conditions. From these results, it has been found that the die lip configuration in coating bead regime considerably affects the sensitivity to disturbances as well as the operability window.

Interestingly, all amplitude ratio curves (Figs. 4(a) and 4(b)) in the frequency domain obtained under different upstream die lip angle and frequency conditions can be efficiently unified in a single curve by defining the dimensionless time ($\tilde{t}$) between two time scales [18] - characteristic fluid time considering sloped upstream die feature (t_f) and characteristic time for perturbed oscillation (t_p),

$$\tilde{t}=\frac{t_f}{t_p}=\frac{\rho\bar{h}_u^2/2\eta}{1/2\pi\omega}=\frac{\pi\rho\bar{h}_u^2\omega}{\eta} \tag{6}$$

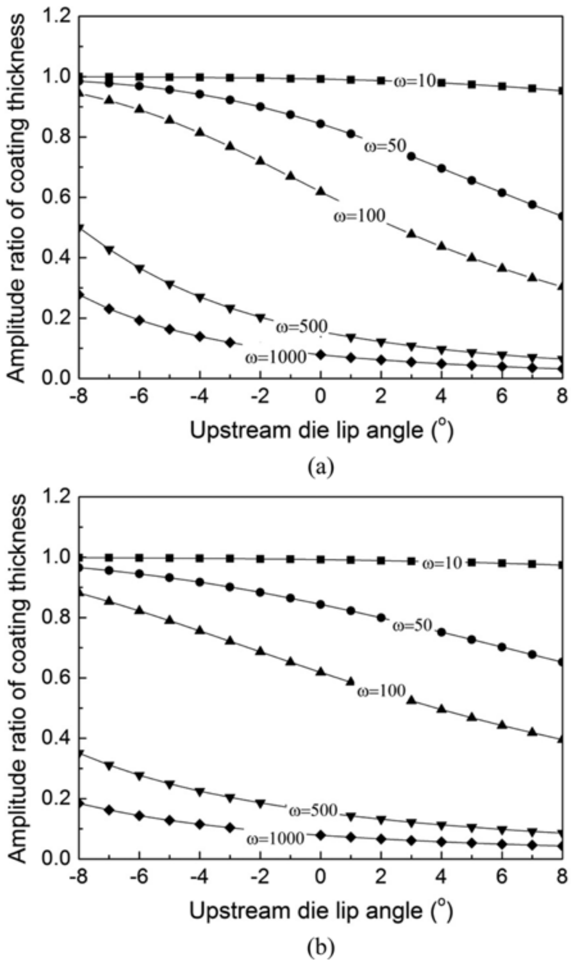

Fig. 4. Effect of upstream die lip angle for (a) case 1 and (b) case 2 on the amplitude ratio of coating thickness at several input frequencies.

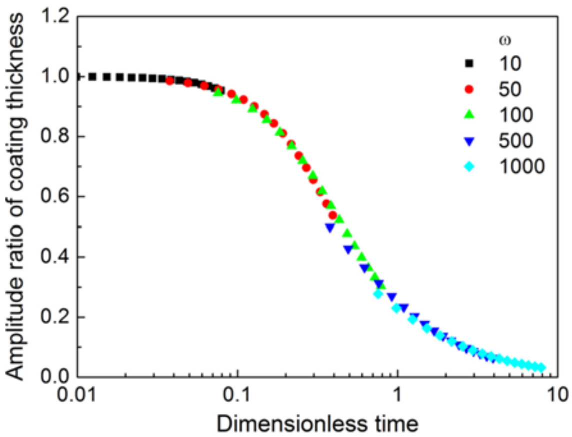

Fig. 5. (Color online) Unified amplitude ratio of coating thickness along with dimensionless time.

where, $\bar{h}_u=\dfrac{h_u|_{upstream\ position}+h_u|_{feed\ exit}}{2}$.

Note that the frequency (ω) plays a role as a shift factor in defining the dimensionless time. Fig. 5 shows the single master curve of amplitude ratio for coating thickness plotted against the dimensionless time, notably combing all data of Fig. 4. It is possible to easily and directly extract amplitude ratio result of an output variable, representing its sensitivity with respect to a specified disturbance, from a master curve like Fig. 5 for all input frequencies and sloped upstream die lip shapes.

CONCLUSION

Frequency response analysis has been performed to theoretically address the sensitivity of slot coating process with different sloped upstream die shapes, employing the simplified viscocapillary model for a Newtonian coating liquid. Considering that the upstream die lip geometry significantly affects coating dynamics by altering the position of upstream meniscus in coating bead region, the effect of upstream die lip angle on the transient oscillation of coating thickness with respect to a sinusoidal flow rate disturbance has been mainly focused in this study. From amplitude ratio data of coating thickness under various process conditions, the system becomes less sensitive to an imposed disturbance as the upstream die lip angle is larger. This might be ascribed to the damping effect of the larger space for a coating liquid in the upstream die lip region. A unified amplitude ratio curve obtained in the domain of new dimensionless time could be very beneficial to directly determine the amplitude ratio of output variable for any conditions of input frequency and upstream die lip angle.

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NOMENCLATURE

A : perturbed amplitude (=0.05)
AR : amplitude ratio
Ca : capillary number ($\equiv \eta U_{web}/\sigma$)
h_0 : base coating gap (=200 mm)
h_d : downstream coating gap (=200 mm)
h_u : upstream coating gap as a function of upstream position
h_∞ : final coating thickness (=80 mm)
L_d : downstream die lip length (=1000 mm)
L_u : upstream die lip length (=1000 mm)
P_d : applied downstream pressure
P_v : applied upstream pressure
ΔP : pressure difference (Bead pressure$\equiv P_d - P_v$)
Q_f : flow rate as a function of time
$Q_{f,s}$: steady state flow rate
t : time
U_{web} : web speed (=0.2 m/s)
x : x-direction coordinate
x_d : position at the end of downstream lip
x_f : position at the feed
x_u : position of the upstream meniscus

Greek Letters

ϕ : dynamic contact angle (=120°)
η : liquid viscosity (=0.045 Pa·s)
ϑ : static contact angle (=60°)
θ_u : upstream die lip angle
ρ : liquid density (=1210 kg/m^3)
σ : surface tension (=66 mN/m)
ω : input frequency

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