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Dynamics and Stability of Curtain Flow: Comparison of 1D and 2D Models

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Abstract

In the curtain coating, liquid curtain that falls freely before impinging on the substrate is subject to more instabilities, for example, the periodic oscillations in viscous curtain, and is more susceptible to external disturbances, air pressure and substrate speed for example, than other coating methods. Thus, computer-aided theoretical modeling is valuable in understanding, predicting, and controlling the curtain behavior. In this study, flow dynamics and stability of simplified curtain flow developed in our previous study (Jung and Scriven, 2001) have been revisited. Effects of process conditions such as Reynolds number, capillary number, air pressure difference, etc. on the process stability and sensitivity have been fully examined. Also, how accurate and valuable the simplified model will be has been investigated by comparing results of both simplified 1D and 2D models.

Introduction

Curtain coating, in its precision mode, is a premetered coating process (Fig. 1) that has been used to manufacture single-layer and, most notably, multiplayer coatings and patch coatings by falling freely on substrates moving at relatively high speeds (e.g., faster than 5m/s). The curtain can be delivered by a slot die, as in casting of polymeric sheet, or, if the number of layers exceeds two or three, by a slide die (Miyamoto and Katagiri, 1997).

What is unique to this process is the unconstrained liquid sheet that falls freely one to many centimeters before impinging on the substrate being coated. In general, the sheet is subject to more instabilities, for example, the periodic oscillations of “draw resonance” in viscous curtains (Yeow, 1974), and is more susceptible to external disturbances, air pressure variations for example (Finnicum et al. 1993, Weinstein et al., 1997), than other coating operations. Therefore, computer-aided theoretical modeling is valuable in understanding, predicting, and controlling curtain behavior.

The excellent analysis of curtain coating process has been pioneered by Kistler (1983) and followed by Ogawa and Scriven (1990) by means of the 2D Navier-Stokes modeling for viscous free surface flow. Such theoretical analysis is so challenging and time-consuming that a simpler, approximate model would be valuable, once its range of validity were known by comparison with fuller theory and with experiment. In this study, simplified model of curtain flows has been developed and compared with 2D case and the stability/sensitivity of this system have also been investigated.

Simplified Equations of Curtain Flow

Simplified model rests on one-dimensional sheet profile equations for curtain thickness and curtain trajectory based on the integral momentum balance approach (Jung and Scriven, 2001). It also draws on the one-dimensional film profile equation of film thickness variation in flow down a slide. Curtain forming region between two regions was roughly approximated using simple matching conditions.

Flow model on the slide:

$$\frac{1}{\mathrm{Ca}}\frac{\mathrm{dk}}{\mathrm{dx}} = \left(-\frac{6}{5}\mathrm{Re}\frac{1}{\mathrm{h}^3} + \mathrm{St}\cos\theta\right)\frac{\mathrm{dh}}{\mathrm{dx}} + 3\frac{1}{\mathrm{h}^3} - \mathrm{St}\sin\theta \tag{1}$$

where h denotes dimensionless film thickness, x dimensionless spatial coordinate along the slide wall, θ slide inclination angle from the horizontal line, k dimensionless curvature of the free surface, Re Reynolds number, Ca capillary number, and St Stokes number.

Flow model on the curtain flow:

$$\frac{1}{\mathrm{Ca}}\frac{\mathrm{d}}{\mathrm{ds}}\left(\frac{\mathrm{d}^2\left(\mathrm{H}/2\right)/\mathrm{ds}^2}{\left(1+\left(\mathrm{d}(\mathrm{H}/2)/\mathrm{ds}\right)^2\right)^{3/2}}\right) = -\frac{\mathrm{Re}}{\mathrm{H}^3}\frac{\mathrm{dH}}{\mathrm{ds}} + \frac{4}{\mathrm{H}}\frac{\mathrm{d}}{\mathrm{ds}}\left(\frac{1}{\mathrm{H}}\frac{\mathrm{dH}}{\mathrm{ds}}\right) - \mathrm{St}\sin\alpha \tag{2}$$

$$-\frac{\mathrm{d}\alpha}{\mathrm{ds}}\left(\frac{\mathrm{Re}}{\mathrm{H}} + \frac{4}{\mathrm{H}}\frac{\mathrm{dH}}{\mathrm{ds}}\right) + \Delta\mathrm{P} + \frac{2}{\mathrm{Ca}}\frac{\mathrm{d}\alpha}{\mathrm{ds}} + \mathrm{St}\cos\alpha\ \mathrm{H} = 0 \tag{3}$$

where α denotes inclination angle of the curtain from the horizontal line, s dimensionless spatial coordinate along the curtain trajectory, H dimensionless curtain thickness, and ΔP dimensionless air pressure difference across the curtain.

Steady-state flows of 1D system are found by solving above governing equations with appropriate boundary conditions of two flow regions in finite difference approximation by Newton's method with continuation. Instability is determined by solving, in finite difference approximation, the generalized eigenproblem that arises from linearizing the transient equations for tiny disturbances from a steady state. Sensitivity by frequency response method is also determined by solving the linearized transient equations for tiny forced sinusoidal oscillations around a steady state. Alternative ways of solving the frequency response equation system were compared.

Results and Discussion

Effects of process parameters such as inertia (Reynolds number), gravity (Stokes number), surface tension (capillary number), and air pressure difference on the film profile and trajectory can be estimated using the simplified model suggested in this study. For example, Fig. 2a shows how inertia (or Reynolds number) affects the film profile. As Reynolds number rises, the upstream film profile on the slide flow becomes more slightly wavy, as predicted by the asymptotic inflow boundary condition. It was already confirmed that asymptotic boundary condition included standing wave properties of the liquid film, and this trend was more prominent when Reynolds number rose. Also, it can be seen from Fig. 2b that curtain profile become more and more thicker at the same position as Reynolds number increases under the given conditions.

It has been confirmed that flow behaviors by 1D system qualitatively agree with 2D results solved by 2D FEM simulation with auto-remeshing scheme and commercial software Flow-3D.

Stability results of 1D model show how process parameters affect the critical conditions beyond which a curtain is unstable with respect to oscillations of curtain thickness and of curtain shape that propagate along its length as kinematic waves resembling the venuous mode.

That changes in sensitivity, i.e. amplification ratio from frequency response, as operating conditions are varied agree with the corresponding trends in eigenvalues was also confirmed. Moreover, alternative ways to effectively solve the frequency response equation system were compared. Interestingly, in the cases examined, integrating the linearized equations over the length of the curtain proved far more efficient than modal analysis using the eigenfunctions or solving the matrix problem from the entire length by either a direct method or an iterative one (GMRES).

Effect of pressure difference between the curtain (ΔP) on the stability and sensitivity is portrayed in Fig. 3, as examples of stability and sensitivity results. It can be found that increasing ΔP, leading to the deflection of the curtain, makes the system more unstable to any disturbances.

Acknowledgements

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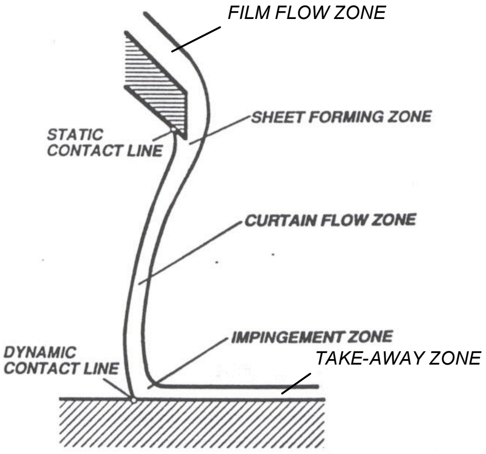
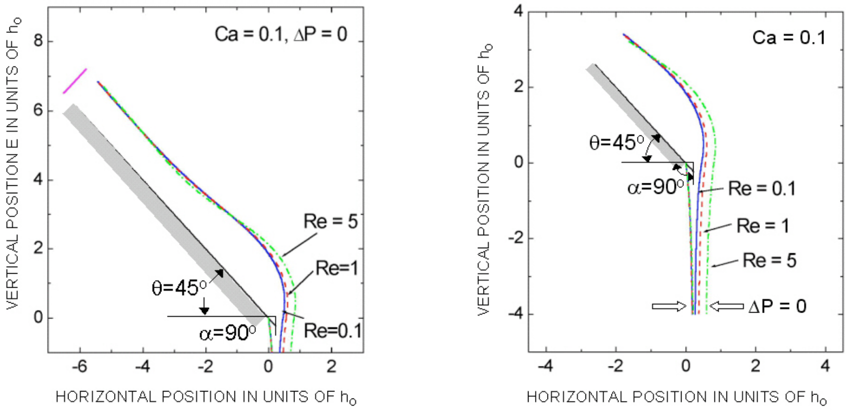
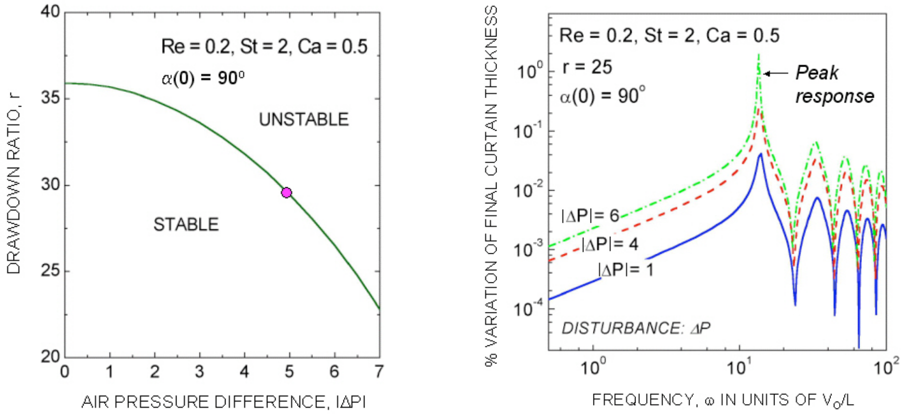


Fig. 1. Schematic diagram of curtain coating.



(a) (b)

Fig. 2. Effect of inertia (Re) on film profiles in (a) slide flow region and (b) curtain flow region.



(a) (b)

Fig. 3. Effect of pressure difference on (a) the stability and (b) the sensitivity of the system.