SHEAR-INDUCED SUPPRESSION OF RUPTURE IN TWO-LAYER THIN LIQUID FILMS

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Several coating and printing processes rely on the stability of thin liquid films [1,2]. Stability of these films are affected by various forces such as gravity, capillarity, electric fields, thermocapillary forces or molecular forces. When liquid layer thicknesses are of the order of 100-1000 A^o long-range molecular level forces such as van der Waals forces become significant. Several prior works have examined the destabilizing effect of van der Waals forces in thin film flows. However, the effect of a mean flow such as what would result from shear is not considered in these prior studies. Here, we examine the combined effect of shear and van der Waals forces on a bounded two-layer stratified thin film flow. We also consider the special case where the bounding surfaces may be chemically patterned in such a way that selected regions of these surfaces are preferentially wet by one of the two liquid layers [3]. The lithographic printing process is a practical motivation for examining such a configuration [4]. A schematic of the relevant section of a lithographic printing press is shown in Figure 1. In lithographic printing, the printing ink stored in the ink rollers is transferred to the image areas of the plate cylinder through a thin barrier film of water. High shear rates on the order of 10^4 s^{-1} are known to result in the nip between the form roll and the plate cylinder. It is however, a mystery as to how the shear in the nip would affect the mechanisms of displacement of one liquid layer by another. The model considered in this study tries to examine this effect by an idealization of this nip with curved surfaces into a channel of flat parallel plates.

Figure 2 depicts the stratified two-layer flow of liquids 1 and 2 between solid surfaces 3 and 4. The top surface 4 is moving a dimensionless speed V_0 in the horizontal direction relative to the bottom surface 3. The dimensionless height of the liquid-liquid interface is h(x,t) where t is the dimensionless time. Using the lubrication approximation [5], we simplify the momentum equations and along with the boundary conditions we derive a single evolution equation to describe the height of the liquid-liquid interface:

$$0 = \frac{dh}{dt} + \frac{d}{dx}\left[\frac{1+(\mu_r-1)h}{f(h,\mu_r)}\left\{\frac{dh}{dx}\left(A_1\frac{1-h^3}{h} + \gamma(1-h^3)h^3\frac{d^3h}{dx^3} + \frac{\mu_r V_0 h^2}{2(h\mu_r - h + 1)}\right)\right\}\right] \quad (1)$$

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In the above equation A_1 is a constant denoting the magnitude of van der Waals attraction of the liquid-liquid interface to the bottom surface 3, γ is the interfacial tension, and μ_r is the ratio of the top layer viscosity to the bottom layer viscosity.

We performed linear stability analysis as well as nonlinear simulations of Eq. (1) to study the rupture behavior of the liquid-liquid interface in presence of shear. In particular, we studied the effect of liquid viscosities and relative heights of the liquid layers on the time of rupture, which is a key time scale for applications desiring intentional rupture. Consider the following dimensionless parameter values: $A_1=1$, $\gamma=1$, $\mu_r=1$, and $h_0=0.5$ (Note: h_0 is the dimensionless initial height of the liquid-liquid interface). The linear stability analysis with these parameter values reveals that infinitesimal perturbations to the liquid-liquid interface will be grow with time, amplified by van der Waals forces, causing the system to be unstable. More interestingly, the analysis predicts that the system admits traveling waves with a wave speed proportional to the velocity V_0.

Nonlinear simulations revealed the rupture behavior of the liquid-liquid interface in presence of shear. It is found that shear distorts the liquid-liquid interface due to the presence of traveling waves. The key result here is that the shear delays interfacial rupture and the rupture is eventually suppressed when the shear rates exceed a critical value. This interface stabilization is attributed to the steepening of the interface by transfer of the fluid element at the location of minimum interface height due to traveling waves.

We use parameters relevant to lithographic printing in our simulations to examine shear effects in printing. At first glance one might expect that high shear rates would alter rupture times in printing significantly, and consequently the rupture mechanism. However, our simulations showed that that rupture times in printing in presence and in the absence of shear are of the same order of magnitude (~ 100's of μs), and thus indicate that the displacement of the water layer in the nip by ink may not be affected by the high shear rates.

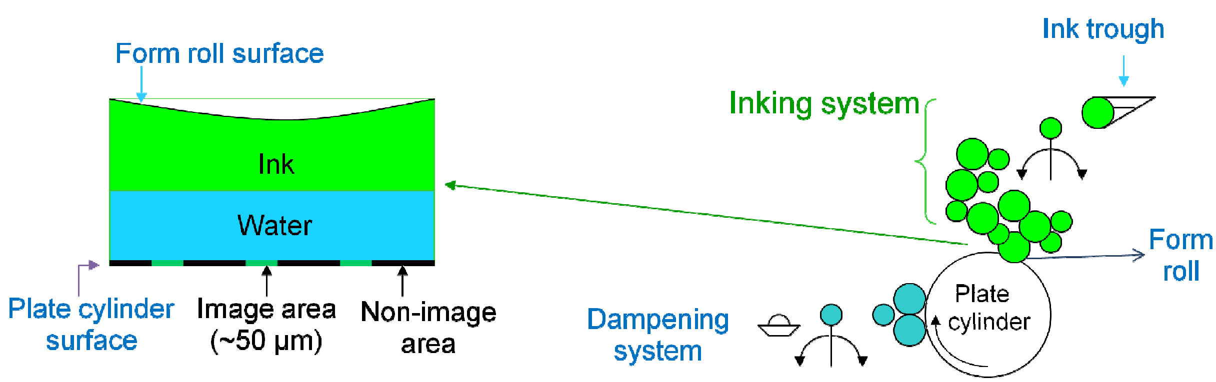

Figure 1: Schematic of the nip between form roll and plate cylinder in a lithographic printing press

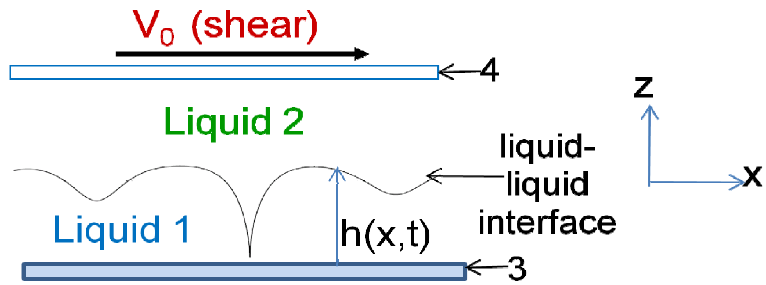

Figure 2: Stratified flow of two liquids between two solid surfaces

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