Effect of viscoplasticity on slot coating flows

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1. Introduction:

Slurries, pastes, suspension foams and emulsions are frequently handled in industrial processes [1]. When the microscopic structures inside such materials consisted of particles such as polymeric microgels, liquid or gas droplets, are developed significantly, they allow the materials to maintain the shape or deform in the same way as solids below a certain level of stress. But above this critical stress, the materials behave like liquid. This threshold stress is called yield stress [2].

The yield stress is already important in many engineering fields, including food processing [3], ceramic slurries processing for semiconductor [4], measuring rheological parameters for fresh concrete paste [5], etc. However, the yield stress is not widely considered in a liquid coating process for high speed thin-film productions.

The yield stress will affect the force balance inside coating flows that will change flow patterns and meniscus shapes of coating flows. Clearly desirable coater designs and operating conditions need to be changed, as described by Lee and Nam [6].

2. Effect of viscoplasticity in desirable operating conditions in slot coating:

The slot coating is considered as a precision method for producing commercial film products in high speed, such as adhesive tapes, optical films, and battery electrodes. The coated film thickness is directly determined by the liquid pumping rate into a coating device, so called slot die, and substrate speed. When the liquid passes through the die via the feed slot, it forms a liquid bridge between the moving substrate and the die lip surfaces, and is called the coating bead.

For the successful coating operation at a given coating device, the flow near the coating bead needs to be steady-state, two-dimensional and stable that can be achieved by proper operating conditions, e.g., vacuum pressure, flow rate, and substrate speed. A coating window is used to represent the range of such desirable operating conditions, and it can be predicted by theoretical and/or computational analyses [7] or obtained by experiments typically via flow visualizations [8].
In this study, we choose a neutralized aqueous Carbopols 941 solution (Lubrizol Advanced Materials, Inc., Ohio, USA) as a model transparent simple yield stress fluid and follows Herschel-Bulkley constitutive equation

$$\sigma = \sigma_{\mathrm{y}} + K\,\dot{\gamma}^{n} \qquad (1)$$

where σ is shear stress, σ_{y} is the extrapolated dynamic yield stress and K is the consistency index. A custom-designed lab-scale slot coating flow visualization device is used to observe the coating bead of the viscoplastic slot coating flow through the transparent roll. The visualization results are used to construct the coating window and identify the flow patterns under the die. Although the defect causing phenomena for the viscoplastic solution are similar to Newtonian solution, critical operating conditions for the onsets of defects are different, as shown in Fig. 1.

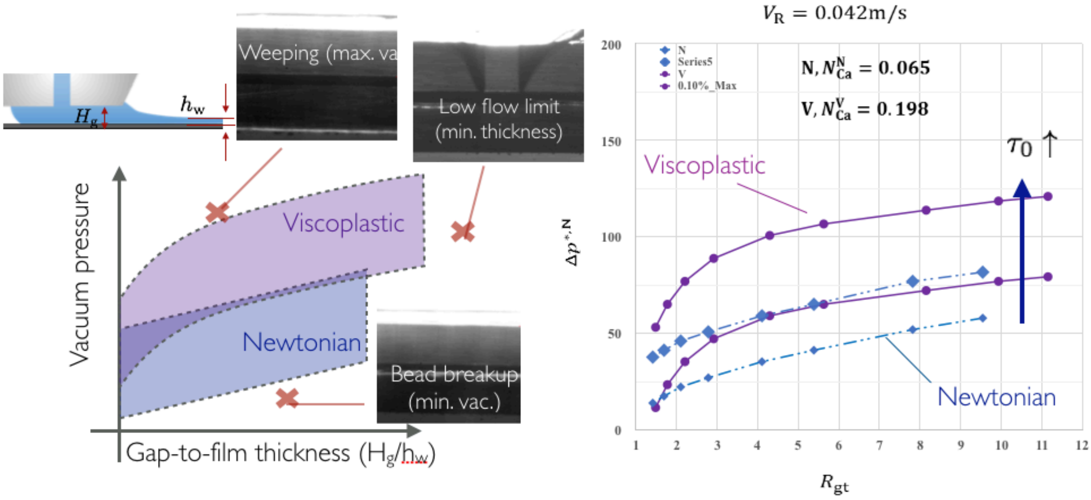

Fig.1 Effect of viscoplasticity in desirable operating conditions (coating window). Comparing with Newtonian fluid, the overall window shift to higher vacuum pressure.

3. Conclusions:

In this study, a custom-made slot coating flow visualization apparatus is used to examine the coating bead for the viscoplastic Carbopol solution. The introduction of viscoplasticity not only affects the force balance of the small-scale channel flows, but also the pressure jump across curved menisci. Consequently, the yield stress causes the upward shift of desirable vacuum range, and the shear-thinning viscosity leads to curved window boundaries. The most exceptional change is shoulder-wetting-induced low flow limit delay, which is potentially useful in practical thin-production with slow drying process.

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