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A Study on the Effect of Drawing on Extrudate Swell in Film Casting

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Abstract:
We present a numerical study of the film casting process, with a focus on the effect of the draw ratio on the swelling of the extruded sheet. So far, studies regarding film casting have dealt mainly with the phenomenon of neck-in and have neglected swelling of the material as it emerges from the die lips. Knowledge of the amount of swelling is important for accurate determination of the effect of stretching and orientation phenomena. The problem is tackled by studying the gap-wise swelling of the sheet or film as it emerges from a wide rectangular die and is subsequently drawn down under different draw ratios. The material is treated as viscoelastic by utilizing the Linear Phan Thien-Tanner (LPTT) model. Newtonian simulations are also carried out. A decoupled iterative algorithm is used for the determination of the shape of the extruded sheet, based on the fact that the sheet's surfaces belong to streamlines. Our results are in qualitative agreement with results in the literature, with the latter being limited in number and available mainly for the (similar) process of fiber melt spinning.

Key words:
Extrudate swell, viscoelastic, film casting

1 INTRODUCTION

Film casting is a very important industrial process for the production of plastic film, sheet, or tape that finds applications in a wide range of technologies such as in food packaging, automotive, housing, and agriculture. In the process of film casting, the polymer melt extruded from a flat or a slit die is stretched in the machine direction (flow direction) by coming in contact with a roller often of controlled temperature, which rotates at higher speed (the take-up or draw-down speed) than the speed of the extruded material. The extent of imposed stretch is quantified by the drawing ratio DR, which is the ratio of the take-up speed to the average velocity of the melt at the die exit. This speed differential leads to the formation of a sheet of reduced width through a mechanism called neck-in, along with higher thickness near the side edges (edge-beading).

In film casting as well as in other similar industrial processes (e.g. melt spinning), the emerging polymer has the tendency to locally swell near the die exit (extrudate swell).The extrudate or die swell problem itself, in the absence of a take-up roller has been extensively studied experimentally, theoretically, and numerically for Newtonian as well as viscoelastic fluids emerging from planar or axisymmetric dies [1–9]. Specific to film casting, several studies have also studied the neck-in and to a far lesser extent the edge-beading effects – experimentally or utilizing, theoretical, 1D, 2D and 3D numerical schemes [10–21]. These have offered useful insights concerning the different parameters affecting the process with the most important one being the draw ratio *DR*, the value of which defines the dimensions, shape and properties of the final product. The stretching of the extruded sheet caused by the rotation of the chill roll results in the formation of a product the dimensions of which are reduced compared to the dimensions of the die lip exit. For instance, in film casting the thickness of the extruded sheet is lower than the gap of the rectangular die and in melt spinning the extruded fiber's radius is lower than the radius of the round extrusion orifice or spinneret. However, immediately after the material exits the die it has the tendency to swell, significantly for very elastic melts and the dimensions of the product at this location are generally higher than the dimensions of the die gap. This swelling behavior in the presence of drawing has been neglected in the technical literature even though it is of practical significance as it directly determines the mechanical and stress-relaxation history of the sheet prior to its eventual stretching by the rolls.

While no comparable studies exist for film casting, a small number of studies exist concerning the prediction of swelling under stretching conditions of the extrudate for the process of wet or melt spinning. White et al. [22] studied experimentally and theoretically the melt

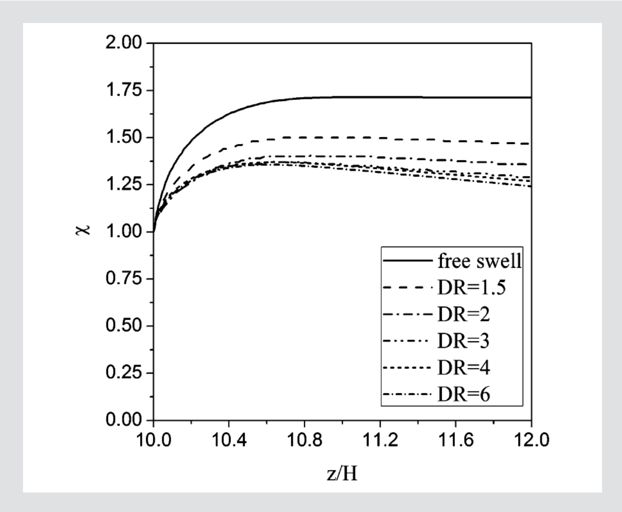

Figure 5: Extrudate shape (viscoelastic model) of the sheet's upper half for a region close to the die exit.

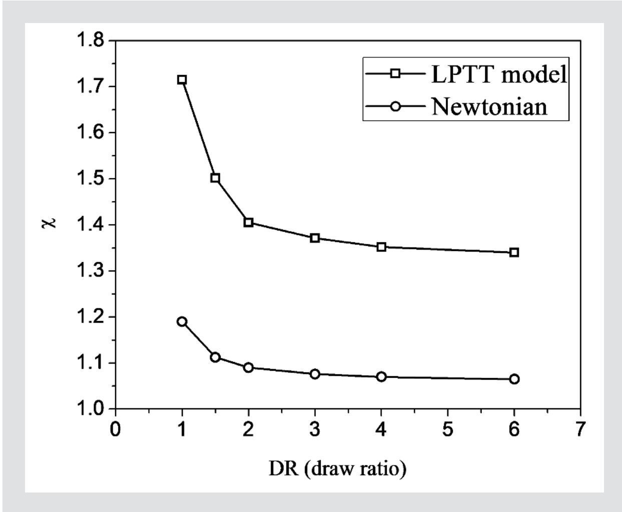

Figure 6: Effect of the drawing ratio on the maximum swell of the sheet for the Newtonian case and the viscoelastic LPTT fluid.

also shown in Figure 6 with the maximum free swell of χ = 1.1825 asymptotically decreasing to χ = 1.06 for *DR* = 6. These trends are in qualitative agreement with the experimental observations by White et al. [22] and by Ouyang et al. [25] for the similar process of wet spinning.

When the extruded sheet or film freely swells as it emerges from the slit die, it will leave the die with a velocity V_s (at the point of maximum swell) which is considerably lower than the average velocity $\bar{V}$ of the fully developed velocity profile. The velocity V_s at the location of maximum swelling for the LPTT fluid shown in Figure 4 and Figure 5 is 30 ~ 40 % smaller than the average velocity $\bar{V}$ and it is expected to be even smaller for more elastic fluids, which may exhibit swelling ratios perhaps up to 4. This suggests that any subsequent correlations or calculations regarding orientation stretching and determination of crystallinity as for example by Lamberti et al. [34] should use the ratio of the take-up speed V_R over the velocity at the maximum swell V_s rather than the average velocity at the die exit. Consequently, the actual draw ratio will be higher than the drawing ratio defined by Equation 7 and frequently encountered in film casting and melt spinning analyses in the technical literature. This suggestion is fully in agreement with a proposal by Paul [35] that V_R/V_s is 'a more realistic parameter' for describing the orientation stretching in (acrylic) fiber formation by the process of wet spinning.

5 CONCLUDING REMARKS

We presented two dimensional numerical results on how the maximum swelling of a sheet or film emerging from a slit die is affected by different drawing speeds for the process of film casting, neglecting the neck-in and edge beading formation. Two cases were examined: (a) Newtonian and (b) viscoelastic LPTT model as the constitutive equation. The extrudate shape was obtained via a decoupled iterative scheme by assuming that the top and bottom surfaces of the sheet lie on streamlines. The numerical results for the viscoelastic case indicate a rapid decrease of the maximum amount of swell as the drawing ratio increases. Similar behavior for a Newtonian fluid was also reported. However, a certain amount of swelling persists near the die exit even at drawing ratios of 6. Expressing the draw ratio in terms of the velocity at the point of the sheet's maximum thickness may give a more realistic picture of the process especially when any subsequent orientation stretching calculations are involved. The obtained results are in qualitative agreement with experimental, numerical and analytical studies for the (similar) processes of melt and wet spinning.

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