Analogy between the modelling of pullout in solution spinning and the prediction of the vortex size in contraction flows

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ANALOGY BETWEEN THE MODELLING OF PULLOUT IN SOLUTION SPINNING AND THE PREDICTION OF THE VORTEX SIZE IN CONTRACTION FLOWS

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Solutions of high molecular weight polymers in suitable solvents show a pronounced shear thinning behaviour combined with strong elastic effects and wall slippage. During spinning, these solutions are pulled out of the spinneret at a certain draw ratio. This process is studied. After surveying the equations governing the spinning process, attention is focused on the position of the detachment point in dependence of the solution properties and the processing conditions. A simple force balance at this point equilibrates the spinning tension (dominated by the elongational viscosity, the draw ratio and the strain rate) and the first normal stress difference (which depends on shear rate and die geometry). This analysis yields the upstream position of the detachment point. Intriguingly, the same analysis applies to the almost classical rheological problem of the entrance flow in a contraction. Following the same procedure, the size of the vortices can be predicted in dependence of the Deborah number, provided that both the transient elongational viscosity and the first normal stress difference of the solution are known. In fact, the latter problem might be less complicated because the flow occurs under isothermal conditions. However, one has to neglect the two-dimensional character of the flow in order to reach analytical results.

INTRODUCTION

In the search for the ultimate mechanical properties of polymers, nowadays, solutions of ultra high molecular weight materials are spun, using conventional spinning techniques. A striking example is the so called 'gelspinning' process, named after the intermediate spun yarn which forms a gel during the crystallisation of the polymer in the presence of a solvent. Due to the combination of ultra high molecular weight polymers and relatively high concentrations, viscoelastic effects are pronounced. This is illustrated by the need for extruders in the continuous preparation of homogeneous solutions. In our research, the problem of spinning highly concentrated solutions of ultra high molecular weight polyethylene in decalin had to be solved, in order to reach a stable process even at high throughputs. Because of the extreme character of the fluid, a careful design of the spinnerets proved to be important during the debottlenecking procedure. In the gelspinning process the solutions are pulled out of the capillary, at usual values of the draw ratio. More upstream, in the inflow of the capillary, vortices occur, which at higher throughputs tend to become unstable, as reflected in a poor extrudate quality, and hence impose a limitation on the process.

In this analysis pullout and the position of the detachment point is modelled and, as an extension thereof, the vortex size in the upstream contraction is predicted. The aim is a model which is as simple as possible, while still accounting for the dominant viscoelastic effects.

1. SPINNING EQUATIONS

The analysis of a one dimensional isothermal spinning process yields expressions for the velocity profile and the spinning force. For a Newtonian fluid it follows that:

$$\frac{v_z}{v_0} = \left(\frac{v_1}{v_0}\right)^{\frac{z}{L}} \quad \text{and} \quad F = \frac{Q\eta_e}{L} \ln \frac{v_1}{v_0} \tag{1}$$

While for a generalised viscoelastic Maxwell model it is found that:

$$F = \frac{3Q\eta \ln(v_1/v_0)}{L + \lambda(1 - 2a)(v_1 - v_0)} \tag{2}$$

Also, non-isothermal spinning and solution spinning with evaporating solvents have been modelled. Simulations show that, in the gelspinning process, the velocity and temperature profiles are hardly influenced by the introduction of viscoelasticity. The reason is that boundary conditions are given in terms of prescribed velocities and that the problem is dominated by fast cooling due to evaporation of solvent. However, viscoelasticity has a pronounced influence on the spinning force–draw ratio relations.

2. PULLOUT

As stated in the introduction, solutions can be pulled out of the capillary if the draw ratio is increased. The position of the detachment point is set by balancing the force necessary to stretch the filament (spinning force) and the stress that the fluid exerts normal to the wall due to its deformation history. The total normal stress due to the spinning force (σ_{zz}) and the normal stress at the wall (σ_{rr}) are connected through the first normal stress difference N_1:

$$N_1 = \sigma_{zz} - \sigma_{rr} \tag{3}$$

In a first approximation the spinning tension at the detachment point can be set equal to the average total normal stress in z-direction:

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$$\sigma_{zz} = \frac{F}{\pi R^2} \quad (4)$$

Furthermore, at the detachment point the total normal stress exerted on the wall is zero, in order to allow the fluid to leave the wall:

$$\sigma_{rr} = 0 \quad (5)$$

Combining of equations (3), (4) and (5) gives a relation between the spinning force F and the normal stress difference N_1 at the detachment point:

$$F_c = N_1 \pi R^2 \quad (6)$$

A more accurate stress balance at the detachment point can be obtained from an integral momentum balance:

$$F_c = 2\pi \int_0^R \left(N_1 + \frac{N_2}{2}\right) r dr \quad (7)$$

with N_2 the second normal stress difference, which is much smaller than the first ($N_2 \simeq -0.1\ N_1$).

The position of the pullout length or the detachment point can now be understood. Figure 1 reveals the flow of a solution through a contraction into a cylindrical die. A spinning force is applied on the solution in order to make pre-oriented yarns. Above the critical spinning force F_c the solution is pulled out of this die, since outside the die strongly non-isothermal conditions exist due to the evaporation of solvent, resulting in a steep stress–strain curve. Inside the die more or less isothermal stretching conditions exist, because the ambient air is saturated with solvent. As a consequence the spinning force necessary to accelerate the fluid from v_0 to v_1 strongly depends on the isothermal stretch length L, inside the die, see equations (1) and (2). Moreover, the spinning force depends on the total draw ratio. On the other hand, the normal stress that the fluid exerts on the wall not only depends on the shear rate, but also on the distance from the contraction, due to the – relaxing – extra stress generated during the flow through the contraction. The intersection of both lines gives the position of the detachment point, as revealed in equations (6) or (7). Figure 2 shows the effect of an increase in throughput, which influences both lines. Whether the detachment point will move in the direction of the contraction or in opposite direction now will depend on the more detailed rheology of the fluid, i.e. the transient elongational viscosity and the shear rate dependent first normal stress difference.

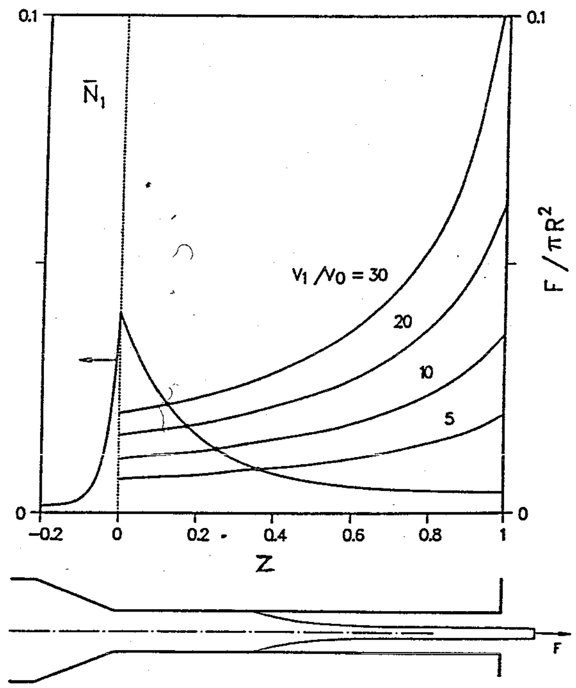

Figure 1. Development of the averaged normal stress ($\bar{N}_1$) versus the distance z from the contraction (qualitatively) and the spinning tension as a function of the isothermal stretch length $(1-z)$. Parameter: draw ratio. The intersection of both lines gives the position of the detachment point.

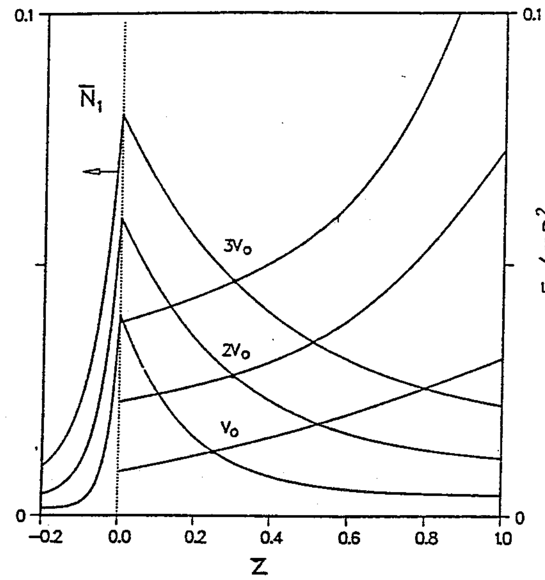

Figure 2. As Figure 1. An increase in throughput, at constant draw ratio, influences both lines. The shift of the detachment point now depends on more detailed rheology.

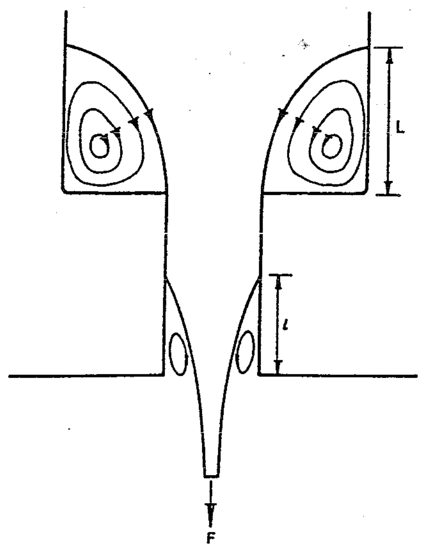

Figure 3. Analogy between the pullout length in solution spinning and the vortex size in contraction flow.

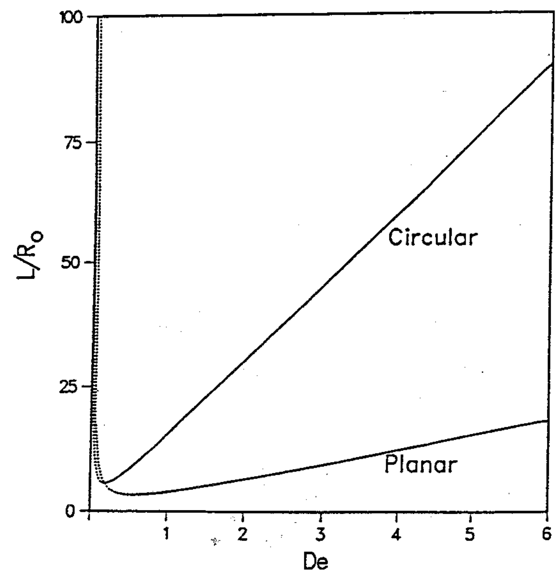

Figure 4. Vortex size versus Deborah number as calculated with the UCM model for a circular and a planar 4:1 contraction.

3. VORTEX SIZE IN CONTRACTION FLOWS

The analogy between the pullout length and the vortex size in the upstream flow is demonstrated in Figure 3. If the attention is focused on the detachment point of the vortex, where the fluid leaves the wall, again the condition:

$$\sigma_{rr} = 0 \tag{8}$$

should be met, setting the 'isotropic' pressure in the vortex to zero. This yields again the criterion of equation (7). The only problem which remains is to determine the 'force' F which is necessary to accelerate the fluid. With some simplifications this is an isothermal spinning process with:

$$v_0 = Q/\pi R_0^2 \tag{9}$$

$$\frac{v_1}{v_0} = \left(\frac{R_0}{R_1}\right)^2 \tag{10}$$

and the stretch length L equal to the vortex size.

For this problem the force F is explicitly given in equation (1) for the Newtonian case, while for the transient viscoelastic Maxwell model equation (2) can be used. The vortex size for different fluids can now be found by a combination of the expression for the critical force (equation (7)) and one of the equations for the spinning force (equation (1) or (2)). For example, for the generalised Maxwell fluid:

$$L = \frac{3Q\eta \ln(v_1/v_0)}{2\pi \int_0^R \left(N_1 + \frac{N_2}{2}\right) r \, \mathrm{d}r} - \lambda(1 - 2a)(v_1 - v_0) \tag{11}$$

For an upper convected Maxwell model ($a = 1$), the right-hand side of equation (11) can be simplified, while for $n = 1$ (constant viscosity), the expression finally reads:

$$L = \frac{3R_0^2}{16\,\lambda\, v_0} \ln\frac{v_1}{v_0} + \lambda(v_1 - v_0) \tag{12}$$

In Figure 4 the dependence of the vortex size in a circular 4:1 contraction, according to equation (15) is given as a function of the Deborah number:

$$De = \frac{\lambda\, v_0}{R_0}$$

As a comparison, the vortex size in a planar contraction, calculated in a similar way, is presented. Although detailed data on both the shear rate dependent first normal stress difference and the transient viscosity combined with measurements of the vortexsize as a function of throughput or Deborah number are very rare, the results of the analysis presented here compare reasonably well with experimental data.

FURTHER READING:

Bulters, M. J. H. and Meijer, H. E. H., 1990, *JNNFM*, 38:43–80.