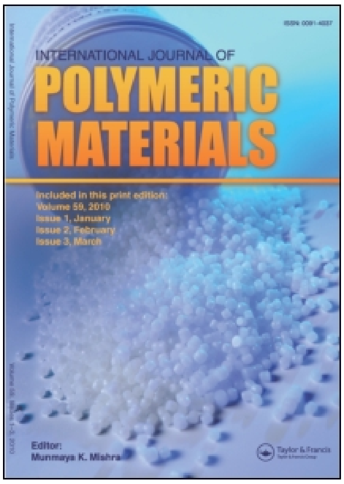

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Description of Jet Swelling

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Jet swelling is interpreted in terms of normal stresses and high elasticity deformations developed during the flow through the channel.

KEY WORDS Die swell, jet swell, channel geometry.

ANALYSIS AND RESULTS

The increase of the jet cross-section in comparison with the area of the outlet channel during forcing of polymer materials through the die-head is observed. This phenomenon is named the jet swelling or the high-elasticity recovery of the extrudate. It is currently an accepted practice to call the relationship between the extrudate and forming channel diameters the swell ratio. A particular area of importance in the processes of free extrusion is the calculation of the swell ratio and the control of the elastic recovery.

The analysis of experimental data shows the swelling value to be dependent on stress-strain state, molecular characteristics and temperature of the material, channel geometry and conditions under which the measurements have been performed.

In this paper the jet swelling is interpreted in terms of normal stresses and high-elasticity deformations developed in the process of flow. Two approaches are used to calculate swell ratios. The first employs the elastic recovery model, which is based upon the assumption that energy accumulated by a medium flowing in a channel is released due to elastic compression of the jet in the axial direction. Following this method we succeeded in relating recoverable shear deformations and normal stress differences to the swell ratio. In the second case, the elastic fluid on emerging from the circular tube is numerically investigated. The problem was solved by the finite element method.

Let us consider the one-dimensional motion of fluid flowing through a cylindrical tube. The properties of the fluid are described using the integral model

$$\frac{d\tau}{dr} + \frac{\tau}{r} = \frac{dP}{dZ} \equiv \text{const}, \tag{1}$$

$$\dot{\gamma} = \psi(\tau)\frac{\lambda_1}{\lambda_2} - \int_0^t \psi[\tau(\theta)]\frac{\lambda_1 - \lambda_2}{\lambda_2^2}\exp\left(-\frac{t-\theta}{\lambda_2}\right)d\theta, \tag{2}$$

where P is the pressure, r and Z are the cylindrical coordinates, τ and $\dot{\gamma}$ are the stress and the shear rate, t and θ are the present and current times, respectively, λ_1 and λ_2 are the relaxation and retardation times. In order to obtain a satisfactory description of the flow curve, we have chosen the function of the form

$$\psi = \varphi_0\tau + \varphi_1\tau^{\alpha+1}. \tag{3}$$

For $\lambda_1 = \lambda_2$ the Equation (2) reduces to the three-parameter Ellis model.

The material in the tube under the constant pressure gradient is subject to the shearing flow. The shearing flow rate is determined from relations (1) and (2)

$$\dot{\gamma} = \psi[\tau(r)]\left[1 - \frac{\lambda_1 - \lambda_2}{\lambda_2}\exp\left(-\frac{t}{\lambda_2}\right)\right]. \tag{4}$$

It is seen that the shear rate is a function of radius and residence time of the material particle in the tube. The shear rate is equal to the sum of the recoverable and non-recoverable components. Moreover, the first component defines the high-elasticity deformation stored in the material during its flow through the tube. This deformation causes the development of aftereffect deformation in the material at the residence time in the channel that precedes the jet swelling.

To specify the recoverable part of the shear rate we divide the integration interval into two parts

$$0 \leqslant \theta \leqslant T, \qquad T \leqslant \theta < \infty,$$

where T is the residence time of the particle in the tube. Thus, use of the formula (4) gives the recoverable shear rate

$$\dot{\gamma}_e = \psi[\tau(r)]\,\frac{\lambda_1 - \lambda_2}{\lambda_2}\exp\left(-\frac{T}{\lambda_2}\right).$$

Integrating this expression, we obtain the high-elasticity deformation accumulated by the material during its flow through the tube

$$\gamma_e = \psi(\tau)(\lambda_1 - \lambda_2)\left[1 - \exp\left(-\frac{T}{\lambda_2}\right)\right]. \tag{5}$$

Using Equations (1), (3) and (5), we obtain the average elastic deformation

$$\gamma_{av} = \langle\gamma_e\rangle = \psi_{av}(\lambda_1 - \lambda_2)\left[1 - \exp\left(-\frac{T_{av}}{\lambda_2}\right)\right], \tag{6}$$

where the subscript av signifies the averaging.

Use of the well-known formula which relates the high-elasticity deformation to the swell ratio provides us with an opportunity to eliminate the average deformation from Equation (6). Assuming

$$\gamma_{av} = \left(B^4 + \frac{2}{B^2} - 3\right)^{1/2}$$

we obtain

$$B^4 + \frac{2}{B^2} - 3 = \psi_{av}^2(\lambda_1 - \lambda_2)^2\left[1 - \exp\left(-\frac{T_{av}}{\lambda_2}\right)\right]^2 \tag{7}$$

where B is the swell ratio.

In the case where the tube is rather long we have

$$B^4 + \frac{2}{B^2} - 3 = \psi_{av}^2(\lambda_1 - \lambda_2)^2 \tag{8}$$

Equation (8) allows us to calculate the swell ratio of the jet upon emerging from the long tube. If the relaxation and retardation times are dependent on the shear stress (or shear rate) it is necessary to use their averaged values.

The use of the Leonov model as the rheological equation allows us to perform numerical calculation of the viscoelastic fluid swelling:

$$\sigma + P\delta = 2\eta s e + 2\sum_{K=1}^{N}(W_{K.1}C_K - C_K^{-1}W_{K.2}),$$

$$e_K^P = \frac{1}{2\mu_K\lambda_K}\left[\left(C_K - \frac{I_{K.1}}{3}\delta\right)W_{K.1}^S - \left(C_K^{-1} - \frac{I_{K.2}}{3}\delta\right)W_{K.2}^S,\right.$$

$$W_{K.j} = \frac{\partial W_K}{\partial I_{K.j}}, \qquad \overset{\circ}{C} = \frac{dC}{dt} + \omega\cdot C - C\cdot\omega, \qquad I_{K.1} = tzC_K,$$

$$I_{K.2} = tzC_K^{-1}, \overset{\circ}{C} - C_K\cdot(e - e^P) - (e - e^P)\cdot C_K,$$

$$\det C_K = 1, 2W_K(I_{K.1}, I_{K.2}) + W_K(I_{K.2}, I_{K.1}),$$

where W is the elastic potential, K is the kth relaxation mechanism, C_K is the elastic deformation tensor (Finger measure), $I_{K.1}$, $I_{K.2}$ are its main invariants, η is the maximum Newtonian viscosity, μ is the shear modulus, S is the dimensionless rheological parameter, e is the rate of deformation tensor, e^P is the rate of non-recoverable deformation tensor.

In a previous paper[1] we presented the algorithm of solution and developed a program to calculate the viscoelastic fluid flow in axisymmetrical channels.

In the present work we extend the above-cited algorithm to calculate the swelling of the fluid upon emerging from the channel. The problem is solved using the finite element method. The channel is prolonged into the outflow zone and the free surface is replaced by a moving boundary. Neglecting the surface tension forces, we can write the following boundary conditions

$$\sigma \cdot n = 0, \tag{9}$$

$$V \cdot n = 0, \tag{10}$$

where σ is the total stress tensor, V is the velocity vector, n is the normal to the surface. According to Equation (9), it is the boundary motion that realizes in proportion to the elastic deformation value. The finite-element net is rearranged at every iteration. The end of the iteration process was conditional on the normal stresses going to zero in the boundary elements.

It should be noted that in the case of the fully developed flow at the entry section, it is the predicted pressure that must be uniform over the cross-section. This is verified by the ratio of $\Delta P/\tau_w$ (where ΔP is the difference between maximum and minimum pressures, τ_w is the wall shear stress). In most cases it did not exceed one per cent.

Calculations show that these results are in fairly good agreement with the well-known solutions. Thus, upon emerging from the tube (L/d = 0,2), it is the swell ratio for Deborah number of $\dot{\gamma}_w\lambda$ = 0,3 that leads to B = 1.137. Following Reference 2 and Tanner theory for the analogous flow, the value of B = 1.145. The pressure loss was determined from the following relation[2]

$$\delta P/\tau_w = (P_0 - 4\tau_w L/d)\tau_w$$

where P_0 is the pressure drop at the input section. The value of $\delta P/\tau_w$ obtained in the present work is smaller than the similar one in Reference 2; they are 0.59 and 0.66, respectively.

It is seen from the numerical results that the elastic deformations have relatively stable values both in the channel and in the zone of changing boundary conditions. The axial pressure varies uniformly as well. It is the zero pressure point that is displaced to some extent from the channel exit down the flow. The wall pressure is more unstable. In general, the numerical scheme developed is rather stable. It gives stable solutions for small Deborah numbers. We did not perform calculations for large Deborah numbers due to computer time expenditure.

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