1. INTRODUCTION

The properties of polymer extrudates are mostly determined by the flow in the extrusion die and possibly by the flow history and temperature history upstream in the processing equipment. The analysis of these effects is quite involved since the flow in the extrusion die is inhomogeneous, i.e. the strain and temperature history is different for a polymer element of a layer near the wall and a polymer element flowing more in the middle of the flow channel (Fig. 1).

Fig. 1: Sketch of 3 annular die geometries to be investigated. For comparison, a fourth geometry will be used: An annulus of cross section (300 mm to 302 mm) which is constant throughout ("die 4").
2. RHEOLOGICAL CONSTITUTIVE EQUATION

The rheological behaviour of the flowing molten polymer will be described by the rubberlike liquid equation of Lodge\(^1\) as modified by Bernstein, Kearsley and Zapas\(^2\), and by Kaye\(^3\):

\[
\mathcal{Q}(t) = -p 1 + \int_{-\infty}^{t} m(t,t') \cdot \mathcal{Q}^{-1}(t,t') \, dt'
\]

where \(\mathcal{Q}(t)\) is the stress at time \(t\), \(p\) the isotropic pressure contribution, \(1\) the unit tensor, \(m(t,t')\) the memory functional, and \(\mathcal{Q}^{-1}(t',t)\) the relative Finger strain tensor between time \(t'\) and \(t\). The material behaviour is contained in the memory functional \(m(t',t)\) which not only depends on the time difference \(t-t'\) (as the rubberlike liquid does) but also on the time dependent invariants of the strain tensor \(\mathcal{Q}^{-1}\).

A factorized discrete memory

\[
m(t,t') = \mathcal{N} \sum_{i=1}^{N} \mathcal{G}_i \cdot \exp \left[ - (t-t')/\tau_i^r \right]
\]

with \(h = \text{relaxation damping function}; I, II = \text{first and second invariants of } \mathcal{Q}^{-1}; \mathcal{N} = \text{number of relaxation times}; \mathcal{G}_i = \text{relaxation moduli of linear viscoelasticity}; \tau_i^r = \text{relaxation times of linear viscoelasticity, tested in a most comprehensive test series, was found to describe all phenomena in shear and uniaxial extension of a low density polymer sample (called "melt I")}^{4-6}. The damping function used was

\[
h = \sum f_i \cdot \exp \left[ -n_i (\alpha I + (1-\alpha) II)^{\gamma/2} \right]
\]

where \(f_i\), \(n_i\), and \(\alpha\) were material parameters. In most applications, the strain invariants \(I, II\) are decreasing functions of time difference \(t-t'\). Counter examples are recovery experiments (extrudate swell, i.e.). In these cases the minimum value of \(h\)

\[
h^*(t,t') = \min_{t=t'} \mathcal{N} \sum \mathcal{G}_i \]

has to be used in the memory functional (irreversibility assumption of Wagner\(^8\)). The temperature dependence of the rheological model can be described by the temperature dependence of relaxation times \(\tau_i^r\). The relaxation moduli \(\mathcal{G}_i\) and damping function seem to be independent of temperature. The components of Finger tensor are

\[
\mathcal{Q}^{-1} = \begin{pmatrix}
\frac{(1+\gamma^2)}{\delta_x^2} & -\gamma/(\delta_x \delta_y) & 0 \\
-\gamma/(\delta_x \delta_y) & \frac{1}{\delta_y^2} & 0 \\
0 & 0 & \frac{1}{\delta_z^2}
\end{pmatrix}
\]