

Flow Instabilities in Viscoelastic Fluids

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SUMMARY The paper summarizes a comprehensive study of the behavior of viscoelastic polymer solutions in the entry region upstream of abrupt circular contractions. Streak and streamline photography were used for flow pattern visualization and for point velocity measurement. The fundamental properties of the test fluids were independently measured using a Weissenberg Rheogoniometer. Two stable flow regimes were identified: a vortex growth regime, and a diverging flow regime. For stable entry flows, the quantitative flow pattern observations and point velocity measurements enabled the determination of the entry flow characteristics, which were correlated with the Reynolds number and Weissenberg number of the flow field. In the unstable flow regime, the nature of the entry flow disturbances was identified and a quantitative criterion for the onset of unstable flow was obtained in terms of the fluid properties. A motion picture film will be presented which graphically illustrates the observed flow phenomena.

1 INTRODUCTION

The rapid expansion of the polymer processing industry has been accompanied by a growing need for a fundamental understanding of the mechanics of the materials involved. These materials, such as polymer melts and solutions, have flow properties intermediate between those of purely viscous fluids and those of purely elastic solids - thus they are called viscoelastic.

One of the most widespread and economically important flow geometries found in the polymer processing industry is the accelerative flow from a large reservoir or pipe into a smooth orifice or tube. This is the geometry of a spinneret, which is the fiber forming element in synthetic fiber production. Entry region flow is also found in the extrusion moulding of plastic tube, rod and sheet products, and in the capillary rheometer, an instrument widely used for fundamental fluid property measurements.

The fundamental mechanisms governing the behavior of viscoelastic fluids in accelerative entry region flow are not completely understood. However, it is clear that at low and moderate flow rates the entry flow is stable, and at higher flowrates the entry flow of sufficiently elastic fluids can be disturbed by low Reynolds number instabilities, of a kind not seen for purely viscous fluids. The stable laminar entry flow is characterized by the development of large vortex flow patterns upstream of the small tube entrance, due to the non-linear viscous fluid properties, as well as the elastic properties of the fluid. Theoretical approaches to modelling viscoelastic entry region flow are limited by formidable mathematical complexities. Experimental investigations have not been accompanied by adequate characterization of fluid properties. To quote a recent review article by White (1973), "A thorough quantitative experimental study relating basic rheological measurements to (entry) flow patterns is needed". One of the major objectives of this investigation was to fulfill this need.

The development of low Reynolds number instabili-

ties in viscoelastic entry region flow has puzzled researchers for some time. Interest in this phenomenon stems from observations of extrudate distortion, or "melt fracture", in the processing of polymer melts. Briefly, it is found that above a certain flowrate in the extrusion process, the smooth extrudate surface becomes rough and irregular, even though the flow in the die is still in the laminar regime. In many cases, the occurrence of extrudate distortion can be directly related to the development of instabilities in the die entry region. While this is not the only instance of unstable laminar flow in polymer processing it has attracted the most attention in the literature. Comprehension of the mechanisms involved will hopefully lead to a broader understanding of viscoelastic instability phenomena. Many criteria have been put forward for the onset of unstable entry region flow, but none has been directly substantiated by experimental flow pattern observations and independent fluid property measurements. Another objective of the study was to determine experimentally the nature of the entry flow disturbances for viscoelastic fluids, and to establish quantitative criteria for their inception, based on independent characterization of fluid properties.

2 PREVIOUS WORK

Extensive reviews are available which describe the significant volume of work which has appeared in the past twenty years concerned with various aspects of laminar entry flow into a tube (Dennison, 1967; Den Otter, 1970; White, 1973; Petrie and Denn, 1976; Cable, 1976). The behavior of Newtonian fluids in hydrodynamic entrance regions has been well established by theoretical analysis and experimental studies. However, a need does exist for clarification of the behavior of highly shear thinning inelastic fluids in real contractions and at low Reynolds numbers. Numerical solutions of the equations of motion using constitutive equations more realistic than the power-law model would be useful so that non-linear viscous effects could be separated from

fluid memory effects in viscoelastic entry flows.

Theoretical approaches to the behavior of viscoelastic fluids in tubular entries have been limited by formidable mathematical complexities, which have resulted in over simplified constitutive and kinematic approximations. The first theoretical attempt which examines the influence of high elasticity on flow through abrupt changes in geometry has just appeared (Perera and Walters, 1977). Other analyses have largely relied on perturbation techniques where only slight deviations from inelastic behavior have been investigated. The experimental investigations, which are summarized by Cable (1976) for polymer melts and solutions, in general have either failed to adequately characterize the fundamental properties of the test fluid, or to quantify entry flow pattern observations. However, it is clear that at low and moderate flow rates the entry flow is stable, and at higher flow rates the entry flow of sufficiently elastic fluids can be disturbed by low Reynolds number flow instabilities. Stable laminar entry flow is characterized by the development of large vortex flow patterns upstream of the small tube entrance, due to the non-linear inelastic fluid properties, as well as elastic properties of the fluid. The characteristics of this vortex and how it is related to the fundamental flow properties and the kinematic variables is not understood.

Entry flow instabilities have been observed in most polymer melts and solutions and appear to develop in two stages. Regular, spiralling or oscillating distortions occur at relatively low flow rates. At higher throughputs, the disturbances become random and chaotic, with material of different deformation histories alternately entering the downstream tube. Of fundamental and practical interest is when these flow patterns are to be expected, and how criteria for their inception are related to fundamental fluid properties, geometry, and kinematic variables.

3 EXPERIMENTAL METHODS

The detailed flow kinematics of viscoelastic fluids flowing in a 2 to 1 and 4 to 1 abrupt circular contraction were investigated in a continuous flow loop. Streak photography, using a continuous light source, was employed for flow visualization studies and for determination of the size of the secondary flow vortex observed on the upstream side of the abrupt contraction. A multiple flash technique was used for point velocity measurement in the flow field. Mearlin A (Mearl Corp., N.Y.) was used as a tracer particle in polyacrylamide solutions (Separan AP30 and MG 500, Dow Chemical).

The test fluids were characterized using an R-16 Weissenberg Rheogoniometer. The instrument was used in the steady rotational mode with a cone and plate geometry. Measurements of the torque on the upper plates, and the total thrust on the lower cone enabled calculation of the shear stress (τ) and the first normal stress differences (N_1) as a function of shear rate ($\dot{\gamma}$). The characterizations were carried out under controlled temperature conditions, within $\pm 0.2^\circ\text{C}$ of the temperature at which the flow visualization studies were made in the flow loop.

A general non-linear regression analysis computer program (Coulter, 1970) was used to determine the power-law and Ellis model parameters to give the least squares fit of these models to the experimental shear stress and first normal stress difference data. The specification of the model parameters

for the shear stress-shear rate data allows calculation of the Reynolds number for the flow loop experiment from

$$N_{Re}' = \rho \frac{D^n V^{2-n}}{K} \quad (1)$$

where n and K are defined from the power-law model

$$\tau = K \dot{\gamma}^n \quad (2)$$

Knowledge of the model parameters also allows calculation of the fully developed velocity profile. From the shear stress and first normal stress difference, the Weissenberg number, stress ratio and Maxwell relaxation time can be calculated as a function of shear rate.

$$N_{WS} = \frac{\theta V}{D} \quad (3)$$

$$S = \frac{N_1}{\tau} \quad (4)$$

$$\theta = \frac{N_1}{2\tau\dot{\gamma}} \quad (5)$$

where V is the average velocity in the downstream tube and D is its diameter. Equations 3, 4 and 5 all represent useful measures of fluid elasticity.

The point velocity field and the size of the secondary flow vortex were observed in a 2 to 1 and 4 to 1 contraction as a function of the Reynolds number and Weissenberg number. Critical conditions for the onset of unstable flow were specified in terms of a critical stress ratio (Equation 4). The size of secondary flow vortex was defined as the observed reattachment length relative to the upstream tube diameter. All fluid properties were evaluated at the wall shear rate for fully developed flow in the downstream tube. A discussion in great detail on experimental methods, procedure and data reduction is available in the original thesis (Cable, 1976) where also a complete listing of the flow properties of all the test fluids can be found.

4 RESULTS

Space limitations do not allow the results to be presented here. They are available elsewhere (Cable, 1976 and Cable and Boger, 1977) and will form a major portion of the oral presentation. The experimental results are summarized as follows:

Two distinct flow regime are identified for the stable entry flow of viscoelastic fluids; a vortex growth regime at low flow rates and a divergent flow regime at moderate flow rates. In the vortex growth regime, the characteristic secondary vortex which formed in the corner upstream of the small tube entrance increases in size with flow rate. Velocity profile development in the entry region is smooth and continuous, and the flow is fully developed at the small tube entrance. Extensive parallels can be drawn between the entry flow characteristics in the vortex growth regime observed for the polymer solutions in this study, and those reported previously for polymer melts.

The divergent flow regime is characterized by an unexpected fluid deceleration at the upstream tube centerline, while the secondary vortex decreases in size with flow rate. Developing axial velocity profiles in the entry region exhibit pronounced concavities, large off-center velocity maxima being separated by a local minimum at the centerline. The secondary vortex characteristics for both flow regimes, for all the fluids studied, are

correlated in terms of dimensionless groups based on system variables, kinematics and independent fluid property measurements, i.e., the Reynolds number and the Weissenberg number. Both the 2:1 and 4:1 contraction exhibit identical asymptotic behavior at low Reynolds numbers.

The divergent flow regime is in fact metastable, and multiple steady flow states are obtainable at the same volumetric flow rate and temperature over a limited range of conditions in the 4:1 contraction. The preferred entry flow configuration is time-varying, and consists of a spiralling disturbance to the entry flow pattern, wherein an asymmetric distortion in the upstream tube rotated about the centerline with a regular frequency. Divergent flow could also occur at the same flow rate. Alternatively, for a limited number of cases, a third flow pattern was observed, consisting of a superposition of two out-of-phase spiralling disturbances, which resulted in a periodic pulsing flow.

The occurrence of multiple entry flow states is interpreted as an instability in the laminar entry flow. Based on the quantitative flow pattern observations and independent fluid property measurements, a simple linear correlation was obtained between the critical stress ratio and the generalized Reynolds number for the onset of unstable flow for all fluids which exhibited multiple flow states in the 4:1 contraction. In the case of spiralling flow disturbances, further similarities were noted between polymer melts and solutions.

At higher throughputs, random entry flow distortions are observed. Although still in the laminar regime, the flow patterns showed little semblance of order. This phenomenon was regarded as a second-stage instability, separate from the spiralling disturbance. Under these conditions, the "Uebler effect" was observed, wherein a relatively large air bubble could persist in the region just upstream of the small tube entrance, rather than being swept downstream. High speed photography was used to ascertain the probable mechanisms behind this effect.

5 CONCLUSIONS

The following specific conclusions can be made from this work:

- In the stable entry flow of viscoelastic fluids in axisymmetric tubular contractions, a characteristic of the flow is the formation of a secondary vortex upstream of contraction plane. Two distinct flow regimes exist, a vortex growth regime at low flow rates and a divergent flow regime at moderate flow rates.
- In the vortex growth regime, rheological forces dominate the flow. For contraction ratios of 2 and 4, the vortex detachment length is a linear function of Weissenberg number as

$$X = 2.5 N_{WS}$$

For this flow condition, the velocity profile development in the entry region is smooth and continuous, and the flow is fully developed at the small tube entrance.

- In the divergent flow regime, the flow diverges at the centerline upstream of the vortex detachment plane, and the vortex size decreases

with increasing flow rates. The developing velocity profiles exhibit severe concavities, off center velocity maxima being separated by a local minimum at the centerline. The velocity profile at the small tube entrance approaches uniformity.

- The entry flow characteristics for both geometries may be quantified in terms of the secondary vortex detachment length as a function of Reynolds and Weissenberg numbers, for all the fluids studied, over the range $0.2 < N_{Re}' < 200$ and $0.10 < N_{WS} < 0.77$.
- The divergent flow regime is metastable, and multiple steady flow states occur at the same flow rate. The preferred entry flow configuration in the 4:1 contraction is time-varying, consisting of a spiralling disturbance to the entry flow pattern. The frequency of the disturbance is regular, increasing with flow rate, and is approximately inversely proportional to the fluid relaxation time. In a limited number of cases, a third flow configuration was observed in the divergent flow regime, wherein a superposition of the two out-of-phase spiralling disturbances results in a periodic pulsing flow.
- Criteria for the inception of spiralling flow, based on quantitative flow pattern observations and independent fluid property measurements, show that to a first approximation the critical stress ratio is a linear function of the generalized Reynolds number, as

$$\frac{N_1}{\tau/c} = 5 + 0.07 N_{Re}$$

- At higher throughputs in the laminar entry flow regime, a second stage flow instability develops. The entry flow patterns become subject to random violent distortions. High frequency, nonperiodic disturbances to the secondary vortex are accompanied by almost complete stagnation of the flow in the center of the tube.
- Under the conditions at which the random distortions to the entry flow occur in the 4:1 contraction, the "Uebler effect" is observed, wherein a relatively large air bubble remains trapped for some time in the semi-stagnant region upstream of the small tube entrance, before eventually being swept downstream.

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