Summary

Consideration is given to the reasons why the Coleman and Noll second order fluids are unsuitable for use in the solution of unsteady flow problems for elasto-viscous liquids, especially when Laplace transforms are used. A number of unsteady flow problems are then solved using a constitutive equation of the "integral" type. The presence of elasticity in the liquid is shown to have quite a dramatic effect on the velocity profiles.

Zusammenfassung

Es werden die Gründe betrachtet, aus denen die Coleman- und Noll-Flüssigkeiten nicht geeignet sind, um Probleme der instationären Strömung elasto-viskoser Flüssigkeiten zu lösen, besonders wenn Laplace-Transformationen benutzt werden. Einige Probleme des instationären Fließens werden dann mit Hilfe einer Zustandsgleichung vom Integraltyp gelöst. Es wird abschließend gezeigt, daß eine in der Flüssigkeit vorhandene Elastizität einen starken Einfluß auf die Geschwindigkeitsprofile hat.

References


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A theoretical study on fiber spinnability

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With 6 figures

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I. Introduction

In preparing polymer solutions or melts for manufacturing synthetic fibers, one of the fundamental questions one faces is the criterion for spinnability. It is commonly understood that only a certain class of liquids is spinnable under the set of spinning conditions. It is also possible that the liquid which is spinnable at one set of spinning conditions may not be spinnable at another set of spinning conditions. It is generally known that spinnability depends, among many other things, on (a) the rheological properties of liquids to be spun, (b) jet stretch, (c) the hole size and shape, and (d) the rate of mass and heat transfer between the extruded filament and the coagulation medium (in the case of wet spinning) or the cooling medium (in the case of melt spinning). Here jet stretch is defined by the ratio of the velocity of the filament at the take-up device to the average velocity of the spinning solution at the exit of a spinnerette hole.

Nitschmann and Schrade (24) appear to be the first who attempted to explain the problem of spinnability in terms of material properties. Thiele and Lamb (37) investigated the technique of measuring spinnability by devising a suitable apparatus and determined the spinnability of colloidal solutions by means of high speed photography. And in their later study (38) the same authors reported that maximum spinnability was obtained at intermediate values of viscosity and elasticity.

Today it is generally accepted, from practical industrial experience, that almost all spinnable liquids being used for manufacturing synthetic fibers exhibit normal stress effect, i. e., elastic effect. Very recently,
Paul (28) made an interesting experimental study of wet-spinning which shows that elasticity of spin dope is very important to spinnability. Although a number of studies have been made in the past on the problem of spinnability, it appears, however, that no satisfactory theory is yet available.

In the present study, the theoretical aspect of spinnability is considered in the absence of change of temperature and/or composition, so that the effects of the various variables on spinnability can be investigated. The analysis here is based on the force balance equation for a steady liquid jet under axial tension, issuing from a spinnerette hole into a liquid or gas medium. The specific problem investigated is to determine the maximum distance from the spinnerette face at which the liquid thread breaks down, as a function of jet stretch, the rheological properties of spinning solutions or melts. An experimental work together with the further development of the present theory is in progress, taking into account the effects of the hardening process on spinnability.

II. General backgrounds

Elongational viscosity and spinnability

It is essential to recognize that fiber spinning operations involve extensional deformation. Nitschmann and Schrade (24) postulated that liquid systems can only be spinnable if they have a certain anomalous and characteristic viscosity behavior. This consists of an increase in viscosity with increasing stretching, the so-called "apparent Trouton viscosity". However, the concept of Trouton viscosity was first introduced by Trouton (42), who showed that Trouton viscosity $\eta_T$ is three times the Newtonian viscosity $\eta_0$:

$$\eta_T = 3 \eta_0.$$  \[1\]

This relation does not seem to hold for actual polymer substances, in general.

Ziabicki and Kedzierska (50) studied the elongation of a series of polymers from the standpoint of the melt spinning process and they found an increase of elongational viscosity along the spinning way. Ziabicki (47) studied the melt spinning of polycapronamide and measured the tensile force at various positions along the spinning way. He then calculated elongational viscosity $\eta_E$ using the expression

$$\eta_E = T_{xx} \left| \frac{dV}{dx} \right|,$$  \[2\]

where $T_{xx}$ is the axial tensile stress defined by the tension $F$ per unit area at a position $x$, and $dV/dx$ is the axial velocity gradient of a filament under stretching. The calculated elongational viscosity was shown to increase monotonically with distance along the spinning way. However, Ziabicki (47) could not separate the effects of the rate of elongation and temperature from the overall change of elongational viscosity although temperature appeared to be one of the most influential factors in his experiment of melt spinning. The cooling of the spun fiber increases elongational viscosity following the Eyring-Frenkel equation

$$\eta_E = \alpha_0 e^{E/RT}.$$  \[3\]

in which $\alpha_0$ is a constant, $E$ the activation energy, $R$ the gas constant and $T$ temperature. In a separate study Ziabicki and Kedzierska (49) postulated that under the condition of constant tensile force the increase of elongational viscosity is a necessary condition for spinnability so that an increase of axial velocity due to stretching had to be accompanied by an increase of elongational viscosity. To explain this, Ziabicki and Takserman-Krozer (52) treated theoretically the case of a suspension of ellipsoids in a dilute solution and showed that orientation is different for a constant extension than it is in a parallel shear field. This explanation, however, is not convincing.

Recently, Ballman (4) made an experimental study of the extensional flow of molten polystyrene ($M_n = 126,000$) in the range of elongation rate of $7.8 \times 10^{-4}$ to $2.2 \times 10^{-2}$ sec$^{-1}$ at a constant temperature of 300 °F. He found that elongational viscosity was from 3 to 350 times greater in magnitude as compared to shear viscosity, both measured at the same level of stress and temperature. Furthermore, his result indicates that elongational viscosity was much less dependent on stress than shear viscosity. At present, very little data on elongational viscosity are available in the literature.

Following a recent development in rheology, several authors (7, 17, 43, 44, 46) analysed the steady elongational flow of non-Newtonian viscoelastic fluids from the rheological point of view. Some authors (7, 17, 44) obtained expressions that describe elongational viscosity increases with the rate of elongation whereas others (43, 46) obtained expressions that describe elongational viscosity increases at low rates of elongation and then decreases at high rates of elongation.