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Short Communication

Stretching flow tests on polymer-thickened motor oils using an accelerated-film technique

D.R. Oliver

School of Chemical Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

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Abstract

Tests are described in which a film of oil or other liquid is accelerated along the surface of a rotating cylinder. This new technique gives extensional strain rates in the region of 50–250 s^{-1}; this is higher than the values obtained when using an earlier device that involved the stretching of a liquid jet. Five oils that contain different polymers are tested, together with an aqueous elastic liquid, at a temperature of 25.5 °C. The extensional viscosities of the polymer-thickened oils, as measured by the accelerated-film method, lie between 1.53 and 4.18 Pa s, with Trouton ratios between 11.6 and 29.7. (Trouton ratios of up to 120 are shown to be obtained by the jet thrust method for the same oils at an extensional strain rate of 10^3 s^{-1}.) Plots of axial stress against extensional strain rate obtained by the accelerated-film method show good agreement with data obtained by the convergent-nozzle jet thrust technique. The aqueous solution is more elastic than the oils, and permits a horizontal liquid filament to be formed, so that data obtained by this method (low strain rates) may be compared with data obtained by the accelerated-film method (moderate strain rates) and by the jet thrust method (high strain rates). This helps to validate the method and also throws new light on the differences that exist between different types of extensional flow regime. © 1997 Elsevier Science S.A.

Keywords: Stretching flow; Lubricants; Extensional viscosity; Trouton ratio; Load enhancement; Axial stress

1. Introduction

Most extensional flow devices are limited in their range of application; all have strengths and weaknesses. The spinline rheometer of Hudson and Ferguson [1], and variants in which a horizontal jet is pulled out [2], require that the liquid thread does not break and that the stretching force is large enough to be measured. The opposed-nozzle system [3] provides an ill-defined flow field and additional forces may be produced by liquid flow over the nozzle arms. Convergent-jet thrust nozzles probably give rise to stress and velocity profile rearrangement effects near the nozzle lip, which may modify the apparent stresses in the flowing liquid [4].

Polymer-thickened motor oils possess some degree of elasticity, which is measurable in various ways. It seems likely that viscoelastic properties assist in the lubrication process, but the conflicting demands of degradation resistance at very high rates of deformation require that the polymer molecules should be reasonably small and robust; this limits the degree of elasticity that is possible in the solution. Tests using a contoured-nozzle jet thrust system readily distinguish between the elastic properties possessed by different polymer-thickened oils at high extensional strain rates [5], and it was thought to be worth examining whether a horizontal jet of oil could be pulled out of a tube by a rotating cylinder at room temperature [2].

At low surface speeds of the cylinder (10–40 mm s^{-1}), it was found that a jet of diameter 4.7 mm would adhere and be drawn out, although only if the jet was short (1.0–2.0 cm). However, the tensile force at the cylinder could not be measured and, at high cylinder speeds, the liquid bounced off and could not be induced to attach, even by the use of a roughened surface or protruding wires. When the end of the tube was brought close to the rotating cylinder (a gap of about 0.5–1.0 mm), it was found that the oils flowed smoothly on to the surface and were accelerated as a film around the cylinder, before eventually falling off into a vessel below. The force was detectable as a change in torque on the cylinder and this was also the case for a Newtonian oil of viscosity similar to that of the polymer-thickened oils.

Flow is non-equilibrium, with a short time-scale (about 6 ms), the effects of which were recently discussed by Ferguson and Hudson [6]. A novel three-dimensional plot is used to show the way in which time and strain affect the extensional viscosity, and how this reconciles the markedly different results obtained by the various extensional flow techniques available. For long deformation times, an initial peak in the extensional viscosity is followed by a fall, with

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an eventual rise into the strain-hardening region. For short deformation times, the strain-hardening region is entered without the intermediate fall. This behaviour with short deformation times will be seen to be typical of the present results.

2. Apparatus

As shown in Fig. 1, the test liquid is pumped from a vessel (A) by a variable-speed gear pump (B), passing through a copper coil in thermostat (C) to a nozzle (D). The nozzle is circular in cross-section, of diameter 4.70 mm and is parallel sided (it does not produce convergent flow). The liquid then flows on to the moving surface of a rotating cylinder (E) of diameter 40.0 mm, which is driven by a Haake Rotovisco RV3 viscometer (F). This drives at known speed and simultaneously measures torque. The setting of the nozzle in relation to the cylinder is shown in more detail in Fig. 2. Liquid flows smoothly off the cylinder into vessel A, after having been accelerated to the rim speed of the cylinder. The test temperature was 25.5 °C.

Tests are performed by measuring the torque on the cylinder at a fixed speed of rotation in air (with pump B turned off) and then repeating the measurement with the pump operating and liquid flowing. The difference between the readings allows the force accelerating the liquid to be found (see below). The speed of rotation varies between 250 and 425 rev min^{-1} for oils and between 150 and 450 rev min^{-1} for the aqueous polymeric liquid. The liquid flow rate was always 5.0 ml s^{-1} and the initial velocity (at nozzle exit) was 288 mm s^{-1}. The cylinder surface velocity varied between 315 and 945 mm s^{-1}.

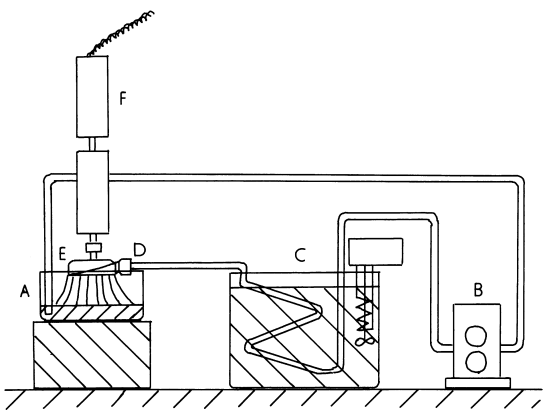

Fig. 1. Apparatus used. For meaning of letters, see Section 2.

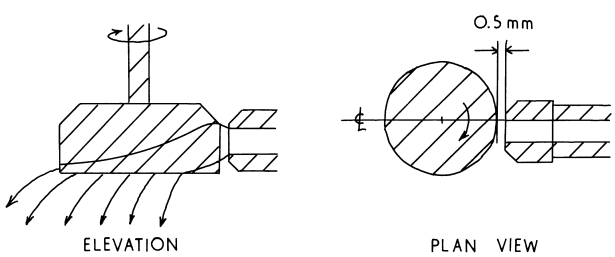

Fig. 2. Detail of apparatus. Two views that show the way in which liquid is accelerated on the surface of the rotating cyclinder.

The convergent-nozzle jet thrust technique was used as described elsewhere [5], while the free horizontal jet method, which only works successfully for the aqueous polymeric liquid, was used as described in ref. [2], the only change being that the liquid flow was provided by the present pumping system and nozzle. This has the advantage of giving a controlled flow rate; when flow takes place from a vessel, both hydrostatic head and elastic tension in the jet affect the flow rate.

3. Liquids used

The oils used were polymer-thickened 10W40 and 10W30 lubricants, which had been supplied by Shell Research, Thornton, UK for work on the journal bearing simulator [7]. These oils contain different types and concentrations of additive that are typical of those in current use in motor oils. The oils are slightly pseudo-plastic in character, with a flow behaviour index of 0.95; Table 1 summarizes their viscosities at a given shear rate. A Newtonian oil of viscosity 0.175 Pa s at 25.5 °C was also used to test the system.

The aqueous solution was a 66.6:33.3 (by volume) glycerol–water mixture that contained 500 ppm of the anionic polyacrylamide Magnafloc E10, supplied by Allied Colloids, Bradford, UK (molecular weight, 20–25 M Dalton). The viscosity was 0.034 Pa s at a shear rate of 4.10^4 s^{-1} and 0.055 Pa s at a shear rate of 10^2 s^{-1} (25.5 °C). Previous work [8] has shown this solution to have a Weissenberg number of 12 at a shear rate of 4×10^4 s^{-1}; it is considerably more elastic in character than the oils and is capable of forming horizontally stretched filaments.

4. Calculation of results

The method is based on a horizontal jet being pulled by a rotating cylinder [2], where the stress σ_1 in the liquid at the high-speed end of the jet is given by the torque on the cylinder minus the torque with the jet unattached, with this then divided by the cylinder radius and the cross-sectional area of the jet at this point. The stress σ_0 at the nozzle is given by

$$\sigma_0 = v_0/v_1[\sigma_1 - \rho v_1(v_1 - v_0)] \quad (1)$$

Table 1
Viscosity of oils (4×10^4 s^{-1}, 25.5 °C)

Oil	Grade	Viscosity (Pa s)
A	10W40	0.141
B	10W40	0.138
C	10W40	0.129
D	10W30	0.111
E	10W30	0.0946

In the case of a horizontal jet, $\sigma_1 \gg \rho v_1(v_1 - v_0)$, because highly elastic liquids develop large tensile stresses at moderate liquid velocities; the fluid inertia term $\rho v_1(v_1 - v_0)$ is not generally important.

In accelerated-film tests, fluid inertia is again provided by the rotating cylinder, by a combination of shear at the cylinder surface and tensile stress in the liquid strand that is wrapped around the cylinder. The value of σ_1 can still be calculated as above; if the value is lower than the fluid inertia term, it follows that the liquid has not been accelerated to the full rim velocity. This occurred for the Newtonian oil at rotational speeds below 250 rev min^{-1}; at higher speeds, the value σ_1 rose progressively above the value of the fluid inertia term. Work is always being performed against viscous forces in stretching the fluid but, when $\sigma_1 > \rho v_1(v_1 - v_0)$, both σ_0 and σ_1 may be calculated.

The flow pattern is complicated, in that fluid emerges from the nozzle in a direction normal to the drum surface; it then turns through a right angle and is accelerated along the surface. Different fluid elements have different histories; some fluid is 'relaxing' following shear flow near the nozzle wall and the subsequent stretching flow is modified by that fact that the fluid is flattened by the drum surface. The assumption will be made that the liquid is accelerated from the velocity v_0 to the velocity v_1 by an axial stress that is the mean of σ_0 and σ_1. This implies the pre-eminence of stretching rather than shear flow in this situation. The Trouton ratios obtained for polymer-thickened oils (12–30) support this contention, because a 10-fold increase in stress (compared with that for a Newtonian oil) could hardly be caused by shear effects alone.

Another problem is to find the distance Δx normally required for the liquid to accelerate from velocity v_0 to velocity v_1. Here, the Newtonian oil was used, assuming that the extensional viscosity μ_E is equal to three times the shear viscosity, to find Δx, knowing that the extensional stress should equal $\mu_E(v_1 - v_0)/\Delta x$. The value obtained (3.0 mm) was used as the typical accelerating distance in other tests. This is clearly an approximation; the accelerating length may increase with increased extensional viscosity. Observation of the attachment region suggests that values of Δx between 2.0 and 6.0 mm are possible.

The results obtained are as follows, for a series of increasing cylinder speeds.

1. In all cases, the initial velocity v_0 is the volume flow rate (5 ml s^{-1}) divided by the nozzle cross-sectional area A_0 (17.4 mm^2), giving $v_0 = 288$ mm s^{-1}.
2. The value of v_1 is taken as the peripheral velocity of the cylinder (420–945 mm s^{-1}).
3. The cross-sectional area of the liquid ligament after acceleration is $A_1 = A_0 v_0 / v_1$.
4. The stress σ_1 is taken as the torque on the cylinder minus the torque in still air, divided by the cylinder radius and the area A_1.
5. The value of σ_0 is found from Eq. (1).
6. The mean stress in the accelerating liquid is $(\sigma_1 + \sigma_0)/2$.
7. The mean extensional strain rate in the accelerating liquid is $(v_1 - v_0)/\Delta x$ ($\Delta x = 3.0$ mm).

The use of mean values of the stress and extensional strain rate was originally suggested by Jones et al. [9] and is further discussed elsewhere [2]. The method is satisfactory when dealing with free jets and, in view of other assumptions made, should also be suitable when dealing with the present flow geometry.

5. Results

Fig. 3 shows the mean extensional stress σ_{Av} plotted against the mean extensional strain rate $\Delta v/\Delta x$ for the aqueous polymer solution. Three different methods were used: the free horizontal jet, accelerated-film and nozzle jet thrust methods. The horizontal jet data were obtained at different times, 6 years apart. No attempt has been made to plot σ_{Av} against extensional strain, because most (but not all) of the data are consistent with the behaviour of a liquid of approximate extensional viscosity 17.5 Pa s (at $\Delta v/\Delta x = 100\ s^{-1}$). The corresponding Trouton ratio is 320. The gradient of the line (1.16) is slightly in excess of unity, which would correspond to a liquid of almost constant extensional velocity, independent of the extensional strain rate.

Fig. 4 shows similar data for polymer-thickened oils A, B and C, although the free horizontal jet method was not practicable in this case (see Section 1). Fig. 5 shows data for polymer-thickened oils D and E. The gradients of the lines

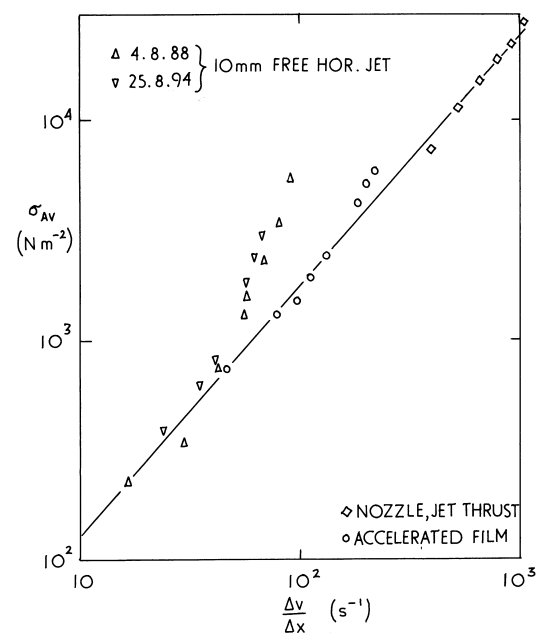

Fig. 3. Relationship between the mean axial stress σ_{Av} and the extensional strain rate $\Delta v/\Delta x$ for aqueous polymer solutions. Two earlier techniques are included, i.e. the free horizontal jet and nozzle jet thrust methods. The accuracy of measurement of σ_{Av} is $\pm 25\%$ for low values of stress and $\pm 10\%$ for high values of stress (accelerated-film method).

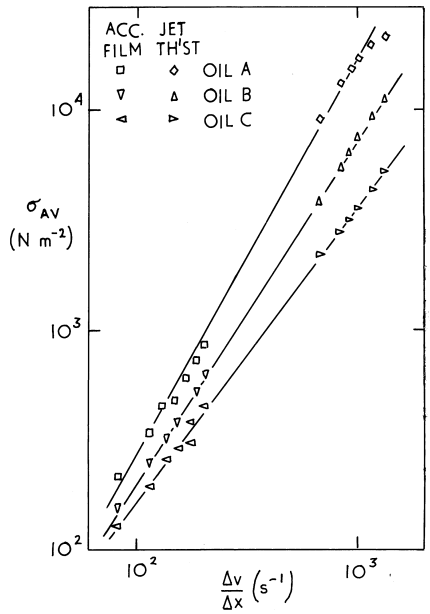

Fig. 4. Relationship between the mean axial stress σ_{Av} and the extensional strain rate $\Delta v/\Delta x$ for oils A, B and C. The accuracy of measurement of σ_{Av} is $\pm 25\%$ for low values of stress and $\pm 10\%$ for high values of stress (accelerated-film method).

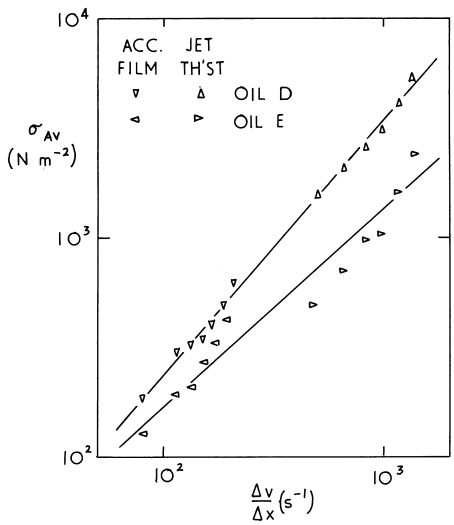

Fig. 5. Relationship between the mean axial stress σ_{Av} and the extensional strain rate $\Delta v/\Delta x$ for oils D and E. The accuracy of measurement of σ_{Av} is $\pm 25\%$ for low values of stress and $\pm 10\%$ for high values of stress (accelerated-film method).

lie between 0.94 and 1.80. Oil A has an extensional viscosity of 2.7 Pa s at an extensional strain rate of 100 s^{-1}, and an extensional viscosity of 17.0 Pa s at an extensional strain rate of 10^3 s^{-1} (Trouton ratios of 19.2 and 120 respectively). Oil E has an extensional viscosity of 1.6 Pa s at an extensional strain rate of 100 s^{-1} and an extensional viscosity of 1.4 Pa s at an extensional strain rate of 10^3 s^{-1} (Trouton ratios of 16.9 and 14.8 respectively).

6. Discussion of results

It was possible to use three different experimental techniques when using the aqueous polymer solution (Fig. 3). Data obtained using the accelerated-film method fall between those obtained by means of the horizontal jet and jet thrust methods, with good alignment of the points obtained at the lower extensional strain rates. This gives support to the assumptions made in calculating the results.

Important differences in the stretching behaviour exist, however, which must be related to the total sequence of events that occur during the deformation process. In the jet thrust method, the fluid is forced under pressure through a short, convergent nozzle into air and, despite the high extensional strain rates achieved, the line of experimental points shows a consistent gradient (slightly greater than 1.16). In the horizontal jet method, however, liquid is dragged from a larger nozzle by a tensile stress exerted from far downstream; this causes a distinct change in the stretching behaviour at extensional strain rates in excess of 50 s^{-1}. The mean stress begins to rise rapidly and the liquid assumes a more solid-like behaviour under these conditions [2]. It is clear that the downstream flow conditions are affecting the liquid behaviour in the test region, just as the upstream conditions (or history) of the solution may affect its behaviour in some cases. It may be noted that chains and rubber strands behave in this way; they are readily 'pulled' but collapse when 'pushed'. The upper three data points obtained by the use of the accelerated-film method show a similar tendency to rise above the line of other points, probably for the same reasons. Thus, it may be suggested that, when the deformation conditions dictate a change to elastic-dominated behaviour, the stress in a polymer solution may be affected by conditions both upstream and downstream of the point in question.

This may occur in industry when elastic liquids are pulled from a hole or slit (spinning and film manufacture), or are drawn by a moving band (blade coating). The fluid being drawn into the region of high velocity may form strands or threads, which may change not only the nature of the final product but also, in some cases, the flow rate. The changes may be beneficial to the process, giving an aligned and strain-hardened product, but this is not necessarily the case, because some product non-uniformity or thickness change may occur.

The main feature of the results obtained using polymer-thickened oils (Figs. 4 and 5) is that the accelerated-film method ranks the oils in the same order—from the point of view of extensional stress—as is given by the jet thrust method. This occurs despite the extensional strain rate being only 80–210 s^{-1} and despite two of the oils (C and E) being close to the lower limit of elastic behaviour which permits extensional stress to be accurately measured. The gradients of the lines for oils E, D and C (0.94, 1.17 and 1.32 respectively) suggest near-Newtonian behaviour in extension, i.e. nearly constant extensional viscosities of 1.4 Pa s, 3.0 Pa s and 2.8 Pa s, respectively, at an extensional strain rate of 500 s^{-1}. The corresponding Trouton ratios of 15, 27 and 22 are much greater than the Newtonian value of 3.0, however, which shows that, even for these oils, the alignment of the polymer molecules during extension is adding markedly to the stresses developed.

For oils A and B, the gradients of the lines are greater (1.80 and 1.55 respectively), which means that the extensional viscosity is rising rapidly with the extensional strain rate, and that the fluid elasticity is of increased importance. At an extensional strain rate of 500 s^{-1}, oil A has an extensional viscosity of 9.8 Pa s (Trouton ratio of 69) and oil B has an extensional viscosity of 4.9 Pa s (Trouton ratio of 36). Oils of this type have also been found to exhibit enhanced load-bearing forces in the journal bearing geometry at similar temperatures [7]. Load-bearing performance has been linked to elastic properties possessed by the oils and this is one of the main applications of this type of work. The industrial importance of this type of work is shown by Shell's development of the journal bearing simulator [7], in which the elastic properties of polymer-thickened oils may be closely linked to the load-bearing capacity of the oils.

There is no evidence of sudden change in the extensional flow behaviour of polymer-thickened oils as the extensional strain rate increases within the range 80–1400 s^{-1} (although the data points for oil E line up poorly, these are the least accurate results and experimental error may account for the behaviour). There seems to be a gradual change from behaviour that is essentially viscous in character to flow that is more elastic in character; this is perhaps not surprising for polymer molecules which are sufficiently small to be resistant to degradation in car engines. Nevertheless, the values of the Trouton ratio obtained show that, in any lubrication situation where the oil is rapidly stretched, the oil film will develop greater stresses than those obtained for a Newtonian lubricant. This will include the lubrication of gear teeth, cams, piston rings and crankshaft bearings under unsteady loading. Such loads are inherently unsteady, because of intermittent firing of the cylinders and the flexing of the crankshaft, which needs to bend by only a few micrometres to have significant effects on the oil film thicknesses.

7. Conclusions

It has been shown that the accelerated-film method is suitable for the measurement of the extensional behaviour of multigrade motor oils and other polymeric solutions. In all cases, the extensional viscosities are much enhanced by the presence of the polymer molecules. The extensional viscosities of polymer-thickened oils lie in the range 1.53–4.18 Pa s, with Trouton ratios between 11.6 and 29.7. The range of extensional strain rates is 50–250 s^{-1}.

An elastic aqueous solution was found to be useful, in that two other techniques could be used (horizontal jet and jet thrust) that straddled the data obtained by the present method, so helping to confirm the validity of the new results.

Acknowledgements

The author thanks Shell Research, Thornton, UK, for the provision of the oil samples used in this work.

Appendix A. Nomenclature

A_0	cross-sectional area of nozzle
A_1	cross-sectional area of jet at final velocity
v_0	initial velocity of liquid at nozzle exit
v_1	final velocity of liquid at cylinder surface
Δx	distance over which acceleration occurs
μ_E	extensional viscosity, defined as $\sigma_{Av}/(\Delta v/\Delta x)$
ρ	density of liquid
σ_0	initial stress in liquid (nozzle exit)
σ_1	final stress in liquid
σ_{Av}	mean extensional stress in liquid, given by $(\sigma_0+\sigma_1)/2$
$\frac{\Delta v}{\Delta x}$	mean extensional strain rate in liquid, given by $(v_1-v_0)/\Delta x$

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