FLOW-RATE CHARACTERISTICS FOR THE PULSATING FLOW OF A NONLINEAR VISCOELASTIC POLYMER SOLUTION IN A PIPE

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Measurements have been made on flow rate as a function of dimensionless combinations characterizing the pulsating flow for a nonlinear viscoelastic liquid.

The mean flow rate in a channel remains constant for a given mean pressure gradient for pulsating and stationary flows of a Newtonian liquid. Theory and measurements on nonlinear viscous [1-4] and nonlinear viscoelastic [5-13] liquids in the 1970s and 1980s showed that pressure-gradient pulsations can increase the flow rate, and if the increase is fairly large, flow pulsation can be a way of raising the throughput. However, this is attained at the expense of increasing the power consumed in pumping the liquid.

The flow rate for a viscoelastic liquid is dependent on the rheological characteristics and working parameters. Theory and experiment show that these have qualitative as well as quantitative effects. In the case of the theory, this is due to the use of various rheological equations that have been tested on simpler flow types. In pulsating flow in a pipe, the effects from nonlinear viscoelasticity are very pronounced, and this type of flow provides a means of judging whether a given equation reflects the actual behavior under more complex deformation.

The fullest theoretical study for such flows has been made in [11], where the McDonald—Bird—Carreau model was employed, which incorporates how the relaxation times and shear moduli vary with the strain rates. The calculations showed that the flow rate as a function of pulsation frequency has descending and rising branches.

Few measurements have been published, which usually relate to narrow ranges in the definitive parameters and involve large errors. The results are also conflicting. We have examined how the rheological characteristics and external parameters (pulsation frequency and amplitude, average pressure gradient, and time variation) affect the flow rate in pulsating polymer-solution flow.

Apparatus. The apparatus consisted of an open circuit (Fig. 1), where the polymer solution passed from tank 1 under pressure to the constant-level tanks 2 and 3 and then to the pulsator 4 or 5. From the latter, the solution passed through the working part 6, which was a tube 10 mm in diameter and 1100 mm long. Two types of pulsator were used. The first type 4 was a chamber with chopper, which received the liquid in turn from the two constant-level tanks. The height difference between them determined the pressure-gradient pulsation amplitude. Such a device produces near-square pressure pulsations. The frequency was $0.15 \leq f \leq 1.75$ Hz. The pressure-difference pulsation amplitude in these experiments was $0.15 \leq A \leq 0.7$, where A is the ratio between the maximum deviation in the pressure gradient from the mean value to the latter. In the second form, the pipe was connected to a tube in which a piston moved, which was coupled to a crank mechanism. The pulsation amplitude and frequency were governed by the stroke period. Here the signal was close to sinusoidal and the amplitude attained $A \approx 0.9$.

The measurements were made as follows: flow rate gravimetrically, pressure at the channel wall by means of strain gauges at several points. The pressure-sensor signal passed via an amplifier to a computer or to a tape recorder. The rheological parameters were determined before the runs on the loop and after them, and were also checked from the stationary flow in the pipe.

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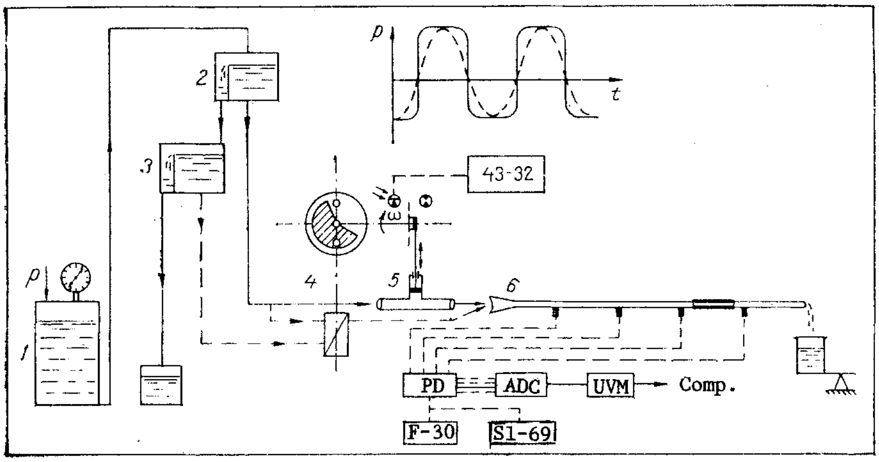

Fig. 1. The apparatus: 1) tank containing solution; 2, 3) constant-level tanks; 4, 5) pulsators of chopper and piston types; 6) working pipe.

The equations for this liquid show that the dimensionless change in flow rate $I = (Q_p - Q_0)/Q_0$, where Q_0 and Q_p are the flow rates in steady and pulsating flow with identical mean pressure gradients, will be dependent on various dimensionless quantities [9, 11-13]: $Re_f = \rho R^2 f/\mu$ the oscillatory Reynolds number, which is the ratio between the shear-wave transit time from the wall to the axis and the pulsation period T (f = 1/T, frequency), $We = \kappa v/R$ the Weissenberg number, which is a measure of the elastic recovery (reversible) in the liquid (κ is relaxation time), and $De = \kappa/T$ the Debourgh number, which is the ratio between the characteristic relaxation time and the pulsation period. The liquids showed nonlinear viscoelasticity, so the general form of I was complicated.

It is very laborious to examine a multiparameter relation by experiment, so we first evaluate what combinations of these quantities will cause the viscoelastic behavior to be pronounced and which will produce virtually no effect. If $Re_f \gg 1$, the pulsating component in the shear wave does not have time to propagate across the tube during an oscillation period and there will be little effect from the pulsations on the flow rate.

For $De \ll 1$, one can say that the flow is of equilibrium type, with little effect from the relaxation. Then the pulsation effects will be determined only by the nonlinearity. That case has several times been considered for liquids showing rheological power laws [1-3], and in [4] for liquids with linear flow laws. One also does not expect major effects from the nonlinear viscoelasticity for small reversible deformations, i.e., small Weissenberg numbers.

Calculations and measurements (including ours [12, 13]) show that the relative flow change is proportional to the square of the amplitude for a wide range in it, so all the results are plotted against I/A^2.

We used polyacrylamide solutions with variable frequencies and mean pressure differences to provide some of the combinations:

a) $Re_j \ll 1$; $De < 1$, $We \approx 1$. These conditions apply for a 1% polyacrylamide solution in the frequency range used (here and subsequently, we use κ and μ for $\tau \to 0$ in the numbers).

Figure 2 shows measurements on I/A^2 as a function of the Debourgh number for four values of the Weissenberg number. As the latter increases, so does the flow rate, while there is a slight tendency for I/A^2 to fall as the frequency rises for Debourgh numbers up to 0.15 (right-hand part of Fig. 2a and b). However, with the first type of pulsator, increasing the frequency (chopper speed) reduces the amplitude, and therefore the accuracy in determining I/A^2.

b) $Re_j \leq 0.2$; $De \ll 1$. These conditions occur at low concentrations, where the viscosity is reduced by about a factor four (Fig. 3). Above 1 Hz ($Re_f \approx 0.1$), I/A^2 is much reduced. Under these conditions, the pulsating shear wave does not have time to penetrate into the flow core, and the effects on the flow rate are reduced. A calculation for a linear yield law [4] (dashed line) confirms this.

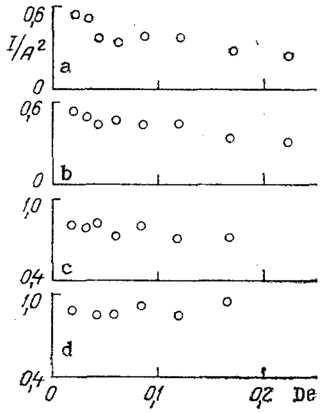

Fig. 2

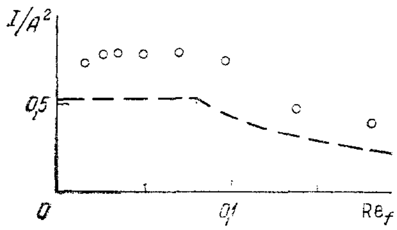

Fig. 3

Fig. 2. Flow rate as a function of Debourgh number for $Re_f \leq 0.045$, We = 0.8 (a), 1.1 (b), 1.3 (c), 1.5 (d) (κ = 0.12, μ=1).

Fig. 3. Flow rate as a function of oscillatory Reynolds number, where the dashed line is from theory [4] for a nonlinear viscous liquid, De $\leq$ 0.05, We = 1.4 (κ = 0.03, μ = 0.25).

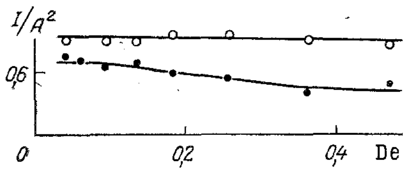

Fig. 4

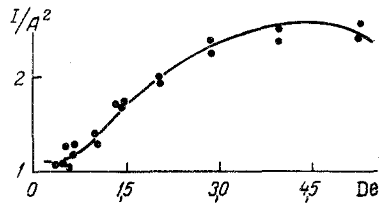

Fig. 5

Fig. 4. Flow rate as a function of Debourgh number for $Re_f \leq 0.01$, We = 1.2 (lower curve) and 1.7 (upper curve) (κ = 0.27, μ = 4.3).

Fig. 5. Flow rate as a function of Debourgh number for $Re_f \leq 0.002$, We = 2.5 (κ = 3, μ = 22.2).

c) $Re_j \leq 10^{-2}$; $0.04 \leq De \leq 0.5$; We = 1.2; 1.7. The experiments were performed with 2% polyacrylamide in water (Fig. 4). As the pressure gradient (Weissenberg number) increases, so does the flow rate, as for the 1% solution. The reduction in I/A^2 as a function of frequency is found only at the smaller We. The large errors in these experiments are due mainly to the low pulsation amplitudes (particularly for small ∇p_0 and large f).

d) $Re_f < 2 \cdot 10^{-3}$; $0.5 \leq De \leq 5.3$; We ≈ 2.5. These conditions were attained on increasing the concentration to about 3.5% (Fig. 5). I/A^2 increases with De and becomes quite large.

Calculations [11] showed that two different pulsating-flow states can exist. When the elastic effects are slight and are described by the McDonald–Bird–Carreau equation, one gets a reduction in the relative flow increment with frequency, whereas there is an increase in the relative flow rate for highly elastic behavior. Up to now, measurements have yielded usually only one curve, which falls as the frequency increases. In these experiments with a single apparatus, we were able to demonstrate a reduction in I/A^2 as the frequency increased or an increase in it.

The time course of the pressure gradient affects the pulsating flow substantially. For given Δp_0 and frequencies, the increase in I/A^2 with square pulsations was much larger than with sinusoidal ones.

NOTATION

f, frequency, Hz; A, amplitude; Q_0, stationary flow rate in m^3/sec; I, dimensionless excess flow rate; ρ, density, kg/m^3; R, tube radius in m; μ, viscosity, Pa·sec; T, pulsation period in sec; κ, relaxation time, sec; v, speed, m/sec; $\dot{\gamma}$, shear rate, sec^{-1}; Δp_0, mean pressure difference, Pa; De, Debourgh number; We, Weissenberg number; Re_f, oscillatory Reynolds number.

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RHEODYNAMICS AND MASS TRANSFER DURING PERIODIC AND NONUNIFORM CYLINDER MOTION IN POLYMER SOLUTIONS

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Rheodynamics and mass transfer features are studied using periodic and uniform cylinder motion in viscoelastic fluids of the dilute polymer solution type. Estimates are performed of the characteristic time of the solutions.

It has been shown earlier [1] that during cylinder vibrations with low amplitudes ($a/d \gg 1$) in viscoelastic fluids of the dilute polymer solution type the secondary flow pattern changes as compared with a Newtonian fluid, resulting in elevation of the intensity of mass transfer (∿ 12-15% in a 100 ppm concentration of a WSR-301 solution).

In contrast to vibrations with low amplitudes where secondary stationary flow play a fundamental part in transfer processes, cylinder vibrations with high amplitudes are accompanied by separate periodic flows [2] and the viscoelastic properties of the fluid can be due to other effects.

Taking account of the complexity of the theoretical analysis of such flows, the main attention was paid to selection of the methodology of the experiment that would permit a study of the flow structure and the mass transfer near the cylinder.

The electrodiffusion method we used in combination with visualization is well recommended for the investigation of separation flows [3].

Visualization of the separation flow near a 5 mm diameter cylinder ($a/d = 1.35$) performing harmonic vibrations at the frequency $f = 1$ and 5.5 Hz was carried out on an installa-

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