INSTABILITY OF A VISCOELASTIC FLOW

V. I. Popov, A. Ya. Roitman, and E. M. Khabakhpasheva

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The kinematic characteristics of the unstable (fluctuating) flow of a 1% solution of polyacrylamide in plane channels have been studied. The profiles of the time-average velocities, the rms velocity fluctuations, and the fluctuation probabilities were found on a computer.

Unstable motion arises in the flow of a viscoelastic liquid subjected to a large shear stress. This problem must be dealt with in several technological processes in which liquid polymers and polymer solutions are produced and treated. The instability problem attracts interest because of the effort to significantly accelerate these processes.

Previous work has not clarified questions regarding the reasons for and behavior of unstable flow in channels (see the review in [1] and e.g., [2, 3]).

In recent experiments we were able to establish certain features of the motion of a viscoelastic flow in plane channels [4]. We found that the inlet geometry has a strong effect on the nature of the flow. For the unstable flow of a liquid in a horizontal channel with a rectangular inlet we found three zones which appear in succession along the length of the channel: the inlet zone, with an asymmetric velocity profile, whose configuration changes over time; a zone with a symmetric velocity profile; and an exit zone with a eddy region near the lower edge of the channel. The particular features of the flow of a viscoelastic liquid lead to the onset of a fluctuating (oscillatory) regime over the entire length of the channel, to a change in the velocity gradient, and to slip at the wall.

We report here a study of the kinematic characteristics of a viscoelastic flow in the unstable (fluctuating) regime. The experiments were carried out in channels $2.5 \times 25 \times 250$ mm in size (rectangular inlet) and $3 \times 30 \times 600$ mm in size (a smooth inlet).

For these experiments we slightly modified the method which we used previously [4-6] for stroboscopic visualization of the flow (Fig. 1).

The flashes of an IFK-120 flash lamp are synchronized with the shutter rotation in a Konvas motion-picture camera. The shutter is rotated by an RD-09 motor through a reducing gear. The rotation frequency of the motor is monitored; it remained constant with 1.5%.

By increasing the capacitance of the capacitor banks of the thyratron unit in the electron stroboscope to 1000 μF we were able to photograph the events continuously at a rate of 2.5 frames/sec.

Using three-pulse side illumination we photographed the light reflected from aluminum dust particles added to the liquid flow. Information on the resulting particle tracks was transferred to perforated tape by means of a semiautomatic PUOS-1 apparatus and then processed on an M-220 computer by means of the appropriate program.

Each frame on the film gives an instantaneous picture of the flow. By averaging over many frames we can obtain time-average characteristics of the flow. In these experiments we obtained the instantaneous and time-average velocity field and rms fluctuations in the velocity over the channel cross section. These measurements were carried out at a dimensionless distance $L/d_{equ} = 34$ from the inlet (in the zone with the symmetric velocity profile).

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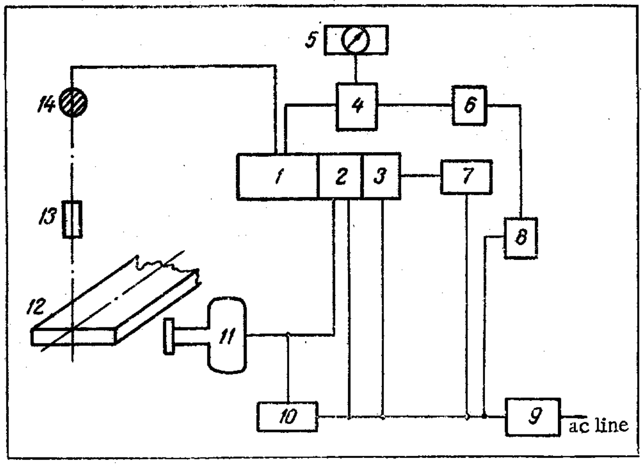

Fig. 1. Block diagram of the apparatus. 1, 2) Thyratron and control units; 3) sonic-frequency oscillator; 4) capacitor bank; 5) high-voltage recorder; 6) high-voltage rectifier; 7) digital frequency meter; 8) autotransformer; 9) voltage regulator; 10) oscilloscope; 11) Konvas motion-picture camera; 12) channel; 13) Gelios-40 condensor; 14) IFK-120 flash lamp.

We studied the flow of a 1% solution of polyacrylamide in water. The flow curves of the solution were measured with a type RV Rheotest rotary viscometer. Over the shear-stress range 10-80 N/m^2 the viscosity of the polymer solution ($\varphi = 1/\mu$) varied linearly from 2.5 to 19 $m^2/N \cdot sec$. The first normal-stress difference, $P_{11} - P_{22}$, was measured on a rotary cone-plane device (up to τ = 40 N/m^2). The coefficient of reversible elastic strain varied over the range 2.5-4.

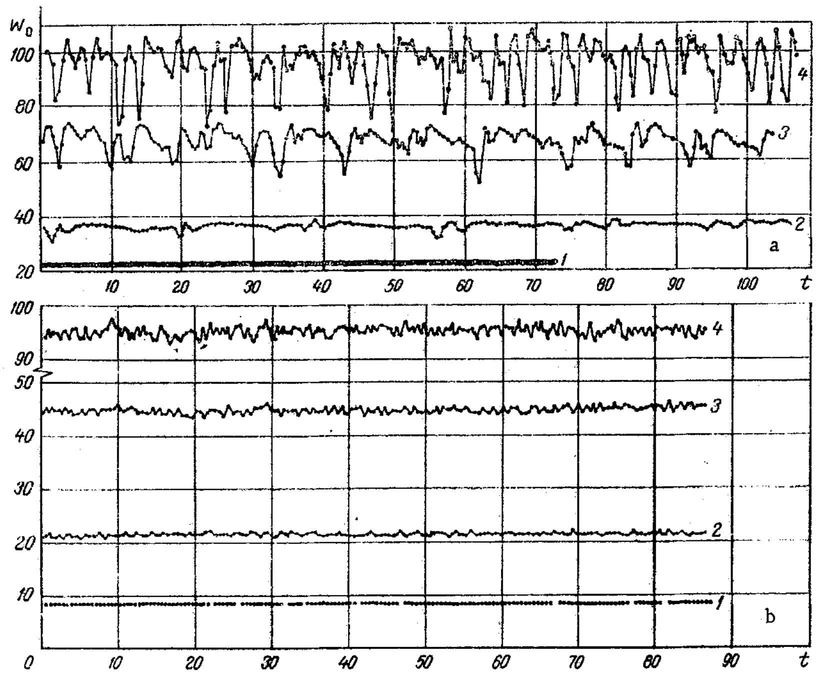

Fig. 2. Time distribution of the axial flow velocity. a: liquid in channel with a rectangular inlet. 1) τ_{wa} = 64 N/m^2, 90% water-glycerine mixture; 2) 52 N/m^2; 3) 66.5; 4) 76.5; 2-4) 1% solution of polyacrylamide in water. b: Polymer solution in a channel with a smooth inlet. 1) τ_{wa} = 18.2 N/m^2; 2) 28.5 N/m^2; 3) 39.5; 4) 58.5. Here W_0 is in centimeters per second and t is in seconds.

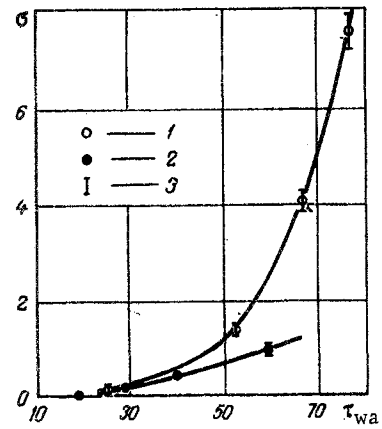

Fig. 3. Dependence of the rms fluctuations in the axial velocity on the shear stress at the channel wall. 1) Channel with rectangular inlet; 2) with smooth inlet; 3) statistical errors in the determination of the rms velocity deviations. Here σ_x is in centimeters per second and τ is in Newtons per square meter.

The experimental procedure and the quality of the working channels were tested by passing a 90% water-glycerine mixture through the apparatus.

Figure 2a shows instantaneous values of the axial velocity W_0 as a function of the time, plotted for various shear stresses at the channel wall for the case of a rectangular inlet; Fig. 2b shows the same function for a channel with a smooth inlet.

Above a certain shear stress, velocity fluctuations arise in the flow of the polymer solution. The amplitude and frequency of these fluctuations increase with increasing shear stress at the wall. The nature of the fluctuations differs in channels with different types of inlets: both large-scale and small-scale velocity fluctuations are observed in the channel with a rectangular inlet, but the large-scale fluctuations are not observed in the case of a smooth inlet over the same stress range (Fig. 2b). We can therefore conclude that these large-scale fluctuations are due to the shape of the inlet (due to features of the behavior of the liquid in the inlet region). When a polymer solution flows through a channel with a rectangular inlet, fluctuating eddies arise near the inlet and lead to a periodic partial "blockage" of the channel [4]. Estimates for various shear stresses show that the time interval of the periodic blockage at the inlet is roughly the same as the period of the large-scale velocity fluctuations in channel. Furthermore, the large-scale fluctuations are asymmetric with respect to the average velocity, perhaps because of the periodic blockage at the inlet.

Control experiments with a water-glycerine mixture over the same shear-stress range confirmed that there were no velocity fluctuations in the flow of a Newtonian liquid (Fig. 2a).

Using the results in Fig. 2 we calculated the rms fluctuations in the axial velocity, σ_x; the results are shown in Fig. 3, from which we see that the fluctuations become appreciable at τ_{wa} = 20-25 N/m^2. At such shear stresses the values of γ_e measured under steady-state conditions are about 2.5.

The amplitude of the velocity fluctuations in the channels increases with increasing shear stress at the wall, and increases in τ_{wa} are also accompanied by increases in the relative velocity fluctuations (σ_x /W_x). At a shear stress at which the velocity fluctuations are pronounced, the fluctuation level in the channel with the rectangular inlet is much higher (by a factor of about five for τ_{aw} = 75 N/m^2) than in the channel with the smooth inlet. This difference is due to the large-scale velocity fluctuations.

Figure 4a and c, shows the distribution of the time-average velocity over the channel cross section. These profiles were obtained by averaging the data from 57 and 85, respectively, successive frames. The

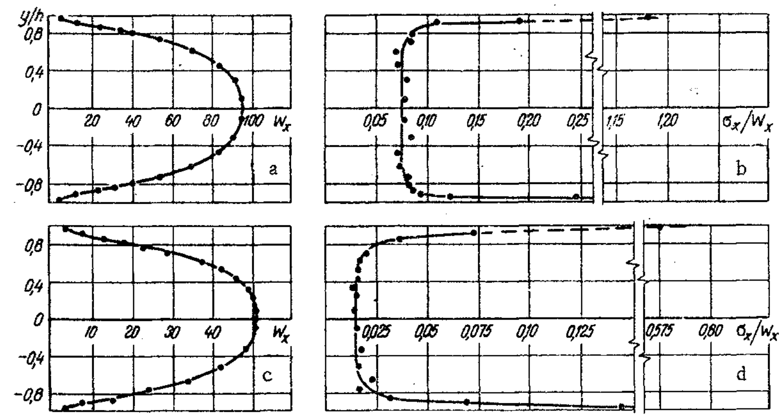

Fig. 4. a, c) Time-average velocity profiles for the flow of a polymer solution in a channel; b, d) profiles of the relative rms velocity fluctuation over the channel cross section; a, b) rectangular inlet; c, d) smooth inlet.

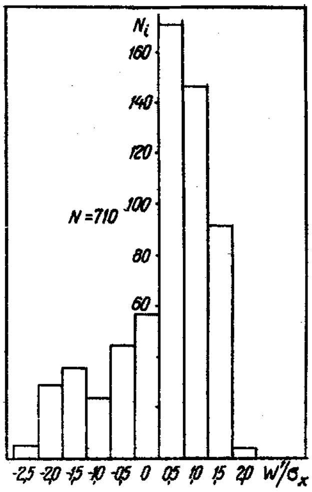

Fig. 5. Histogram of the longitudinal velocity fluctuation over the range $0 < y/h < 0.78$. Here N is the total number of events and N_i is the number of events in the given W'/σ_x interval.

average profile typically has a bending point and a nonvanishing velocity at the wall, obtained by extrapolation. The instantaneous velocity profiles observed in [4] displayed similar features.

The errors of a single measurement of the instantaneous velocity are the error in determining the magnification used in the photography, the uncertainty in the time interval between light flashes, and the error in determining the distance between the images of the particles on the film. The error increases as the velocity decreases toward the wall. The total error of a single measurement of a velocity equal to the average velocity near the wall ($1 < y/h < 0.96$) is about 2.5%, while that in a single measurement of the instantaneous velocity in the center of the channel ($0.22 < y/h < 0$) is about 1%.

The average values obtained in these experiments also incorporate a certain statistical error, because the results are obtaned by averaging over a finite number of cases (there is a finite number of instantaneous values in each y interval). An estimate from the equation $\sigma = \sigma_x/\sqrt{N}$ (which holds for a random function having a normal distribution) yielded the rms statistical error in the determination of the average velocity: about 4% near the wall and about 0.5% at the center of the channel.

It is extremely interesting to examine the distribution of the relative rms velocity fluctuations (σ_x/W_x). This distribution remains approximately constant over the entire channel cross section, except near the wall, where the relative fluctuations increase sharply (Fig. 4b, and d), perhaps becuase of liquid slip ("stick-slip") at the wall.

Figure 5 shows a histogram of the distribution of the velocity fluctuations in a channel with a rectangular inlet for the interval $0 < y/h < 0.78$. We see that there is a pronounced asymmetry; this asymmetry results from the asymmetry of the large-scale fluctuations with respect to the average velocity. At the center of the flow these fluctuations make an important contribution to the energy of the turbulent motion.

NOTATION

$\tau_{wa} = \Delta ph/L$	is the tangential shear stress at the channel wall, N/m^2;
y/h	is the dimensionless distance from the channel axis, where h is the half-height of the channel;
W_0	is the instantaneous axial velocity, cm/sec;
W_x	is the time-average longitudinal velocity at a distance y from the channel axis, cm/sec;
W'	is the velocity fluctuations, cm/sec;
σ_x	is the rms velocity fluctuations, cm/sec;
μ	is the dynamic viscosity, $N \cdot sec/m^2$;
$\gamma_e = P_{11} - P_{22}/\tau$	is the reversible elastic strain;
$P_{11} - P_{22}$	is the first normal-stress difference, N/m^2.

LITERATURE CITED

1. A. Ya. Malkin and A. I. Leonov, in: Progress in the Rheology of Polymers [in Russian], Khimiya (1970).
2. O. Bartos and J. Holomek, Polymer Engineering and Science, 11, No. 4 (1971).
3. J. L. Den Otter, Plastics and Polymer, 38, No. 135 (1970).
4. V. I. Popov, A. Ya. Roitman, and E. M. Khabakhpasheva, Inzh.-Fiz. Zh., 26, No. 5 (1973).
5. V. V. Orlov and Yu. M. Fedoruk, Teplofiz. Vys. Temp., No. 4 (1968).
6. V. V. Orlov, E. S. Mikhailova, and E. M. Khabakhpasheva, Izmeritel'. Tekh., No. 3 (1970).