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HYDRODYNAMIC ACTIVITY OF POLYMERS IN HIGH-SPEED FLOWS

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The roles of longitudinal and transverse velocity gradients in the manifestation of distinctive features of polymer solution flows are analyzed.

Up to now, two mutually exclusive experimental facts are not explained. The first is that at rather high velocities the magnitude of the Toms effect starts to decrease [1], and the second is the substantial decrease (by 40–50%) of the hydrodynamic resistance of tubes of small diameter ($\sim 10^{-3}$ m) observed at a mean flow velocity of ~ 100 m/sec [2]. Therefore it was of particular interest to set up an experiment that together with existing data on the deformational action of parietal turbulence [3] and convergent flows [4–7] on macromolecules could resolve this contradiction. Such an experiment was carried out with the use of an industrially fabricated pulsed water jet. The description of its hydrodynamic unit, parameters, and method of determination of the mean velocity, momentum, and energy of the ultrajet are given elsewhere [8].

To determine the parameters of the ultrajet, shooting was performed with a physical pendulum, whereas for the qualitative determination of energy possibilities of the jet the interaction of the jet with a target installed at the pendulum was studied experimentally. The target was fabricated from steel (St3) plates with the dimensions $(220\times220\times3)\cdot10^{-3}$ m with mounting holes $16\cdot10^{-3}$ m at the corners. A gap of width $5\cdot10^{-2}$ m was left between the plane of the target and the body of the physical pendulum. Polyethyleneoxide with a characteristic viscosity of 2.42 m^3/kg and a molecular weight of $6\cdot10^{6}$ was used in the experiments.

Results of the experiments are presented in Table 1, whence it is seen that:

1) the maximum distance from the water jet to the target when punching is still observed comprises 1.5 m for water, whereas for 0.0008% polymer solution it comprises 2.5 m;

2) the efficieny of polymer additions was observable starting from a concentration of 0.0004%;

3) polymer additions lower the mean jet velocity.

The experimental data obtained in the experiments can be explained rather well from the viewpoint of the strong deformational action of the hydrodynamic field on the molecular coils [4]. It was proved [4, 9] that deformation of a molecular coil in a longitudinal field is substantially greater than in a shear one, since in the case of a longitudinal flow, positive feedback arises between molecular dimensions increasing as a result of deformation and the velocity gradient, and the unfolding process starts at relatively low critical velocity gradients, building up in an avalanchelike manner. In the case of a shear hydrodynamic field, negative feedback arises instead of the positive one, as in the case of the longitudinal field, between the dimensions of the molecules and the velocity gradient and, naturally, considerable deformations of coils are hindered.

If one calculates the longitudinal velocity gradient realized in the barrel (in the case of Newtonian liquid flow) it appears that it did not exceed (in our experiments) $1.8\cdot10^{3}$ sec^{-1}, i.e., despite such high velocities ($\bar{U} \simeq 250$ m/sec) and consequently high transverse velocity gradients the deformation conditions for macromolecules in the cone barrel of the water jet compare well with those at the entrance to a capillary with a rectangular entrance at a mean flow velocity of ~ 1 m/sec [4, 5]. This circumstance bears witness to the fact that in movement of a polymer solution along a water jet barrel the molecules as in the case of a short capillary [4–7] are, first of all, subjected to the strong deformational action of the longitudinal hydrodynamic field since the velocity

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TABLE 1

No. of experiment	Distance from the pendulum, m	Polyethyleneoxide concentration, %	Mean jet velocity, m/sec	Target punching character
1	0.5	–	255	Hole diameter $(18-20)\cdot 10^{-3}$ m, punched holes
2	1.5	–	255	Hole diameter $(15-18)\cdot 10^{-3}$ m, punched holes
3	1.75	–	250	No punching
4	2.5	–	250	No punching
5	1.5	0.0004	240	Hole diameter $(15-18)\cdot 10^{-3}$ m, punched holes
6	1.75	0.0004	240	Depression with rupture $(3\times 10)\cdot 10^{-3}$ m
7	2	0.0004	235	No punching
8	2.5	0.0008	230	Hole diameter $(8-10)\cdot 10^{-3}$ m

gradients realized under these conditions are higher than certain critical values (connected with the relaxation time of the macromolecules by the relationship $\Theta\varepsilon_{cr} \simeq 0.5$ [10]) sufficient to ensure unfolding of the macromolecules. Therefore the outgoing water jet appears to be armed with macromolecules unfolded to a great extent. A portion of its energy goes into structural reorganization of the flow [4, 5], which causes an increase in the compactness of the jet with polymer additives and decreases its mean velocity. The latter circumstance is favorable for an increase in the threshold distance from which the target is still broken through.

The vanishing of differences in the behavior of jets of water and polymer solution observed in the experiments at such velocities when the longitudinal velocity gradient becomes less than ε_{cr}, whereas at the same time the transverse gradient can exceed substantially (by 1–2 orders) the value of ε_{cr}, also bears witness that the extent of the hydrodynamic action on the molecular coils is practically independent of the transverse velocity gradient.

The experiments considered confirm the above conclusion that the extent of the hydrodynamic action on polymer solutions is determined primarily by the value of the longitudinal velocity gradient achieved [6] and the duration of the action of the stretching hydrodynamic field [11, 12].

In the case of parietal turbulence its structure should be affected by highly unfolded macromolecules. In this case special conditions [3, 11] should be met in the turbulent flow, namely: the longitudinal velocity gradients and the deforming time in such flows should be greater than $0.5/\Theta$ and Θ, respectively. At some rather high v_*, when the creation of zones with stretching and their destruction proceed at a high frequency, as follows from [12], an increase in the deformation rate should lead to the decrease in the deformation factor as a result of a decrease in the action time of the longitudinal velocity gradient. The last-mentioned decrease is a result of small-scale turbulence, the fraction of which increases sharply at high v_* [13, 14]. The Toms effect is reduced appreciably also by degradation of polymer solutions [6]. Therefore the hydrodynamic activity of polymers should decrease in high-speed turbulent flows both as a result of nonconformity of characteristic times of the polymer solution and the time scale of the flow (spikes) and as a result of degradation of polymer molecules.

An analysis of data on the viscosity anomaly of polymer solutions [15] shows that in the case of flow of concentrated solutions the phenomenon of slipping (flow separation) at the wall, which is called elastic turbulence, can be observed already at low velocities. In the case of flow of semidilute solutions elastic turbulence may occur only at comparatively high velocities. Recall that solutions of hydrodynamically active polymers are divided into three concentration regions [7]. The first one is the region of dilute solutions when macromolecules affected by the hydrodynamic field are subjected to the action (unfolding); however they still interact weaky with one another. The second region is the region of semidilute solutions when in precritical flow regimes the solutions are dilute whereas in supercritical regimes they appear to be concentrated as a result of formation of hypomolecular structures due to the shift of the curves of phase separation under the action of the hydrodynamic field. And the last region is the region of concentrated solutions ($[\eta]_0 C > 1$) when considerable interactions between macromolecules take place without the action of the hydrodynamic field. On this basis the observed decrease in the hydrodynamic resistance of small-diameter tubes to the flow of semidilute (rather than dilute) solutions at high velocities (~100 m/sec) [2] should be classified with elastic turbulence.

In summary the experiments under consideration and data [3–7] bear witness to the decisive role of the longitudinal velocity gradient realized in the flow in deformation of molecular coils, whereas the transverse velocity gradient counts very little in this process.

NOTATION

Θ, relaxation time of macromolecules; ε, longitudinal velocity gradient; v_*, dynamic velocity; $[\eta]_0$, characteristic viscosity; C, polymer concentration in solution; $\overline{U}$, mean jet velocity.

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