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UNROLLING OF MACROMOLECULES UNDER THE CONDITIONS OF WALL TURBULENCE

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The results of polarization–optical studies of turbulent wall flow of a solution of polyethylene oxide are presented, showing the existence of strong deforming action of the hydrodynamic field on macromolecules in certain zones of the boundary layer.

It has been shown experimentally [1-3] that macromolecules are subject to strong (up to 100%) unrolling in laminar streams with stretching. Macromolecules that are unrolled under the action of the longitudinal hydrodynamic field affect the structure of that field and cause a considerable increase in energy dissipation [4]. The influence of the unrolling macromolecules on the structure of the hydrodynamic field that unrolls them occurs at the molecular level in dilute polymer solutions and at the supermolecular level in semidilute and moderately concentrated solutions [3]. These results are decisive for the interpretation of the Toms effect. The lack of adequate experimental confirmation of the significant unrolling of macromolecules under the conditions of wall turbulence lowers their value, however.

Experimental data [5, 6] indicate that in a turbulent stream near a wall there are zones containing both elements of shear flow and flow elements (jet ejections) with stretching, which have their own time dynamics. The turbulence associated with ejections is considered to be primary, while the turbulence due to the instability and breakup of jets (liquid ejections) is secondary. The latter is very important, since in this case it is sufficient to reduce the frequency of ejections to ultimately reduce the frictional resistance.

It can be assumed that flow in the immediate vicinity of a wall, as in the case of laminar shear flow, should hardly change; at the same time, with increasing distance from the wall, where jet flows with large longitudinal velocity gradients start to occur, unrolling of macromolecules with all its consequences should be observed. Experiments showing the unrolling of macromolecules under the conditions of wall turbulence are therefore fundamental,

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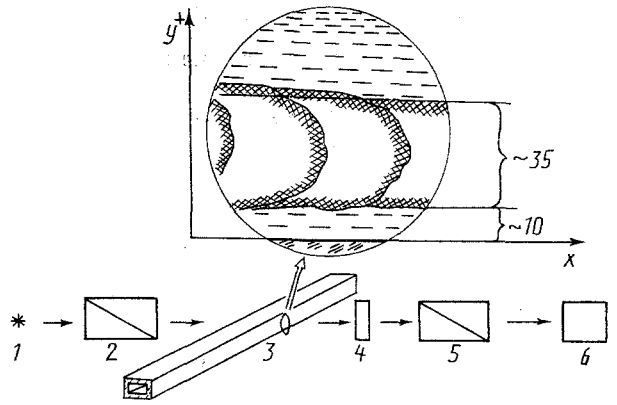

Fig. 1. Sketch of the pattern of the birefringe zone and diagram of the experimental installation: 1) mercury lamp; 2) polarizer; 3) hydrodynamic channel; 4) quarter-wave plate; 5) analyzer; 6) still or motion picture camera.

not only at the level of the development of the mechanism of the Toms effect, but also at the level of a more profound understanding of the nature of turbulence itself.

In the present work we have carried out just such experiments, based on the intrinsic anisotropy and shape anisotropy of linear macromolecules of a polymer [7]. In the case of complete unrolling of macromolecules, which can occur only in streams with stretching [1-4], a very pronounced (three or four orders of magnitude larger than in simple shear) and rapid increase in the birefringence coefficient occurs upon an increase in the velocity gradient acting on molecular coils, up to the extreme possible amount [2]. This dependence of birefringence on the degree of unrolling of macromolecules gives hope for detecting a birefringent region in zones with large longitudinal velocity gradients in the boundary layer, despite the great decrease in the sensitivity of the polarization–optical method at low concentrations of the polymer solution.

For polarization–optical visualization of the turbulent boundary flow of polymer solutions, we used an experimental installation consisting of an optical bench, a light source, a polarization microscope, a light filter, and a quarter-wave plate. A schematic diagram of the installation may be found in [8]. A DRSh-250 mercury–quartz lamp served as the light source. A transparent rectangular channel made of glass and having a cross section $(4 \times 4)\cdot 10^{-3}$ m and a length 1 m was used as the hydrodynamic cell. It was fastened to a special coordinate stand and could be moved in three mutually perpendicular directions. Visualization was carried out in the wall region of the channel at a distance 0.25 m from its end.

The experiments were carried out* with aqueous solutions of polyethylene oxide (PEO) with molecular mass $4\cdot 10^6$ and a characteristic viscosity 1.72 m^3/kg for the concentration range 0.01-0.05% at a Reynolds number $2\cdot 10^4$. To create a laminar flow regime with the same frictional wall shear stress as in turbulent flow, we used a channel with a cross section $(0.5 \times 0.5)\cdot 10^{-3}$ m.

In Fig. 1 we show a sketch of the pattern of the birefringent zone of the turbulent boundary layer in the flow of a 0.05% aqueous PEO solution. Most of the photographs of birefringent zones were obtained with the planes of polarization of the polaroids oriented so that the axis, forming a 45° angle with them, formed a 35° angle with the direction of the main stream, since the intensity of the observed birefringence pattern hardly changed in the range of angles 25-45°. This may be due either to the low sensitivity of the experimental technique or to the presence in the stream of some distribution of orientations of the unrolling macromolecules, the axes of which form angles of 25-45° to the stream.

The absence of birefringence in the immediate vicinity of the wall ($0 \leq y^+ < 10$), where the largest shear velocity gradients occur, attracts attention. That result is additional evidence of the weak deforming action of shear velocity gradients on macromolecular coils. This is also confirmed by the fact that replacing the turbulent flow by laminar flow, by reducing the channel cross section, leads to the disappearance of the birefringent zone,

*S. V. Tverdokhleb took part in the experiments.

despite the fact that the frictional shear stress at the wall remained unchanged. But increasing the PEO concentration in the solution to 0.1% enables one to observe birefringence due to the orientations of macromolecules in the laminar shear stream at fairly high dynamic velocities. The patterns obtained (see Fig. 1) indicate that the birefringent zone extends into the region $10 < y^+ \leq 45$, where longitudinal velocity gradients occur whose character depends on the local conditions. Birefringence is absent from the core region ($y^+ > 45$). That result is fully consistent with existing experimental data [6], showing that small polymer admixtures do not affect the structure of the turbulent core, but only thicken the viscous sublayer in the liquid with decreased resistance.

It has been noted that the birefringent zone seems to drift to the region in which it lies at the time of observation. This is probably related to the existence in the turbulent boundary layer of a system of zones [9], in which breakup of the sublayer occurs, that travel downstream at a somewhat lower velocity than that of the liquid outside the boundary layer.

The analyzed experimental data thus serve as convincing proof of the existence of strong deforming action of the hydrodynamic field on macromolecules under the conditions of wall turbulence. Our polarization-optical investigation of a turbulent boundary stream of an aqueous PEO solution confirms the generally accepted concepts about the structure of a turbulent boundary layer [5]. Despite the lack of quantitative data on the stress state of macromolecules under the conditions of wall turbulence, the acquisition of which is associated with considerable experimental difficulties (but not of a fundamental nature), we may say confidently that the experimental results presented here are basic to confirming the idea that the mechanism of reduction of resistance is uniquely related to the process of strong (~60%) [3] deformation of macromolecular coils, leading to the appearance of nonlinear elastic effects.

NOTATION

v_*, dynamic velocity; ν, kinematic viscosity; x and y, coordinates; $y^+ = v_* y/\nu$.

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