



The Nature of Hydrodynamic Drag Reduction of Oil Flow in Pipelines by Polymer Additions

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Abstract: As a result of experiments it was confirmed the unfolding of molecules under wall-adjacent turbulence conditions, as well as it was proved that dynamic structure formation in polymer solutions is occurred under the influence of supercritical longitudinal gradients of speeds. On the basis of data that characterize macromolecule dynamics in non-turbulence flow with stretching and the proved evidence of strong deformation effect on macromolecules in wall-adjacent turbulence, it has been established the molecular-and-supermolecular mechanism of effect reduction for flow resistance when injecting soluble polymer additives in a turbulence flow. Understanding the mechanism of reducing drag flow of oil in pipelines by small polymer additions will allow to develop recommendations on the choice of rational hydraulic regimes oil pipelines, as well as to outline ways for the directed synthesis of high-performance polymer additions that reduce friction in the turbulent oil pipelines.

Keywords: Oil Pipeline, Reduction of Turbulent Friction, Polymer Solution, Macromolecule, Deformation Effect, Dynamic Structure Formation, Toms Effect

1. Introduction

The problem of reducing the energy intensity of the oil-trunk pipelines by increasing their productivity remains one of the key problems of economic development of different countries. It is obvious that the task of improving the hydrodynamic characteristics of the oil pipelines is to find the ways to reduce the oil flow drag - fluid friction. Among the known methods of artificial influence on the boundary layer, in order to reduce the hydrodynamic drag in oil pipelines, special place is taken by a method, based on the injection of polymer solutions. This method is the only one in the development that has certain practical progress [1-4].

Laboratory and field tests of the influence of small polymer additions to reduce the drag of oil flow in pipelines began conducting since the late 70-ies of the XX century [3, 5-8]. The design development of oil pipeline by using polymeric additions for turbulent drag reduction was justified, because the actual increase of the Trans-Alaska oil-trunk pipeline capacity [2] has amounted 20%. However, the

resulting friction drag reduction effects by applying polymer solutions in oil pipelines are far from the theoretically predicted. Therefore, the technical task of reducing the hydrodynamic resistance of oil flow in the pipelines by applying the polymer solution into the boundary layer needs to be resolved.

This applies to all questions above regarding the nature of turbulent drag reduction by using polymer additions.

Understanding the nature of reducing drag flow of oil in pipelines by small polymer additions will allow to develop recommendations on the choice of rational hydraulic regimes of oil pipelines, as well as to outline the ways for the directed synthesis of high-performance polymer additions that reduce friction in the turbulent oil pipelines.

In the hydrodynamics of polymer solutions there takes place the transition from accumulating experimental information to understanding the physical essence and establishing main regularities of manifestation of memory and elasticity effects. Toms effect revealed as an experimental fact in the late 40-ies, up to now has been causing great difficulties when interpreting it from the point

of view of modern ideas of the hydrodynamics of turbulent flow.

Among the attempts to explain the nature of effect Toms', lying in drag reduction by the polymeric components, special place is taken by a hypothesis, based on strong deformation effect of a near-the-wall turbulence on macromolecules [3, 9]. For the substantiation of this hypothesis experimental proofs of presence of large degrees of deformation of macromolecules in a wall-adjacent zone of a turbulent flow are necessary. The skepticism concerning strong deformation effect of wall-adjacent turbulence on macromolecules is stipulated yet by the fact that, as a rule, shift effects wall-adjacent a turbulence are analyzed, and not the, jet flows ("explosions") with a longitudinal gradient of speed which arise in the wall-adjacent area [10, 11]. It is possible to hope, that the way to understanding and describing phenomena reduction of turbulent friction by polymer additions lies through the study of hydrodynamic effects of big reversible (as well as non-reversible) deformations of molecular coils in flows with stretching.

Therefore the experiments proving the stretching of molecules in conditions of wall-adjacent turbulence have a fundamental character not only in point of developing the mechanism of drag reduction by polymer additions but also in point of more profound insight into the nature of turbulence itself.

2. Methods and Materials

For polarization-optical visualization of wall-adjacent turbulence flow of polymer solutions using the experimental installation, consisting of the optical bench, the light source, a polarizing microscope, filter and a plate equal to a quarter of a wavelength. The scheme of the installation can be found in the [12, 13]. The light source was a mercury-quartz lamp DRSh-250. Transparent rectangular channel was used as hydrodynamic cells. It was made of glass and had the cross-section $(4 \times 4) \cdot 10^{-3} \text{m}$ and the length of 1m. It was fixed to the special coordination table and could be moved in three mutually perpendicular directions. Visualization was made in the wall-adjacent area of the channel, that was located at a distance of 0.25 m from its end.

Due to the significant experimental difficulties in obtaining data on the stress state of macromolecules in conditions of wall-adjacent turbulence in the oil flow, experiments were carried out with water solutions of polyethylene oxide (PEO), which were used as a model polymer solutions in oil.

PEO having the viscosity-average molecular weight of $4 \cdot 10^6$ was used as a polymeric additive and latent root of a The solutions of polymer had concentration 0.01-0.05%. Special hydrodynamic canal a rectangular cross-section $(4 \times 4) \cdot 10^{-3} \text{m}$ and height of 1m was used. Visualization made in wall-adjacent of area located on a distance 0.25 m from its extremity of the channel.

3. Results and Their Discussion

3.1. Deformation of the Molecular Coils of Flexible Polymers Under Wall-Adjacent Turbulence Conditions

Experiments proving macromolecule unrolling under wall-adjacent turbulence have fundamental character not only in relation to the development of the Toms' effect mechanism but as well as to the more profound insight of the nature of the wall-adjacent turbulence itself.

Such tests can be carried out due to polymer linear macromolecules having their own anisotropy and anisotropy of form. Moreover in case of full macromolecule unrolling that can be realized only in flows with stretching, there takes place rather significant (by 3-4 orders of magnitude greater than for simple shift) and quick increment of the birefringence factor with the increase of velocity gradient acting on molecular coils up to extremely possible Δn_{∞} [14]. The given peculiarity of birefringence dependence on the degree of macromolecule unrolling just gives hope for the occurrence of birefringence area in zones with greater longitudinal velocity gradients of a boundary layer despite the sharp sensitivity reduction of the polarization-optical method under small polymer solution concentrations.

Figure 1 shows a sketch of a picture birefringence zone of a turbulent boundary layer of a current of a water solution PEO having concentration 0.05% and $Re = 2 \cdot 10^4$.

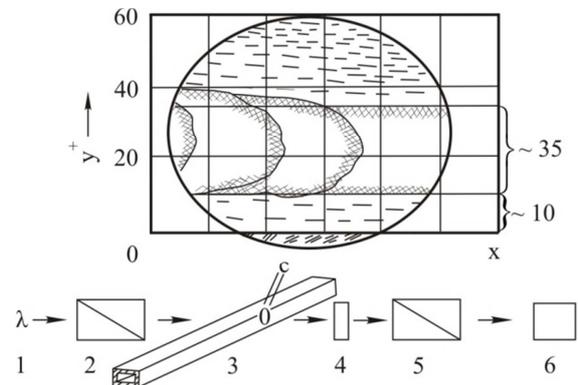


Figure 1. The sketch of a picture of birefringence zone and a diagram of experimental installation.

1 – mercury lamp; 2 – polarizer; 3 – hydrodynamic channel; 4 – plate a equal to a quarter of a wavelength; 5 – analyzer; 6 – camera or cine camera.

Polarization and optical visualization testify, that in the field of $10 \leq y^+ \leq 45$, in which maximum generation of jets of fluid happens, birefringence is localized. In the immediate proximity to the wall ($0 \leq y^+ < 10$) and in the field of the

kernel ($y^+ > 45$) birefringence is un-variable ($y^+ = v^* \cdot \frac{y}{\nu}$,

where: y – is coordinate; v^* – is dynamic velocity; ν – is kinematic viscosity).

This fundamental experiment unequivocally shows the presence of strong deformation effect on the molecular coils in certain zones of a turbulent boundary layer, having

supercritical longitudinal gradients of speeds.

A mean angle of the orientation of polymer molecules with a direction of the main flow is $\sim 35^\circ$. The performed visualization of near-the-wall turbulent flow of water solution PEO has confirmed the conventional ideas about the structure of a turbulent boundary layer.

Adequate experimental verification of macromolecule unrolling under wall-adjacent turbulence made it obvious that using non-turbulence flows with stretching for the study of macromolecule interaction with hydrodynamic field is advantageous as giving the possibility to experimentally investigate “abnormal” effects in controlled conditions and allowing to model the main peculiarities of a turbulence boundary layer.

3.2. Dynamic Structure Formation in Solutions of Hydrodynamic Active Polymers

Let’s examine the tests allowing to reveal the ability of hydrodynamic active polymers to dynamic structure formation effected by hydrodynamic field with stretching. To create hydrodynamic field with stretching there has been used a flow of Newtonian liquid (water, acetone, dioxan) converging to a small outlet $0.3 \cdot 10^{-3} m$ in diameter. At quite a distance from the outlet there have been injected in this flow some jets of PEO solutions or hydrolyzed polyacrylamide (HPAA) with molecular mass $6 \cdot 10^6$ and $4.5 \cdot 10^6$ and intrinsic viscosity 2.42 and $3.70 m^3/kg$ correspondingly. The degree of PAA hydrolysis was 5 percent. Interval of the studied concentrations was 0.001-0.1 percent. Polymer solution velocity in points of injection agreed with velocity of the main liquid flow. Visualization of the flow in the inlet area was done with the help of dye additives injected into polymer solution. Under small outflow velocities dyed jets of polymer solution visualize stream-lines of the main flow (Figure 2).

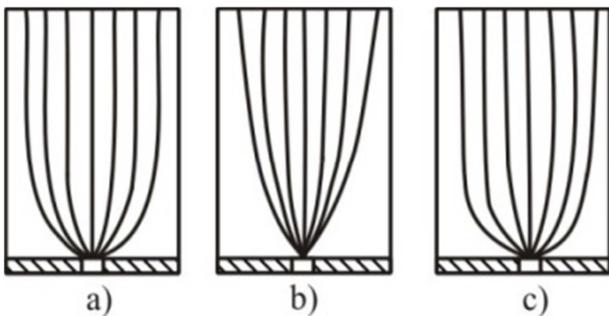


Figure 2. Picture of flow in the inlet area of a capillary when injecting polymer solution into water during pre-critical mode of outflow.

$M_{PEO} = 6 \cdot 10^6$, $C_{PEO} = 0.025\%$; $M_{HPAA} = 4.5 \cdot 10^6$, $C_{HPAA} = 0.05\%$; a) - water into water at $\dot{\epsilon} > \dot{\epsilon}_{cr}$; b) - HPAA into water at $\dot{\epsilon} > \dot{\epsilon}_{cr}$; c) - PEO into water at $\dot{\epsilon} < \dot{\epsilon}_{cr}$.

In his case behaviour of PEO and HPAA solution jets doesn’t differ at all from the behaviour of water jets injected into converging liquid flow. Reaching some critical flow rate

of liquid through the orifice the character of jet flow of polymer solution drastically changes. Rather thick polymer jets transform into thin threads that change their length with time flow (Figure 3).

When observing the dynamics of forming and destructing separate threads (here lies the moving pulsation character of the flooded polymer jets) the following regularity comes to life. At the beginning when polymer jets approach the orifice there can be traced their gradual bend towards the orifice. Here their velocity growth along these curve trajectories becomes more noticeable as the jet thickness gets reduced. Near the orifice discontinuous (for PEO solutions) reduction of jets thickness takes place as they are transformed into thin threads. Transformation area of a thick jet into a thin thread starts to shift up along the jets resulting in the increase of the thread length. HPAA water solutions reveal more gradual change of jet thickness than PEO solutions. As jets approach the orifice not concurrently the length of threads spun by the flow from separate polymer jets is different at each given moment. Birefringence is observed in the area of thread emergence.

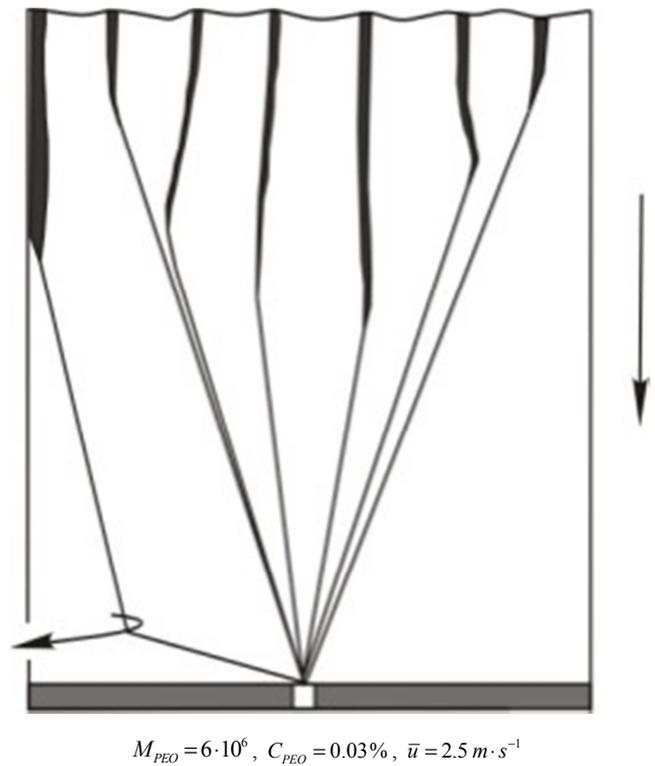


Figure 3. Photo of flow at the point of wire probe effecting a polymer thread spun by hydrodynamic field.

When reaching some critical length a thread cuts off in close proximity to the orifice. After that the remaining at the top thread loses its elasticity and sags marking one of the stream lines of the main flow. When a polymer jet approaches the orifice again the whole thing is repeated anew. This process is resumed with time interval from fractions of a second to several seconds depending upon the outflow mode of the main flow, polymer molecular mass,

polymer type, solvent quality and temperature, as well as polymer concentration in solution.

Outflow velocity growth of converging water flow as well as increase of molecular mass and polymer concentration result in the increase of thread length and reduction of their length-changing rate. Temperature growth leads to the opposite effect. Tests with acetone and dioxan (solvents with poorer thermodynamic qualities than water) showed that under the same velocities as in tests with water pulsation rate of thread length is bigger, but the amplitude of these changes is less than in case of injecting polymer solution into water. It should be also stressed that there are such ejection modes for concentrated (to Debay $[\eta]_0 \cdot C > 1$) polymer solutions, when the emerged polymer threads don't cut off during the whole period of observation.

There also has been studied the effect of initial (non-turbulent by hydrodynamic field) sizes of molecular coils, that in poly-electrolytes (HPAA) depend on the hydrogen measure of the surroundings, on the ejection character of HPAA solution jets injected into water flow. The experiment has shown that in case of pH of the main flow equaling 2 the length of a polymer thread decreases sharply (3-4 times for 0.05 percent concentration) while the thread length-changing rate increases by 1.5-2 times. The increase of pH in the range between 7 and 9.5 practically doesn't influence the ejection character.

The main regularities of the polymer jets behaviour when injected into a flow with stretching, which is the main liquid flow, are similar to those in case of polymer solution outflow through short capillaries [3, 9]. Hence, the observed behaviour peculiarities of the flooded polymer jets in flow with stretching are caused by rather strong polymer coils unrolling effected by hydrodynamic field (the degree of unrolling here reaches ~60 percent [13, 15]). Uncoiling of macromolecule chains leads to decrease of their flexibility, which under certain conditions causes phase separation effected by hydrodynamic field, i.e. it leads to dynamic structure formation.

The following experiment may serve as a proof of dynamic structure formation effected by hydrodynamic field with stretching. A thin wire with a device for polymer thread hold-up is introduced into the inlet area of the orifice during the pre-critical mode of the main flow ejection. This wire travel in the plane perpendicular to jets doesn't change the flow picture, i.e. during these modes the polymer jets are permeable to it. If the experiment is repeated during over-critical mode of liquid outflow, then it would be possible to hold-up one or several polymer threads during their growth and divert them as it is shown in Figure 3. This can be done only if there is a strong interaction between polymer molecules, i.e. when sub-molecular structure is formed, in this case under the effect of stretching hydrodynamic field. The minimum concentration of PEO water solutions allowing to divert a thread spun by hydrodynamic field was 0.008 percent, which corresponds to the range of diluted solutions ($[\eta]_0 \cdot C < 1$).

The given results as well as those obtained while studying

converging flows of polymer solutions allow to state that hydrodynamic active polymer solutions should be divided into at least three concentration ranges. The first is the range of diluted polymer solutions when macromolecules are under strong deformation effect (unrolling) caused by hydrodynamic field, but the interaction between them is still weak. The second is the range of semi-diluted solutions (intermediate) when during pre-critical flow modes become diluted and during over-critical modes they become concentrated due to super-molecule structure formation caused by the shift of phase separation curves effected by hydrodynamic field. These dynamic structures should be classified as dynamic phase transitions that are studied by the theory of dissipation structures [16]. And the last range is the one of concentrated solutions ($[\eta]_0 \cdot C > 1$), when noticeable interaction between molecules do exist without hydrodynamic field. It should be stressed that the first two ranges refer to concentrations when the Toms' effect is manifested.

So, the results obtained by us show that dynamic structure formation and periodic processes subjected to Prigozhin's principles of self-organization may occur in hydrodynamic active polymer solutions in flow with stretching.

3.3. Polymer Solutions in Model Conditions of Wall-Adjacent Turbulence

When changing the orientation of zones with stretching generated with a help of a short capillary tube as to the wall (barrier) position it is possible to simulate ejections of polymer solution micro-jets from the wall-adjacent area.

Figure 4 shows curves that characterize relationship of effective viscosity to u and obtained in PEO water solution flow through a short capillary tube with orientation of a single axis stretching zone along a normal to the "wall" surface.

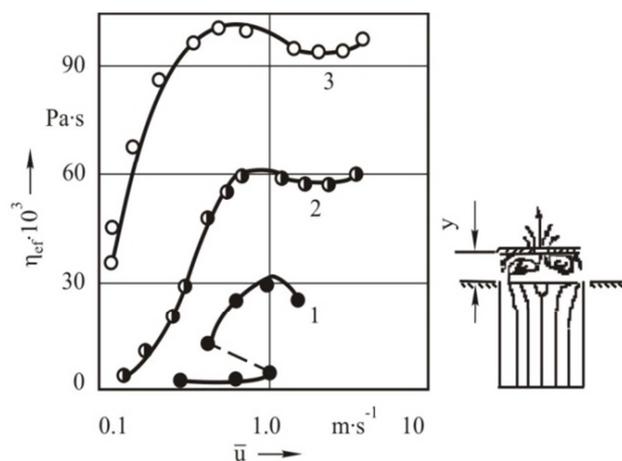


Figure 4. Influence of a space the wall positioned normally to the axis of a longitudinal flow on effective viscosity in polymer solution.

$M_{PEO} = 4 \cdot 10^6$, $C_{PEO} = 0.05\%$; y : 1 – without a wall ($y \rightarrow \infty$), 2 – $5 \cdot 10^{-3} m$, 3 – $10^{-3} m$.

It is seen that when a stretching zone approaches a solid

surface the flow becomes more dissipative, but the critical velocity is shifted to less values. The given situation may serve as a model of normal component in a blasting flow near the wall; then the data obtained testify to the decrease of probability for such “blasts” to occur in the wall-adjacent area when there is a polymer in a liquid. That’s why the thickness of a viscous sub-layer in a liquid with decreasing resistance must be higher and the average (in time) intensity of lateral velocity pulsations must be less than in a liquid without a polymer.

Curves shown in Figure 5 meet the conditions of PEO solution outflow through a capillary tube when its axis is positioned in parallel to the “wall” surface. When surface approaches zone axis with longitudinal velocity gradient the maximum value of effective viscosity is practically unchanged while the critical velocity value is shifted to greater values.

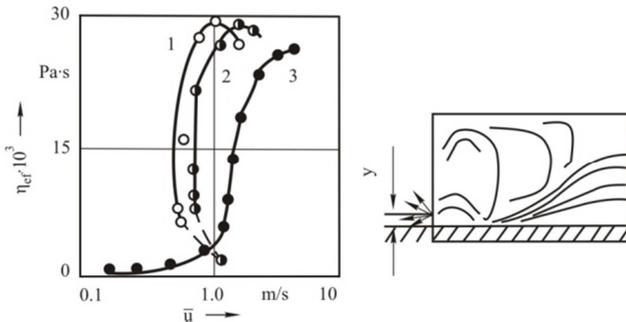


Figure 5. Influence of a space to the wall positioned in parallel to the axis of a longitudinal flow on effective viscosity in polymer solution.

$M_{PEO} = 4 \cdot 10^6$, $C_{PEO} = 0.05\%$; y : 1 – without a wall ($y \rightarrow \infty$), 2 – $5 \cdot 10^{-3}$ m, 3 – $5 \cdot 10^{-4}$ m.

This situation serves as a model of longitudinal component in a blasting flow near the wall. Independence of the maximum viscosity value and insufficient increase of u_{cr} on approaching the “wall” must testify to the fact that average (in time) intensity of longitudinal blasts and, thus, velocity pulsations near the wall are similar to those in flows without polymer additives.

In flows with stretching zones macromolecules of a dissolved polymer, when $\dot{\epsilon} > \dot{\epsilon}_{cr}$, suppress big longitudinal gradients, and just this very feature must lead to the decrease of velocity pulsation intensity near the wall and manifestation of some threshold flow mode that gives way to the hydrodynamic activity of polymer additives to be revealed. The obtained results are in complete conformity with the known ones that prove the existence of a threshold velocity of Toms’ effect manifestation [17].

Summarizing we may say that the studied experiments and the data obtained allow to receive additional information on the structure of wall-adjacent turbulence and to come to the issue on mechanism of turbulence friction reduction effect due to polymer additives; we are to deal with it in the following section.

3.4. Mechanism of Turbulence Friction Reduction Effect Due to Polymer Additives

The data obtained due to this work convincingly prove that the system water-polymer (polymer with flexible chains) under wall-adjacent turbulence in certain flow modes ($v^* > v^*_{threshold}$) is self-regulating with negative feedback that is manifested in the following: the growing longitudinal velocity gradients acting in the area ($0 \leq y^+ < 10$) where jet flows are generated to the maximum as a result of turbulent explosions, lead to macromolecule coil deformation which in its turn causes structure reconstruction of these flows in order to decrease longitudinal velocity gradients. The latter cannot be lower than critical values equaling $\frac{0,5}{\theta_c}$.

If they appear to be lower than $\dot{\epsilon}_{cr}$ then macromolecules will start to form into a coil with no more effect on velocity field; velocity gradient sharply increases here leading to significant deformation of macromolecular coils and everything repeats again. It means that in auto-vibration mode the system regulates velocity gradient in jet flows making it relatively small but still sufficient enough for macromolecular coil deformation. It should be stressed here that namely this ensures Virk’s asymptote and no full laminarization of wall-adjacent turbulence flow.

Growth of deformation velocity as a result of non-linear effects leads to insignificant further increase of deformation factor, but this turns to be enough to stabilize typical velocity gradient within a rather broad interval of flow velocities. In case of rather high v^* , as it comes out from [1, 10, 17] deformation velocity growth leads to deformation factor decrease due to the cut of effect time for longitudinal velocity gradient. The latter is due to small-scale turbulence, which share sharply increases under high v^* [1, 10, 17]. That’s why Toms’ effect dependence on velocity has extremal nature. Degradation of polymer solutions starts to contribute significantly to Toms’ effect reduction at high velocities.

So, liquid ejections from the wall area into the outer area of a boundary layer that nearly periodically interrupt calm flowing, are stabilized by feedback molecule deformation (flooded jet flows with longitudinal velocity gradient). This leads to frequency decrease of these ejections and finally to suppression of normal Newtonian energy processes caused by jet ejections and, thus, to friction resistance decrease. The part of explosion cycle where gradient $\dot{\epsilon} > \dot{\epsilon}_{cr} = \frac{0,5}{\theta_c}$ takes

place is subjected to the greatest effect. The interaction between macromolecular coils and hydrodynamic field in auto-vibration mode takes place in any zone of a flow with stretching in a wall-adjacent area of a turbulence flow, which prevents primary turbulence development.

It is important to compare macromolecular scales describing polymer molecules in solution as well as turbulence scale near the wall. In this case linear and temporal scales must be single-valued. Analysis of experimental data shows that both typical size λ_f and time T_f depend on concentration, molecular mass and some other

factors. On average the following factors can be accepted: $\lambda_f \sim 10^{-4} - 10^{-5} m$, while $T_f \sim 10^{-3} - 10^{-4} s$ [17].

Macromolecules in solution are characterized by a linear scale that depends on the degree of their stretching; contour length of a completely stretched macromolecule should be taken as its characteristic feature, maximum (fundamental) time for relaxation should be treated as typical time.

In case of full macromolecule stretching its contour length has a micro-scale factor of wall-adjacent turbulence. The stretching rate of approximate 60 percent was obtained in model conditions of wall-adjacent turbulence. This demonstrates the fact that interaction between turbulence field velocity and macromolecules may take place both on the level of individual molecules (very watered down solutions) and on the level of super-molecular formations generated by hydrodynamic field (semi-diluted and moderately concentrated solutions). The average relaxation time of polymer solutions [13, 17] coincides in factor with the typical time of wall-adjacent turbulence.

Comparison of concentration dependence of the Toms' effect and the data testifying to the formation of dynamic super-molecular structures in polymer solutions allows to state that in the vicinity of optimal concentration ($C \geq C_{opt}$), where the Toms' effect reaches its maximum, solutions start generating anisotropic super-molecular forms having the lifetime 10-20 times longer than θ_c [3]. Further increase of concentration leads to conditions favorable for interaction between individual polymer molecules even without the hydrodynamic field effecting on them. The longitudinal hydrodynamic field effect in polymer solution gives way to the formation of dynamic super-molecular structures with lifetime significantly exceeding (in several factors) the temporal scale of the wall-adjacent turbulence. That's why unlike the super-molecular forms in semi-diluted solutions these super-molecular forms act as "stiff sticks". As an outcome of this the Toms' effect is decreased at a high polymer concentration in solution as well as at a high dynamic velocity.

On the basis of data that characterize macromolecule dynamics in non-turbulence flows with stretching and the proved evidence of strong deformation effect on macromolecules in wall-adjacent turbulence, and using data of model studies of turbulence peculiarities in a boundary layer there has been established the molecular-and-supermolecular mechanism of effect reduction for flow resistance when injecting soluble polymer additives in a turbulence flow. Mechanism of Toms' effect lies in the occurrence of auto-fluctuating mode of reversible processes of macromolecule deformation caused by longitudinal velocity gradients that quasi-regularly originate in turbulence boundary layer and in macromolecule deformation effect both on molecular (when $C < C_{opt}$) and super-molecular (when $C > C_{opt}$) levels on the wall-adjacent turbulence structure, i.e. as a result of macromolecule deformation oscillations and solubility of dynamic super-molecular forms brought about by the flow-with-stretching effect. All this leads to the increase of liquid ejection periods into the outer zone of the boundary layer and in consequence to the viscous

sub-layer becoming thicker. As an outcome of this generation of primary turbulence gets reduced and general level of turbulence dissipation in the flow becomes lower. In case of sufficiently big molecular masses and concentrations the viscosity growth caused by both "common" intermolecular interaction and dynamic structure formation leads to sharp Toms' effect decrease.

The considered experimental data prove the substantiation to transfer outcomes obtained during the study of macromolecule dynamics in non-turbulence flows with stretching onto jet currents of wall-adjacent ejections in turbulence flow, i.e. turbulence current (to macroscopic scale) is perceived as laminar one (to microscopic scale) when hydrodynamic field interacts with polymer molecules. Macromolecules may serve as an efficient tool of getting additional information about the structure of wall-adjacent turbulence.

4. Conclusions

The developed approach of explaining the turbulent drag reduction mechanism fits well into the general scheme of self-regulatory processes, which are dominated by negative feedbacks. It is typical for systems that can change their properties under the action of external physical effects, in this case, under the influence of jet currents ("explosions") with stretching which locally occurring in the boundary layer of the oil pipeline. The considered experimental data prove the substantiation to transfer outcomes obtained during the study of macromolecule dynamics in non-turbulence flows with stretching onto jet currents of wall-adjacent ejections in turbulence flow, i.e. turbulence current (to macroscopic scale) is perceived as laminar one (to microscopic scale) when hydrodynamic field interacts with polymer molecules.

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