number for case of liquid film motion under action of centrifugal forces; $L_{in} = [G^2/2\pi^2\rho^2\nu\omega]^{1/4}$, size of input segment, $j = \omega^2 R$, centrifugal acceleration; g, gravitational acceleration.

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TURBULENT FLOWS OF POLYOX SOLUTIONS IN A TUBE WITH LARGE ROUGHNESS OF THE SURFACE

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UDC 532.542.4

Experimental results on the measurement of frictional drag in the flow of polyox solutions with concentration $(5 \cdot 10^{-6}-10^{-3})$ g/cm^3 in tubes of diameter d = (32 ± 1) mm with different degrees of surface roughness are presented (R/k_S = 70.8; 11.1; 7.5; 2.9).

§1. At present, the question about the effect of polymer addition to water flow on the frictional drag during flow along smooth surfaces has been adequately studied experimentally, and this effect can be evaluated not only qualitatively, but also quantitatively [1]. However, in real conditions any surface has some roughness. It was established experimentally in [2-4] that in the case of presence of surface roughness R/k_S = 14-60 a reduction of the drag is observed in the transition flow regime of polymer solutions with $k_S v_*/\nu < 100$. As in the flow along smooth surfaces, the reduction in the frictional drag for the values of the tangential frictional stresses exceeds a certain threshold value independent of the state of the surface [2].

A common drawback of all the known experiments for determining the effect of polymer addition on frictional drag of rough surfaces is the absence of parallel determination of the effect of frictional drag resistance

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 31, No. 2, pp. 225-230, August, 1976. Original article submitted June 16, 1975.

TABLE 1. Basic Characteristics of Water Flow in Rough Tubes for the Length of the Operating Segment L = 1030 mm

Parameters	Grains, μm			
	100	500	800	1250
Diam. d = 2R	33,3 mm	32 mm	31,8 mm	31,2 mm
λ_r (water)	0,033	0,068	0,082	0,140
R/k_S	70,8	11,1	7,5	2,9
k_S, mm	0,23	1,44	2,12	5,35
v_S, m/sec	0,7—10,0	0,7—9,5	0,7—9,7	0,4—9,0
v_* m/sec	0,13—1,79	0,20—2,47	0,22—2,78	0,17—3,40
$k_S v_*/\nu$	20—300	200—2500	300—4000	600—12000

of flows of polymer solutions along smooth surfaces. A comparison of such measurements would naturally simplify the problem of the effect of polymer addition on the drag of rough surfaces.

On the basis of an analysis of experimental data in the present work it was decided to: 1) expand the range of values of roughness of the investigated surfaces compared to the earlier experiments; 2) investigate the effect of addition of polymers on the frictional drag of rough surfaces in well-developed flow regimes for $k_S v_*/\nu > 100$; and 3) carry out simultaneous measurements of the frictional drag in the flow of polymer solutions along smooth and rough surfaces.

§2. For producing the roughness on the inner surface of the tubes, sand with grain sizes of 100, 500, 800, and 1250 μm was used. The sand grains were deposited on the inner surfaces with the use of pentaphthal paint, after which the tubes were slowly dried for a month. The rough coatings obtained in this way remained hard and unchanged during the entire period of the tests.

In view of the differences in the grain sizes of sands used for obtaining different variants of roughness, the inner diameter of the rough tubes also varied; this variation was from d = 33.3 mm (100-μm grain) to 31.2 mm (1250-μm grain). The absolute size of the grain used for the formation of surface roughness did not coincide with the grain size of the roughness in the experiments of Nikuradze corresponding to equal values of the drag coefficients in flow of water in rough tubes. Therefore, for each variant of the geometrical roughness, the equivalent roughness k_S was determined from the hydraulic drag [5]

$$\lg (R/k_S) = 0.5 (1/\sqrt{\lambda} - 1.74).$$

The measuring segment of the conduit with rough surface of length 1030 mm was placed immediately after the accelerating segment with 2180 mm length. The static pressures were sampled in the region of the segments with hydraulically smooth surfaces. The correction for the smooth segment of the tube was not more than 1-3% in the general pressure drop in the measuring segment of the tube.

The experiment on water showed that the measuring segment including the rough tube of 1030 mm length is entirely adequate in length for the formation of flow in the rough tube. Therefore, there was no need for having the same magnitude of surface roughness in the accelerating segment. This permitted us to place hydraulically smooth segments of the tube of roughly the same diameter (d = 35 mm) before and after the rough measuring segment of length L = 1030 mm. The summary data on the short segment of the rough tube are given in Table 1. In the case when the measuring segment of the tube with rough surface had larger length (2180 mm), the smooth segment of the tube was placed only in front of it. This arrangement of smooth and rough segments of the conduit permitted us to compare the effect of drag reduction of the flows with polymer addition in smooth and rough tubes simultaneously.

The coefficient of frictional drag λ for water flow around hydraulically smooth surfaces of the tube corresponds to the well-known relationships of Nikuradze, if the smooth segment of the tube is placed immediately after the rough segment and is somewhat higher (by ~10%) than these values for hydraulically smooth surfaces placed in front of the measuring rough segments (Fig. 1a).

In the experiments with the polymer solutions the effect of drag reduction was estimated in relation to the actual value of the frictional drag coefficients obtained for the chosen scheme of installation of smooth and rough tubes. In all four variants of roughness well-developed flow regimes were obtained when the frictional drag coefficient no longer depended on the Reynolds number (Table 1, Fig. 1).

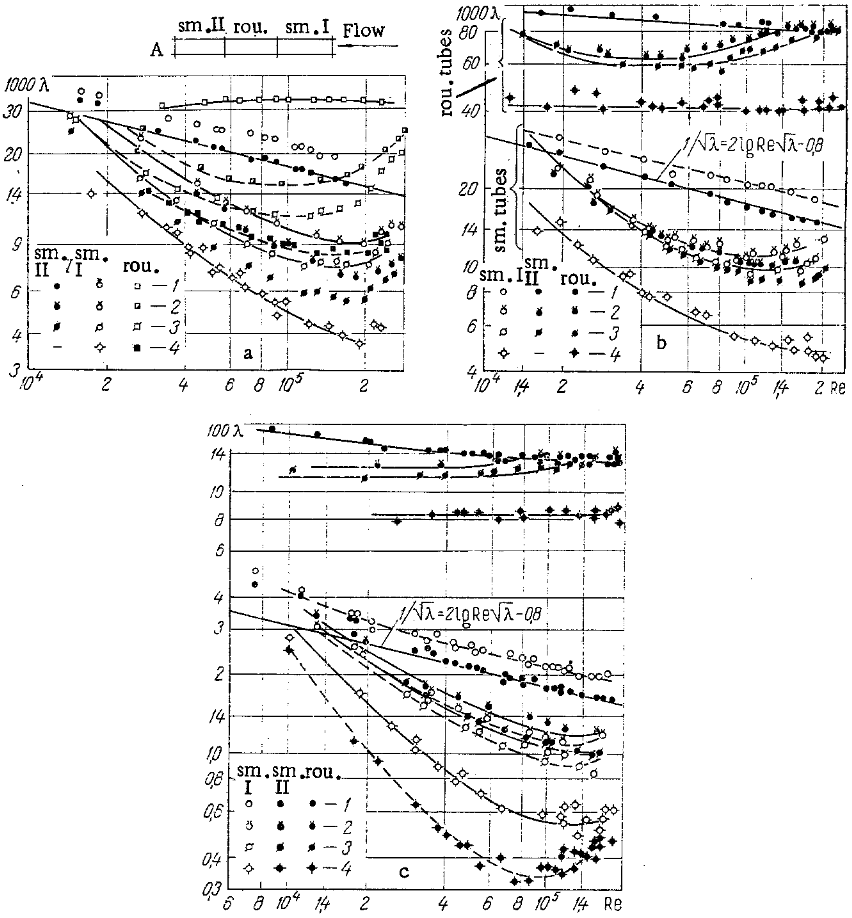

Fig. 1. Dependence of the frictional drag coefficient λ on Reynolds number Re for the flow of polyox solutions in smooth and rough tubes (L = 1030 mm): 1) water; 2) $c = 5 \cdot 10^{-6}$; 3) 10^{-5}; 4) $2 \cdot 10^{4}$ g/cm^3; a) 100-μm grain, R/k_S = 70.8; b) 800-μm grain, R/k_S = 7.5; c) 1250-μm grain, R/k_S = 2.9. A) a scheme of installation of smooth and rough segments.

§3. In order to determine the effect of polymer addition on the frictional drag coefficient, polyoxWSR-301 was chosen as the additive to the water flow in rough tubes; solutions of the following four concentrations were prepared on this polyox: $c = 5 \cdot 10^{-6}$, 10^{-5}, $2 \cdot 10^{-4}$, and 10^{-3} g/cm^3. The results of the experiments are presented in the form of the dependence of the frictional drag coefficient λ on Reynolds number, computed from the viscosity of the solution.

In varying the roughness each time, a fresh polyox solution prepared just before the experiment was used. The use of a common technique of solution preparation gave a good repeatability of the experimental results in the measurement of drag in the smooth segments of the tube. This fact enabled us to compare the effect of surface roughness to the effect of drag reduction under equivalent conditions (Fig. 1).

Examining the dependences shown in Fig. 1, it can be noted that in the flow of polymer solutions along smooth and rough surfaces a reduction of the drag is observed almost in the entire range of the investigated Reynolds number $Re = 10^4$–$2 \cdot 10^5$ and of the tangential frictional stresses at the wall $\tau_W = (15 \cdot 10^4)$ dyn/cm^2. However, the magnitude of this effect for the same concentration of the solution is not uniform for the smooth and rough surfaces, except for the case when the observed effect was identical for roughness R/k_S = 70.8. The relative reduction of the frictional drag of rough surface presented in fractions of the drag reduction on a smooth surface can be approximated by a linear function of the roughness parameter R/k_S for all values of concentration of the solution (Fig. 2). This dependence is also confirmed by the results for decomposed solutions, for which the effect of frictional drag reduction on the smooth surface was appreciably smaller than for a fresh solution. According to the data presented in Fig. 2, the effects of drag reduction on the smooth and rough surfaces are equal for $R/k_S > 20$.

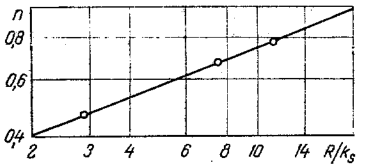

Fig. 2

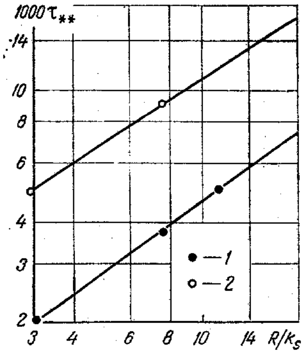

Fig. 3

Fig. 2. The dependence of the ratio of frictional drag reductions $n = S_{o.rou}/S_{o.sm}$ on the surface roughness R/k_S for the flow of polyox solutions in smooth and rough tubes.

Fig. 3. The dependence of the threshold frictional stresses on the surface roughness for flows of polyox solutions: 1) $c = 5 \cdot 10^{-6}$ g/cm^3; 2) $c = 10^{-5}$ g/cm^3.

The data in Fig. 1b, c reveal another important fact: for small values of the concentration of polyox solution ($5 \cdot 10^{-6}$ and 10^{-5} g/cm^3) there is a range of Reynolds numbers in which the increase of velocity leads to a decrease of the effect of frictional drag resistance on the rough surface and to its complete disappearance. The effect of reduction of the frictional drag at smooth surfaces placed before and after the rough segment is retained; this indicates that the solution did not lose its property of reducing the frictional drag. In order to determine the factor influencing the value of the terminal threshold Reynolds number (i.e., to ascertain if it is caused by the destruction of the polymer molecules during the passage of the solution along the length of the rough tube due to high values of frictional stresses above which the decrease of frictional drag is not observed) the experiments were repeated with a rough segment with $R/k_S = 2.9$ (1250-μm grain) and twice as long, L = 2180 mm (Fig. 1c). Since these data indicate the same value of Reynolds number above which the effects of reduction of the frictional drag on rough surfaces disappear for identical values of the solution concentrations, it can be concluded that these Reynolds numbers correspond to the maximum stresses up to which the addition of WSR-301 polymer in water flow causes a reduction of the frictional drag. The data on the values of the terminal threshold frictional stresses at the wall are given in Fig. 3 for two concentrations of the solution — $5 \cdot 10^{-6}$ and 10^{-5} g/cm^3 — as a function of the surface roughness.

Thus, if for the initial threshold frictional stress it is possible to indicate a unique value depending only on the form of the polymer and independent of the concentration of a solution, then the frictional stress above which the effect of reduction of frictional drag disappears is a variable quantity depending not only on the form of the polymer and its concentration in the solution, but also on the surface roughness over which the solution flows. Assuming that for $R/k_S = 20$, when the effects of reduction of frictional drag on smooth and rough surfaces are equal, the value of the terminal threshold frictional stress depends only on the concentration of the solution and is independent of the surface roughness. It is possible to extrapolate the dependence in Fig. 3 to the value $R/k_S = 20$ and the obtained values of τ_{**} may be regarded only as a function of the concentration of the polymer solution. In this case, it is found that for concentrations $c = 5 \cdot 10^{-6}$ and 10^{-5} g/cm^3 the values of the terminal threshold stresses will be $\tau_{**} = 8000$ and 18,000 dyn/cm^2, respectively. These values agree with similar data which were obtained also from the extrapolation of the effect of drag reduction in the flow of polyox solutions of same concentrations in smooth tubes from the tangential frictional stress at a smooth wall [2].

In the range of tangential stresses, where the effect of reduction of frictional drag of a flow of polymer solution is observed, a decomposition of the solution occurs and the degree of decomposition depends on the magnitude of the surface roughness. On the basis of the data in Fig. 1, it can be assumed that for $R/k_S > 20$ (small surface roughness) there is no decomposition, since the reduction of the frictional drag in solutions during their flow along smooth segments separated by a rough surface is similar. For larger degree of roughness (for $R/k_S < 20$), the degree of decomposition determined by the difference in the reduction of the frictional drag at smooth segments comprised 4-5% for $R/k_S = 11.1$, 6-7% for $R/k_S = 7.5$, and 17% for $R/k_S = 2.9$.

§4. On the basis of the measurements of the frictional drag in the flow of polyox solutions with concentrations $c = 5 \cdot 10^{-6}$–10^{-3} g/cm^3 in their flow in tubes with different degrees of surface roughness, the following conclusions can be drawn:

1) the addition of polymer to water flow leads to a reduction of the frictional drag of the flow both in smooth and rough tubes;

2) the magnitude of the effect of reduction of the drag depending on the concentration of the polymer in the solution is independent of the surface roughness, if its relative value R/k_S is not less than 20 ($R/k_S \geq 20$); for larger surface roughness (when $R/k_S < 20$), the effect of reduction of the drag at the rough surface is smaller than at the smooth surface, and this difference increases as the roughness increases (Fig. 2);

3) both on the smooth and the rough surfaces a saturation effect of the drag reduction is observed in polymer solutions with the increase of their concentration; however, the magnitude of the limiting drag reduction depends on the surface roughness; the larger the roughness, the smaller is the maximum attainable drag reduction for the flow of the solution in the tube;

4) the addition of polymer to water flow reduces its frictional drag in a limited range of tangential stresses at the wall; it is assumed that the initial threshold stress depends only on the type of the polymer [3]; the terminal threshold stress depends on the type of the polymer, its concentration in the solution, and the surface roughness; within this range there is a smooth increase of the effect to the maximum saturation corresponding to the chosen concentration of the solution; subsequently, this effect is maintained constant and later on it decreases smoothly.

NOTATION

d, tube diameter; R, tube radius; k_S, roughness equivalent to Nikuradze sand roughness; λ, frictional drag coefficient; v_S, mean flow velocity; ν, kinematic viscosity of the solution of water; ρ, water density; $Re = v_S d/\nu$, Reynolds number; τ_W, tangential frictional stress at the wall during the flow of water; τ_{str}, tangential frictional stress at the wall of the tube during the flow of the solution; $v_* = \sqrt{\tau_W/\rho}$, dynamic velocity; τ_*, initial threshold frictional stress at the tube wall; τ_{**}, terminal threshold frictional stress at the tube wall; $S = (\tau_W - \tau_{str})/\tau_W$ (for v_S = const), effect of reduction of frictional drag during the flow of polymer solution compared to the flow of water; $S_{sm.}$, effect of reduction of frictional drag on smooth wall; S_{rou}, effect of reduction of frictional drag at rough wall; $n = S_{o.rou.}/S_{o.sm.}$; $S_{o.sm.}$, $S_{o.rou.}$, maximum values of the reduction of frictional drag at smooth and rough surfaces corresponding to a given value of the concentration of the polymer solution.

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