HYDRODYNAMIC RESISTANCE OF AQUEOUS SOLUTIONS OF POLYMERS AND SURFACE-ACTIVE SUBSTANCES IN ROUGH TUBES

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Results of measurements of the hydrodynamic resistance coefficient are presented for turbulent flow of polyacrylamide and metaupone solutions in tubes with natural and artificial roughness.

Reduction in the hydrodynamic resistance of liquids in tubes by addition of high-weight polymers and surface-active materials is of great practical interest. Addition of surface-active materials appears more promising than the polymer addition due to the absence of mechanical destruction over a certain range of shear stress [1, 4].

Until the present time the greater number of studies have considered hydrodynamic resistance of polymers and surface-active materials in smooth tubes. But under real conditions all surfaces do possess roughness to some degree. However, there have been only a limited number of studies of polymer flow near rough walls, and there is a total lack of data on the effect of surface-active additives on liquid resistance in rough tubes.

The present study is dedicated to an experimental investigation of the effect of addition of polyacrylamide (PAA) and metaupone upon liquid resistance in flow in rough tubes.

Experiments were performed in four steel tubes with identical inner diameter of $d = 6.78 \cdot 10^{-3}$ m, and different equivalent roughnesses. Two tubes were naturally rough, due to corrosion of the metal; the equivalent roughness of these tubes, as determined by hydrodynamic resistance [2], was $k_s = 0.26$, 0.42. The other two tubes were artificially roughened by a single-cut metric thread with the following parameters: $s = 1.25 \cdot 10^{-3}$ m, $k = 3 \cdot 10^{-4}$ m, $b = b_1 = 5 \cdot 10^{-4}$ m, $R/k = 11.4$. Using the formulas presented in [3], the effective height of the roughness projections was calculated to be $h = 6.7 \cdot 10^{-4}$ m, with an effective diameter which proved to be equal to the inner diameter to an accuracy of 0.001.

An open-cycle apparatus was used to perform the experiments. Pressure drop was measured over a section $l = 0.368$ or 0.610 m long at distances of 224 or 206 diameters from the tube input for the naturally and artificially roughened tubes, respectively. Liquid flow rate was varied by changing the pressure in the upper portion of the reservoir vessel. The resistance coefficient was calculated from the measured pressure drop and volume of exiting liquid. Viscosity of the solutions studied was determined by a capillary viscosimeter.

The solutions studied were those of a surface-active material (metaupone) at concentrations $C = 3.5 \cdot 10^{-3}$, $6 \cdot 10^{-3}$ g/cm^3, and of a polymer (polyacrylamide) at concentrations $C = 10^{-4}$, $2.5 \cdot 10^{-4}$, $6 \cdot 10^{-4}$ g/cm^3. Reduction in hydrodynamic resistance upon introduction of metaupone was observed only upon introduction of electrolytes into the solution. Thus, the metaupone solutions contained sodium chloride at a concentration of $C = 8.8 \cdot 10^{-2}$ g/cm^3. In order to avoid hydrolysis the pH of the metaupone solutions was maintained at pH = 10 (by introduction of sodium hydroxide NaOH).

The experimental results are presented in the form of the dependence of the resistance coefficient λ on Reynolds number Re for the aqueous solutions of polyacrylamide (Fig. 1) and metaupone (Fig. 2).

It is evident from Fig. 1 that the decrease in hydrodynamic resistance in flows with polyacrylamide added at various concentrations begins in practice at Reynolds number values equal to the critical value. With increase in polyacrylamide concentration there is a more significant reduction in resistance coefficient.

With flow of a polyacrylamide solution with C = 0.01% in a tube with artificial roughness there is a finite threshold shear stress $\tau_w = 37.17$ N/m^2 (corresponding to $Re = 2 \cdot 10^4$) at which the function $\lambda = \lambda(Re)$ has a minimum. In the range $Re > 2 \cdot 10^4$ there is an increase in resistance coefficient evidently related to mechanical destruction of the polymer mole-

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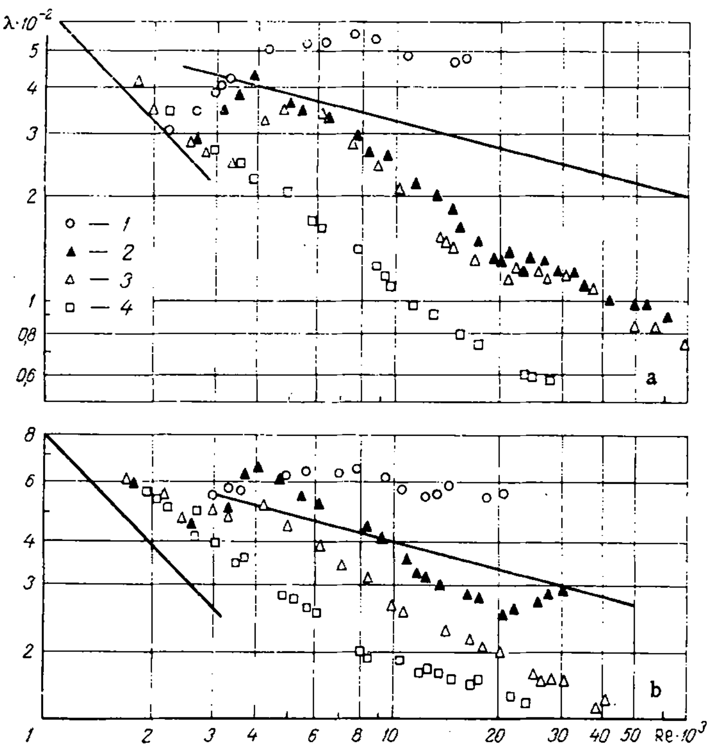

Fig. 1. Hydrodynamic resistance coefficient λ versus Reynolds number Re for flow of aqueous solution of polyacrylamide in tube with natural (a) and artificial (b) roughness: 2,3,4) polyacrylamide concentrations C = 0.01, 0.025, 0.06%, respectively; 1) water.

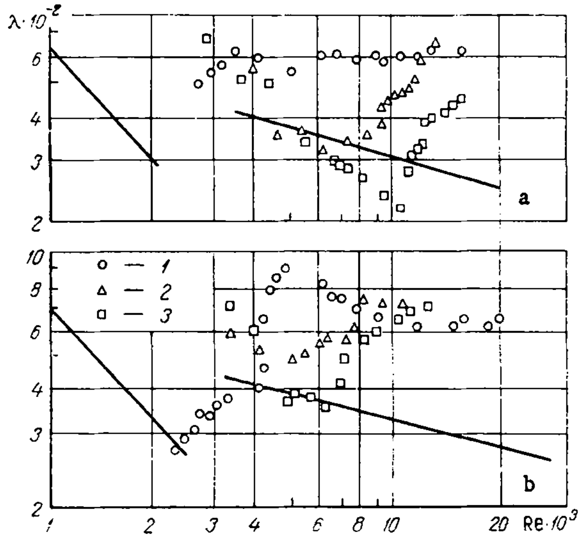

Fig. 2. Hydrodynamic resistance coefficient λ versus Reynolds number Re for flow of aqueous solution of metaupone in tube with natural (a) and artificial (b) roughness: 2,3) metaupone concentrations C = 0.35, 0.6%, respectively; 1) water.

cules, leading to a loss in the solution's hydrodynamic effect. Evidently, at high Reynolds numbers a threshold shear stress will also be observed for C = 0.025, 0.06%.

In turbulent flow of metaupone solutions in rough tubes (Fig. 2) there is also a decrease in hydrodynamic resistance coefficient in comparison to the coefficient for the solvent (water). For each concentration a range of Reynolds numbers is distinguishable, over which resistance is reduced, and there is also a finite threshold Reynolds number. With increase in metaupone concentration the threshold number shifts toward higher values.

The maximum reduction in resistance for the tube with artificial roughness reached 59% at a metaupone concentration C = 0.6% and Re = 6500, while for the naturally rough tube the maximum reduction was 68% at the same concentration and Re = 12,000. With further increase in velocity there is a quite sharp increase in friction coefficient, i.e., a decrease in the reduction of hydrodynamic resistance. This is evidently related to destruction of the mycelial structures of the surface-active substance in the Reynolds number range above the threshold value.

It follows from the experimental studies performed that addition of polyacrylamide and metaupone decrease hydrodynamic resistance in turbulent flow of liquids in rough tubes: in practice the resistance reduction begins in the region of transition from laminar to turbulent flow: the resistance reduction in metaupone solutions is found over a limited range of change of Reynolds number, which range enlarges with increase in metaupone concentration. Comparison of the results obtained with experimental data for smooth tubes [1, 5] shows that to obtain the same resistance reduction effect a larger concentration of the additive is necessary in rough tubes.

NOTATION

d, inner diameter of tube; R, radius; s, screw pitch; k, height of roughness projection; b_1, distance between projections; h, effective height of projections; k_s, roughness value equivalent to sand roughness; l, length of tube section over which pressure drop was measured; λ, friction resistance coefficient; Re, Reynolds number, calculated from solution viscosity; C, concentration of solute; τ_w, threshold shear stress on tube wall; b, width of roughness projections.

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A GENERALIZED HYDRAULIC RESISTANCE COEFFICIENT

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A generalization of the resistance law for rheologically stationary liquids is considered for flow in tubes and channels of various geometry.

In hydrodynamic calculations the necessity often develops of determining hydraulic losses in motion of liquid in tubes and channels of various cross sections.

The present study will consider the possibility of generalizing the resistance law for rheologically stationary liquids for flow in media of various geometries.

It has been discovered [1] by processing of experimental data on the flow of various non-Newtonian systems that in the case of laminar flow, in the consistent variables chosen, rheometric data for media of various geometries form a single curve. According to Bingham, consistency is defined by complete relationships between force factors and flow characteristics. For the force factor the mean over the perimeter of the shear stress τ_w was chosen, while for the flow characteristic the mean velocity gradient $\dot{\gamma}_w$ was selected. The quantity τ_w is determined from the equilibrium of pressure and friction forces acting on a certain volume of liquid, limited by two sections separated by a distance l, i.e.,

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