EXPERIMENTAL INVESTIGATION OF THE TURBULENT FLOW OF WEAK SOLUTIONS OF POLYMERS IN TUBES OF DIFFERENT DIAMETER

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The results are given of an experimental investigation of turbulent flows in tubes of weak solutions of polyox, polyacrylamide, and guar resin. On the basis of the experimental relations obtained, the feasibility is shown of calculating the hydrostatic resistance of the tube for streams of polymer solutions.

1. At present, a large number of experimental reports is known, devoted to the problem of the effect of additions to water of small amounts of certain high-molecular substances on the resistance during turbulent flow of these solutions in tubes. Nevertheless, the results of these investigations [1-8] are difficult to compare with one another, as all the experiments were carried out on different equipments with a different polymer sample and by different procedures. Therefore, data about the nature of turbulent streams of polymer solutions in tubes can be considered only as qualitative. These data reduce to the fact that with increase up to a certain limiting value of the magnitude of the polymer solution concentration the effect of lowering of the resistance by the flow of the polymer solution is greater, the greater is the Reynold's number (flow velocity of liquid in the tube); the magnitude of the threshold value of the Reynold's number defining the start of the appearance of the lowered resistance effect by the turbulent flow of the polymer solutions, decreases with increase of concentration and reduction of diameter; in the case of large concentrations or a very small tube diameter, a delayed transition of laminar to turbulent flow occurs; reduction of the tube diameter leads to an increase of the effect of resistance lowering.

In connection with this, investigations were undertaken to measure the frictional resistance of streams of polymer solutions in tubes for the purpose of obtaining quantitative data about the influence of various factors on the effect of resistance lowering: type of polymer, magnitude of pipe diameter, magnitude of solution concentration and magnitude of the flow velocity of the liquid in the tube.

Polyox, guar and polyacrylamide were chosen as the polymer samples.

All the investigations were undertaken by a single procedure on a hydrostatic equipment [9]. The pipes in which the investigations were conducted were made interchangeable and they had a common length of 4.5 m and diameters of 9.75, 20.9, and 35.5 mm. The liquid flow rates were varied over the range 0.06-12 liter/sec and the Reynold's number over the range $8 \cdot 10^3$ to $3 \cdot 10^5$. The concentrations of the polymer solutions were varied over the range 10^{-6} to $2 \cdot 10^{-3}$ g/cm^3.

All experiments were carried out, as far as possible, under conditions which excluded destruction of the solutions being studied.

The effect of a closed circuit on the authenticity of the results obtained proved to be insignificant. With a volume of 0.5t for the hydrostatic equipment, during the experiment the solution passed through the pump one to two times in the case of small-diameter tubes and up to 5 times in the case of tubing with a diameter of 35.5 mm. The experiment with a solution of each concentration was repeated several (5-10) times, each time with a freshly prepared solution.

2. Only the well-developed turbulent flow of weak polymer solutions in tubes was investigated. The results of all the tests initially were represented in the form of the dependence of the coefficient of resistance on the Reynold's number

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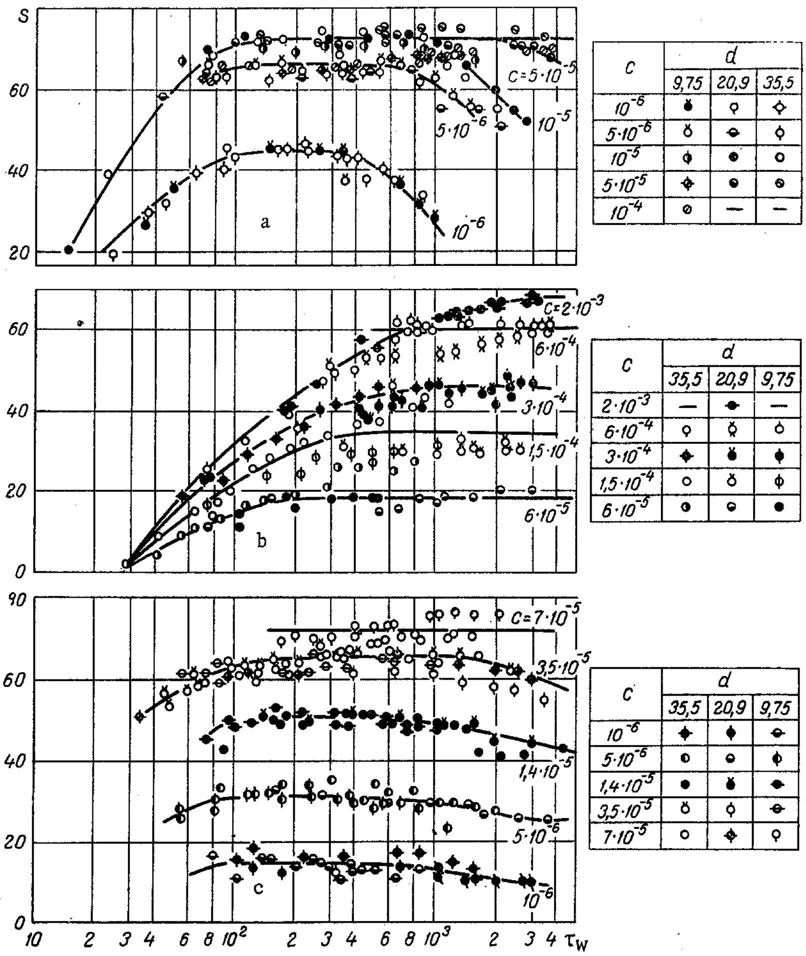

Fig. 1. Dependence of the magnitude of the reduction of resistance $S = (\tau_w - \tau_p)/\tau_w \cdot 100\%$ on the magnitude of the shear stress τ_w, dyne/cm^2, during flow in tubes of different diameter of polymer solutions with different concentrations c, g/cm^3: a) polyox; b) guar resin; c) polyacrylamide.

The characteristic features for the curves $\lambda = f(\mathrm{Re}, d)$ when c = const, for all the types of flow considered, are the following:

a) a shift of the Reynold's number threshold is observed, which defines the start of the appearance of the resistance lowering effect in the direction of large values of the Reynold's number with increase of diameter;

b) the envelope drawn to the curve $\lambda = f(\mathrm{Re}, d)$ when c = const, goes in parallel with the similar relation for water at a distance equal to the maximum decrease of resistance obtained for a given concentration;

c) for each value of solution concentration there is a characteristic maximum of the resistance lowering, which is independent of the magnitude of the tube diameter in which flow is being studied.

For a stream of water in tubes of different diameter, the magnitude of the shear frictional force at the wall is different for the same Reynold's numbers. Because of this, the assumption was made that the effect of the tube diameter when investigating streams of polymer solutions can be excluded if the experimental data is represented in the form of a relation between the magnitude of the decrease of resistance $S = (\tau_w - \tau_f)/\tau_w$ during the flow of the polymer solutions and the magnitude of the shear frictional force at the wall τ_f or on the magnitude of the shear frictional force at the wall for the case of a stream of water τ_w under conditions of equality of the flow velocities of both streams. It is noteworthy that in the method chosen for presenting the experimental data, it is not necessary to take into account the pseudoplasticity

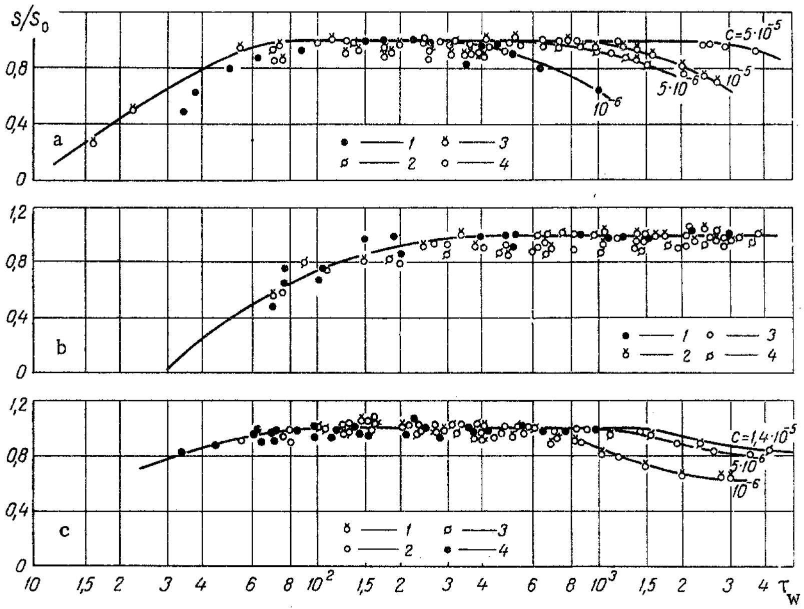

Fig. 2. Dependence of the relative magnitude of reduction of resistance S/S_0 on the magnitude of the shear stress τ_w, dyne/cm^2 during flow of polymer solutions in tubes of different diameter: a) solutions of polyox with concentrations of 1) $c = 10^{-6}$; 2) $5 \cdot 10^{-6}$; 3) 10^{-5}; 4) $5 \cdot 10^{-5}$ g/cm^3; b) solutions of guar resin with concentrations: 1) $c = 6 \cdot 10^{-5}$; 2) $1.5 \cdot 10^{-4}$; 3) $3 \cdot 10^{-4}$; 4) $6 \cdot 10^{-4}$ g/cm^3; c) solutions of polyacrylamide with concentrations: 1) $c = 10^{-6}$ 2) $5 \cdot 10^{-6}$; 3) $1.4 \cdot 10^{-5}$; 4) $3.5 \cdot 10^{-5}$ g/cm^3.

of the polymer solutions. Consideration of similar relations, shown in Fig. 1, permits the following properties to be noted:

1) for polymer solutions of one type, the magnitude of the shear stress $\tau_{w.cr}$ defining the start of the resistance lowering effect, is dependent neither on the concentration of the polymer solution nor on the diameter of the tubing in which the flow of these solutions is being studied;

2) for each value of solution concentration of one type of polymer, there is a characteristic defined maximum value of the reduction of resistance, which is maintained constant under conditions such that $\tau_w > \tau_*$ (τ_* is the value of the shear frictional force at the wall, corresponding to saturation of the resistance lowering effect);

3) the magnitude of the greatest lowering of the resistance S_0 increases with increase of concentration, however when a value of $S_0 \approx 75\%$ is reached, further increase of the effect ceases;

4) the range of shear stresses τ_w, where saturation of the resistance lowering effect is observed, depends on the magnitude of the polymer solution concentration: the higher the concentration, the higher are the values of the shear stresses at which the maximum value of S_0 remain. With a greater shear (at higher values of τ_w) destruction of the solution is observed, which is expressed in a reduction of the resistance lowering effect.

On the basis of the special characteristics noted for streams of polymer solutions, the effectiveness of each type of polymer can be characterized by two graphs: the dependence of its effectiveness S/S_0 on the magnitude of the shear frictional stress τ_w at the wall (see Fig. 2) and the dependence of the maximum effectiveness S_0 on the solution concentration.

The nature of the function $S_0(c)$ is represented in the form of a universal graph illustrating the dependence of the maximum reduction of resistance on the magnitude of its reduced concentration c/c_0 (see Fig. 3), where c_0 is the concentration to which a 60% reduction of resistance corresponds for a given type of polymer. For polyox, $c_0 = 2.7 \cdot 10^{-6}$ g/cm^3, for polyacrylamide $c_0 = 2.7 \cdot 10^{-5}$ g/cm^3 and for guar resin $c_0 = 6 \cdot 10^{-4}$ g/cm^3.

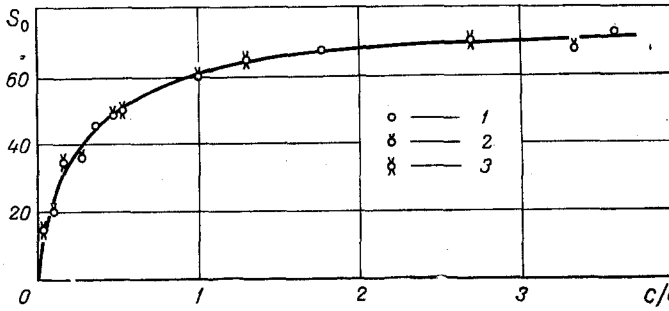

Fig. 3. Dependence of the magnitude of maximum reduction of resistance $S_0 = (\tau_w - \tau_p)/\tau_w \cdot 100\%$ on the magnitude of the reduced viscosity c/c_0 (c_0 corresponds to $S_0 = 60\%$) for different types of polymers: 1) polyox; 2) guar resin; 3) polyacrylamide.

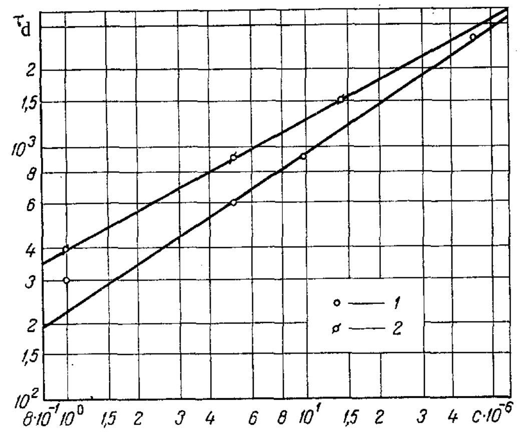

Fig. 4. Dependence of the magnitude of the shear stress τ_d, dyne/cm^2, corresponding to start of breakdown of fresh solutions of polyox and polyacrylamide, on their concentration c, g/cm^3: 1) polyox; 2) polyacrylamide.

The dependence of S/S_0 on the magnitude of the shear frictional stress at the wall τ_w (Fig. 2) is specific for each type of polymer, although the nature of this dependence is identical for the types of polymers considered. It is characteristic for this dependence that the following four zones can be discriminated here: $\tau_{w.cr} < \tau_w < \tau_{w*}$ – increase of the resistance lowering with increase of the frictional stress at the wall; $\tau_w < \tau_{w.cr}$ – absence of the polymer effect; $\tau_* < \tau_w < \tau_{w.d.}$ – saturation (constancy) of the magnitude of the resistance lowering effect and $\tau_w < \tau_{w.d.}$ – reduction of the resistance lowering effect with increase of frictional force at the wall (solution destruction). It has been established experimentally that the magnitude of the frictional shear stress at the wall $\tau_{w.cr}$ and τ_{w*} are parameters of the type of polymer. For polyox and polyacrylamide, $\tau_{w.cr} < 10$ dyne/cm^2 and $\tau_{w*} \approx 80$ dyne/cm^2; for guar resin, $\tau_{w.cr} \approx 30$ dyne/cm^2 and $\tau_{w*} \approx 400$ dyne/cm^2.

The magnitude of the shear frictional stresses $\tau_{w.d.}$ corresponding to the start of breakdown of the polymer solution depends on the concentration of the solution being investigated: the higher the solution concentration, the greater the shear stress $\tau_{w.d.}$.

Figure 4 represents the magnitude of the shear stress $\tau_{w.d.}$ at the wall of the tube, corresponding to breakdown of solutions of polyox and polyacrylamide. The data for the solutions of polyox agree well with Fabula's data [10], obtained with flows in a sink of polyox 301 solutions. It was not possible to obtain data on the magnitude of the shear stress $\tau_{w.d.}$ for streams of guar resin solutions in the experiments mentioned. We note only that for this polymer $\tau_{w.d.} > 2500$ dyne/cm^2. These data permit quantitative confirmation of the widespread opinion concerning polyox as being a polymer which is very unresistant to breakdown and guar resin as a polymer which is very resistant to breakdown.

In the experiments with low-concentration polyox solutions, the magnitude of the shear stresses τ_w exceeded the magnitude of the shear stress $\tau_{w.d.}$, i.e., conditions were created for the breakdown of the solution, which also served as the basis of assuming polyox to be an easily destructible polymer. However, by increasing the concentration of the solution above the optimum, it is possible to extend the range of the shear stresses corresponding to the zone of saturation of the resistance lowering effect ($S_0 \approx 75\%$). In this case, the choice of concentration of the polyox solution is determined by the quantity $\tau_{w.d.}$, which is greater, the higher the solution concentration.

3. On the basis of the discussions set out above, a procedure can be proposed for calculating the resistance to flow in tubes of solutions of the polymers which we have studied in our experiments, over a wide range of concentrations.

TABLE 1. Example of Calculation of Coefficient of Resistance in a Tube

Re	ν_s, m/sec	λ_w	τ_w, dyne/cm²	S/S_0	S	τ_p, dyne/cm²	λ_p
10^4	0,122	0,0300	0,6	0	0	0,6	0,0300
$5\cdot10^4$	0,61	0,200	9,3	0,20	0,14	8,0	0,0172
10^5	1,22	0,0170	31,7	0,78	0,53	14,9	0,0080
$5\cdot10^5$	6,10	0,0130	605	0,94	0,64	218	0,0047
10^6	12,2	0,0115	2140	1,00	0,68	685	0,0037
$1,2\cdot10^6$	14,6	0,0112	3000	1,00	0,68	960	0,0036

The scheme is given below of a calculation for the dependence of the coefficient of resistance $\lambda = 8\tau/\rho v_s^2$ on the Reynold's number $Re = v_s d/\nu_p$ for the flow of a polymer solution (polyox, guar resin, and polyacrylamide), for which the following well-known quantities are assumed: weight concentration of solution c; relative viscosity of solution $\eta = \nu_p/\nu_w$; diameter of tubing, d, in which the flow is studied, and the range of variation of the Reynold's number.

1. For the values chosen for the Reynold's number over a given range, the values of the average flow velocity $v_{si} = Re_i\ \nu_p/d$ are determined.
2. Values of the coefficient of resistance τ_w are determined for flows of water in a tube of given diameter d for conditions of equilibrium flow rate of this stream and of the solution.
3. From the values of the average flow velocity v_s, determined for a given Reynold's number, the frictional shear stress at the wall is calculated:

$$\tau_w = \frac{\lambda_w}{8}\rho v_s^2.$$

4. Using the value of c_0 the maximum reduction of resistance S_0 is determined for a given concentration of solution (see Fig. 3).
5. The values of the resistance reduction $(S/S_0)_{gr}$ expected for the calculated flow of solution, are determined by the calculated values of the frictional shear stress at the wall of the tube τ_w (see Fig. 2), which permits the expected value of the frictional shear stress during flow of the solution in the tube to be calculated:

$$\tau_p = \tau_w[1 - S_0(S/S_0)_{gr}].$$

6. The coefficient of flow resistance λ_p is calculated from the value of the shear stress τ_p:

$$\lambda_p = 8\tau_p/\rho v_s^2.$$

The calculation is given below of the value of the coefficient of resistance as a function of the Reynold's number, for the flow of a solution of polyacrylamide with a concentration of $c = 5\cdot10^{-5}$ g/cm³ ($\eta = 1.22$) in a tube of diameter d = 100 mm, over the range of variation of Reynold's number $Re = 10^4$ to 10^6. In the calculations, the solution temperature was assumed to be 20°C, i.e., $\nu_w \approx 10^{-6}$ m²/sec and $\nu_p = \eta\nu_w = 1.22\cdot10^{-6}$ m²/sec. For solutions of polyacrylamide, $c_0 = 2.7\cdot10^{-5}$ g/cm³ and the value of the reduced concentration $c/c_0 = 1.85$. For a value of $c/c_0 = 1.85$, a maximum resistance reduction of $S_0 = 68\%$ is expected.

A further calculation is given in Table 1. It is inadvisable to carry out the calculation for $Re > 1.2\cdot10^6$ because at higher values of the Reynold's number the quantity τ_w exceeds the value of the shear stress, corresponding to the start of breakdown of the solution of given concentration (see Fig. 4).

NOTATION

d	is the diameter of tube of working channel;
v_s	is the average flow velocity of liquid in tube;
q	is the average feed of liquid into tube cross section;
ρ	is the density of liquid;
ν_w	is the kinematic viscosity of water;
ν_p	is the kinematic viscosity of solution;

$\eta = \nu_p/\nu_w$	is the relative viscosity of polymer solution;
$Re = dv_s/\nu_p$	is the Reynold's number ;
τ_w	is the frictional shear stress at the wall for flow of water ;
τ_p	is the frictional shear stress at the wall for flow of polymer solution ;
$\tau_{w.cr}$	is the threshold value of shear stress at wall;
τ_{w*}	is the value of frictional shear stress at wall, corresponding to saturation of the resistance lowering effect ;
$\tau_{w.d.}$	is the frictional shear stress at the wall, corresponding to start of breakdown of solution ;
$\lambda = 8\tau/\rho v_s^2$	is the coefficient of resistance ;
$S = (\tau_w - \tau_p)/\tau_w$	is the amount of gain in resistance ;
S_0	is the amount of maximum gain in resistance for a defined solution concentration ;
c	is the weight concentration of solution ;
c_0	is the weight concentration of solution, corresponding to $S_0 = 60\%$.

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