AN EXPERIMENTAL STUDY OF THE TURBULENT
FLOW OF AQUEOUS POLYMER SOLUTIONS
IN A TUBE

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An experimental apparatus for determining the hydrodynamic drag coefficient of a tubular conductor is described; data are presented on the decrease in drag in turbulent flow of aqueous solutions of polyacrylamide and the sodium salt of carboxymethylcellulose.

It is known that the introduction into water of small quantities of dissolved polymers leads to a significant decrease in hydrodynamic drag (a review of several studies is presented in [1]). The majority of polymers that reduce drag have a tendency to disintegrate under the effect of various mechanical influences (passage through a pump, tube, etc.). Especially severe destruction of polymer macromolecules occurs upon passage of solutions through pumps, which leads to a significant decrease in the drag reduction effect.

This study will describe an experimental apparatus which practically eliminates destruction of dissolved polymers, and will examine the effect of concentration, Reynolds number, mechanical effects, and medium pH on the value of drag reduction in the flow of aqueous solutions of polyacrylamide (PAA) and the sodium salt of carboxymethylcellulose (NaCMC).

The experimental apparatus (Fig. 1) consists of a hermetic vessel 1 with drainage tube 2, attached to a tubular conductor 3, whose resistance must be determined. The drainage tube 2 is connected to a reservoir 4, in which a constant air pressure is maintained from cylinder 5. Vessel 1 is filled with the liquid to be studied. After stop valve 6 is opened, liquid flows through the tubular pipe, and a vacuum is formed in the upper portion of vessel 1. As a consequence, air is drawn in through tube 2. This process continues if the reservoir pressure is greater than the pressure of the liquid column through which the air bubbles. At a level H a pressure is established equal to the reservoir pressure. The liquid flows from the vessel at a constant pressure determined by the liquid column H and the reservoir pressure. A measurement tube 7 is provided for determination of the outflow time of a fixed volume of liquid.
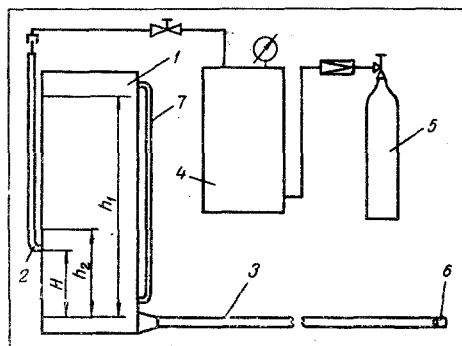

Fig. 1. Schematic diagram of experimental apparatus.

A simple mathematical formula can be obtained for determination of the pipe drag. It is known that for Reynolds numbers $Re_{cr} < Re < 5 \cdot 10^4$ for homogeneous liquids the empirical formula of Blazius [2] is valid

$$\lambda = \frac{0.3164}{Re^{0.25}} = \frac{0.3164}{\left(\frac{ud}{v}\right)^{0.25}}.$$ (1)

The mean flow velocity of the liquid through the pipe will be

$$u = \frac{Q}{\pi d^2/4} = \frac{4V}{\pi d^2 t} = \frac{4S\dot{H}_1}{\pi d^2 t},$$ (2)

where t is the flow time of a volume V of liquid.

We substitute Eq. (2) in Eq. (1) and take the log of the expression obtained. Then
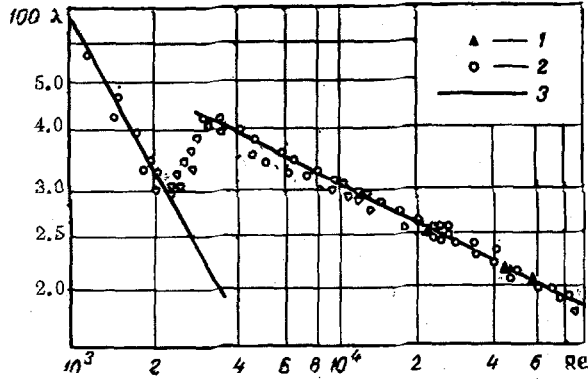
Fig. 2

Fig. 3

Fig. 2. Drag coefficient λ versus Reynolds number $Re = ud/\nu$ for water flow in a pipe; 1) calculation from formula of [3]; 2) experimental data from [2]; 3) theoretical curve of [2].
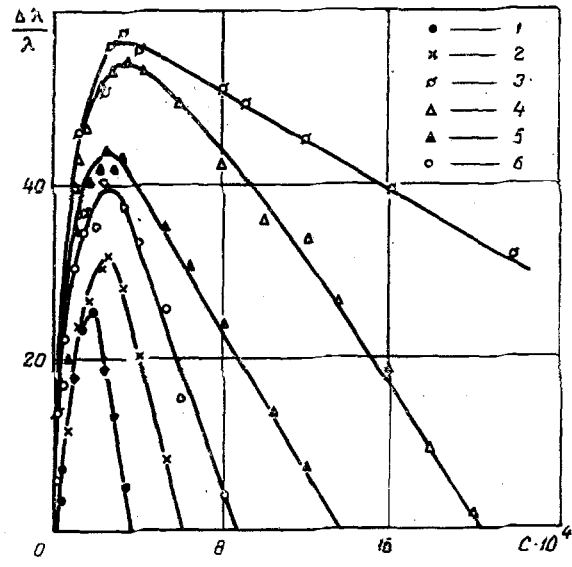
Fig. 3. Drag reduction $\Delta\lambda/\lambda$, %, versus polyacrylamide concentration, g/cm^3. For water, Reynolds numbers: 1) $0.33 \cdot 10^4$; 2) $0.46 \cdot 10^4$; 3) $1.27 \cdot 10^4$; 4) $0.89 \cdot 10^4$; 5) $0.67 \cdot 10^4$; 6) $0.57 \cdot 10^4$. Pipe diameter $d = 7$ mm.

$$\lg \lambda = \lg 0.3164 - 0.25 \lg \frac{4SH_1}{\pi\nu dt} \, . \tag{3}$$

There is only one unknown in Eq. (3), the outflow time of the liquid, which reduces the time required for determination of the drag. In calculating the drag coefficient for Reynolds numbers $Re > 5 \cdot 10^4$ it is necessary to employ the original formula $\lambda = a/Re^m$ with other values of a and m. Results of experimental tests have shown that our measurements agree well with the data of other authors (Fig. 2).

A simple formula may also be obtained for calculation of the drag reduction effect in the flow of polymer solutions. For steady motion of liquid in the tube the following equality is valid [2]

$$\Delta p = \lambda \, \frac{l}{d} \, \frac{\rho u^2}{2} \, . \tag{4}$$

The pressure drop for flow of either solvent or solution in this experimental apparatus will be the same, i.e.,

$$\Delta p_1 = \Delta p_2, \tag{5}$$

where the indices 1, 2 indicate the solvent and solution respectively. In view of the low polymer concentration (of the order of 10^{-3}–10^{-4}) the densities of solvent and solution may be considered equal, i.e., $\rho_1 \approx \rho_2$. Then it follows from Eq. (5) that

$$\frac{\lambda_2}{\lambda_1} = \left(\frac{u_1}{u_2} \right)^2 . \tag{6}$$

Using the expression for mean velocity, Eq. (2), Eq. (6) may be rewritten as

$$\frac{\lambda_2}{\lambda_1} = \left(\frac{t_2}{t_1} \right)^2 . \tag{7}$$

The formula for drag reduction value can now be obtained:

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda_1 - \lambda_2}{\lambda_1} = \left[1 - \left(\frac{t_2}{t_1} \right)^2 \right] 100\% . \tag{8}$$

Using the apparatus described above, the value of the drag reduction effect in the flow of water solutions of two types of polymers was determined.

Figure 3 presents $\Delta\lambda/\lambda$ as a function of polyacrylamide concentration for various Reynolds numbers. It is obvious that in the low concentration range there is an increase in the effect that attains a maximum at some optimal concentration C_*. With an increase in Reynolds number the optimal concentration becomes larger. Moreover, in the range studied the magnitude of the effect increases with increase in Reynolds number for constant concentration.

The increase of the effect in the concentration range $0-C_*$ is evidently related to the fact that with a growth in concentration an even greater portion of the turbulent impulse is subjected to the deforming effect of the polymer macromolecules. This leads to a thickening of the wall layer including a viscous sublayer and a transition (buffer) zone, with an increase in discharge velocity. Meanwhile, the individual macromolecules are kinetically independent of each other. However, in the concentration $C > C_*$ the interaction of the macromolecules with each other becomes significant, due to both direct contacts (leading to entanglement and interweaving of molecular chains) and forces transmitted through the solvent (hydrodynamic interaction). The formation of such interwoven particles as well as the hydrodynamic interaction leads to an increase in the shear viscosity in the flow direction, as a consequence of which the effect is decreased.

An increase in the magnitude of the effect with increase in Reynolds number (with constant pipe diameter and concentration) evidently occurs because with an increase in mean velocity gradient near the wall the angle of orientation of the macromolecules in the flow stream decreases. Moreover, for some polymers deformation takes place, and consequently the mean statistical length of the macromolecules increases. Both of these factors lead to a severe deformation of turbulent impulse and a corresponding increase in the magnitude of drag reduction.

The results of an investigation of the effect of mechanical factors on the magnitude of drag reduction in the flow of a polyacrylamide solution are shown in Fig. 4. As is evident from the graph, with an increase in n, the number of times the solution traverses a centrifugal pump, the value of the drag reduction effect decreases, indicating destruction of polymer molecules.

Aside from those mentioned above, studies were also completed on the effect of medium pH on drag reduction. Change in pH was accomplished by introduction of small quantities of hydrochloric acid or sodium hydroxide. Figure 5 presents the results of experiments with aqueous solutions of polyacrylamide and the sodium salt of carboxymethylcellulose. In the acid range (pH < 7) a sharp reduction in the amount of drag reduction occurs for PAA and NaCMC in comparison with a neutral medium (pH = 7).
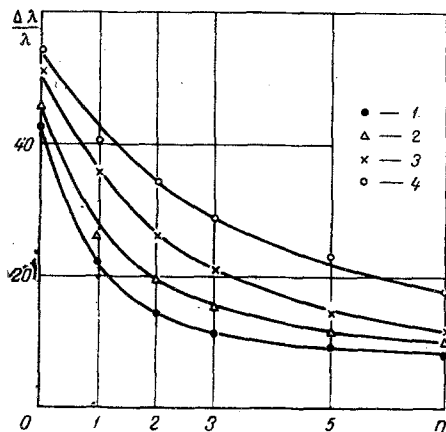

Fig. 4

Fig. 5

Fig. 4. Drag reduction versus number of times (n) that polyacrylamide solution traverses a pump: 1-4) polyacrylamide concentrations $1.0 \cdot 10^{-4}$ g/cm^3; $1.4 \cdot 10^{-4}$; $2.4 \cdot 10^{-4}$; $3.2 \cdot 10^{-4}$ g/cm^3; pipe diameter d = 7 mm.
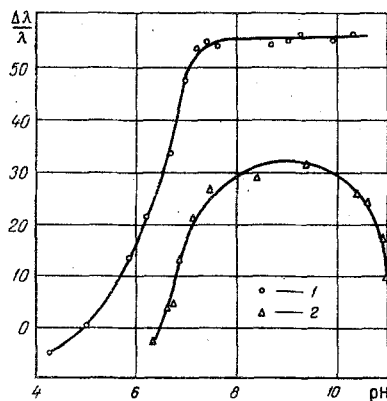
Fig. 5. Drag reduction versus medium pH (Reynolds number Re for water $0.86 \cdot 10^4$): 1) polyacrylamide, $C = 2.4 \cdot 10^{-4}$ g/cm^3; 2) sodium salt of carboxymethylcellulose, $C = 4 \cdot 10^{-4}$ g/cm^3; pipe diameter d = 7 mm.

In the basic region (pH > 7) there is an insignificant increase in the effect for PAA solutions and a significant increase in drag reduction for NaCMC solutions. The value of $\Delta\lambda/\lambda$ for NaCMC solutions increases from 18% in neutral solution to 32% in the basic region at pH = 9, i.e., the effect is 1.7 times as great as compared with a neutral solution. With an increase in basicity of the medium (pH > 9) the value of drag reduction again decreases.

It may be assumed that this phenomenon is related to the internal (molecular) structure of the NACMC molecules. Until recently the opinion was widespread that macromolecules of cellulose and its derivatives were examples of rigid chain molecules [3]. This means that the potential barrier impeding internal rotation in the macromolecule is large. The relative dimensions of the macromolecule and many other important properties (in particular, the degree of elasticity) are dependent on the degree of rigidity. However it has recently been demonstrated that cellulose and its derivatives are not rigid, but elastic polymers [4]. An increase in the value of skeleton rigidity of cellulose macromolecules and their derivatives is conditioned by intermolecular hydrogen bonds, which hinder internal rotation in the macromolecules. If the solvent molecules destroy the intermolecular hydrogen bonds, molecules of cellulose and its derivatives possess a high degree of elasticity. It is evident that in the experiments with NaCMC in the range pH = 7–9 there occurs a disruption of intermolecular hydrogen bonds, as a consequence of which the degree of elasticity and the dimensions of the molecules increase. This in turn causes a large portion of the turbulent spectrum to be subjected to the deforming influence of the solute, which leads to an increase in drag reduction. Further increase in basicity of the medium (pH > 9) evidently leads to destruction of molecular chains (chemical destruction), a consequence of which is the sharp decrease in the value of drag reduction. Thus, variation of the solvent composition can control the properties of the NaCMC macromolecules, and consequently, the degree of drag reduction.

NOTATION

Re	is the Reynolds number;
Re_{cr}	is the critical Reynolds number;
λ	is the resistance coefficient;
u	is the average flow velocity;
d	is the pipe diameter;
ν	is the kinematic viscosity coefficient;
Q	is the liquid flow rate;
S	is the cross-sectional area of tank;
$H_1 = h_1 - h_2$	is the height of outflowing liquid column;
V	is the volume of outflowing liquid;
l	is the pipe length;
ρ	is the density;
$\Delta\rho$	is the pressure drop;
C	is the polymer concentration.

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