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RHEOLOGICAL AND HYDRODYNAMIC CHARACTERISTICS OF HIGH-CONCENTRATION SUSPENSIONS OF WATER-SOLUBLE POLYMERS

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Investigation is made of rheological and hydrodynamic characteristics of the high-concentration suspensions of water-soluble polymers used to solve one of the most important problems of energy conservation: to decrease conservationsin pipeline transport of liquids and in external flows around bodies.

Water-soluble polymers find wide application in diverse branches of technology and the national economy, including, for solving one of the most important problems of conservation of energy, i.e., for decreasing friction resistance in pipeline transport of liquids and in external flows around bodies. Numerous experiments have revealed that polymer solubility in water plays a large part in the combined technicoeconomic effect due to application of polymer additives in various technical units [1]. Direct use of polymer powders, e.g., polyethylene oxide, for preparing polymer solutions requires their vigorous stirring for tens of minutes. On dissolving in sea water at a temperature close to 0°C, the dissolving time is even greater [2]. Optimization of the mechanisms responsible for polymer dissolution require different technical solutions. It has been established [3] that preliminary wetting of a finely dispersed powder by a non-aqueous liquid that neutral to the polymer but readily soluble in water (e.g. glycerin, diethylene glycol) allows preparation of liquid suspensions possessing good solubility in water. The content of the hydrodynamically active polymer in such suspensions can reach 30–35%, the dissolving time is within 10–30 sec, the absolute dynamic viscosity at 20°C is about 1500–2000 cp. Such suspensions are convenient for transportation, batching, storage. In dissolving, the liquid phase of compositions (separator) prevents aggregation of swollen particles of the solid phase (polymer powder) as well as reduction of the active surface of the dissolved powder, thus preserving the required rate of dissolving of the polymer particles.

High-concentration suspensions of this type, being structurized dispersed systems, depending on the content of finely dispersed groups of solid particles and the composition and amount of surfactants introduced into the suspension, can manifest the properties of Bingham plastics, pseudoplastic and dilatable fluids, as well as of thixotropic fluids, whose rheological characteristics depend on time.

Development of the technology of preparing suspensions and their pipeline transportation calls for comprehensive investigations of their rheological and hydrodynamic characteristics.

To describe the rheological behavior of dispersed systems, the following rheological equations of state are most often used:

Ostwald–de Waale

$$\tau = k\dot{\gamma}^{n} , \tag{1}$$

Schvedov–Bingham

$$\tau = \tau_0 + \mu\dot{\gamma} , \tag{2}$$

Balkly–Hershel

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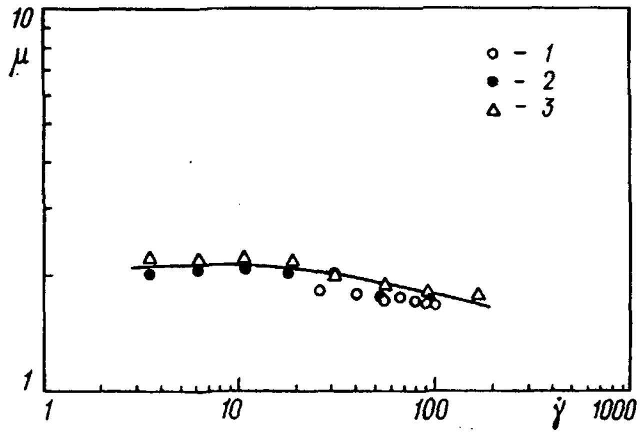


Fig. 1. Measurements made in different systems: 1) flow channel, 2, 3) rotary viscometer; $\kappa = 3.9$, 7.4 mm, respectively, μ, Pa·sec; γ, sec^{-1}.

$$\tau = \tau_0 + k\dot{\gamma}^n, \tag{3}$$

where μ is the dynamic viscosity.

Dispersed systems can also manifest such a property as apparent slipping. The wall layer in which such anomalies are manifested is rather thin, approximately 10–100 μm, but the resultant macroscopic effect can lead to fully erroneous results. Due to the wall effect the flow curves obtained in viscosimetric experiments are branched with variation of capillary diameter or the gap between cylinders.

Wall effects have been found in clay [4, 5] and water-carbon [6] suspensions, polymer solutions [4], as well as in concentrated polymer solutions [7]. To correct viscosimetric data for the wall effect, the concept of apparent slipping velocity was introduced.

In investigations of suspensions in a rotary system [8, 9] an effect of solid phase separation was revealed which leads to nonuniform mass distribution in a gap and distortion of the velocity profile.

We investigated a polymer suspension based on polyacrylamide (30% polymer particles in diethylene glycol), which is used in different technological processes, as well as in form of aqueous solutions for decreasing the friction resistance in turbulent flows.

To study rheological properties, capillary-tube and rotary viscometers were used. A rotary viscometer was employed to investigate rheological characteristics in the temperature range of 2–40°C. To exclude the apparent slipping effect at a fixed temperature, measurements were made in three systems with the gaps of 3.9, 4.7, and 7.4 mm. A comparison of the results (Fig. 1) reveals that the flow curves are invariant. Figure 1 also represents the results of measurements on a straight section 21.6 mm in diameter of the flow channel ($L = 211$ cm). Under these conditions the flow can be considered to be viscometric, since the position of the measuring section provided an extended velocity profile and the absence of inlet effects. As is seen, the data of measurements by a rotary viscometer and in the tube coincide. This is also indicative of the absence of marked near-wall slipping and the separation effect of particles. Next, measurements were made in the system with a 3.9 mm gap.

An analysis shows that at low shear rates ($\dot{\gamma} < 10$), which are realized in slow pipeline flows when structure is still not destroyed, the suspension manifests the properties of Bingham plastic flow (2), whose yield limit changes with temperature

$$\tau_0 = 12.16/T^{0.2}, \tag{4}$$

With decreasing temperature, τ_0 decreases, which is probably due to an increasing coagulation strength. At higher shear rates ($\dot{\gamma} > 10$), suspension behavior is described by power-law rheological equation of state (2) (Fig. 2a), where in the investigated range of parameters

$$n = 0.808 + 0.002T, \tag{5}$$

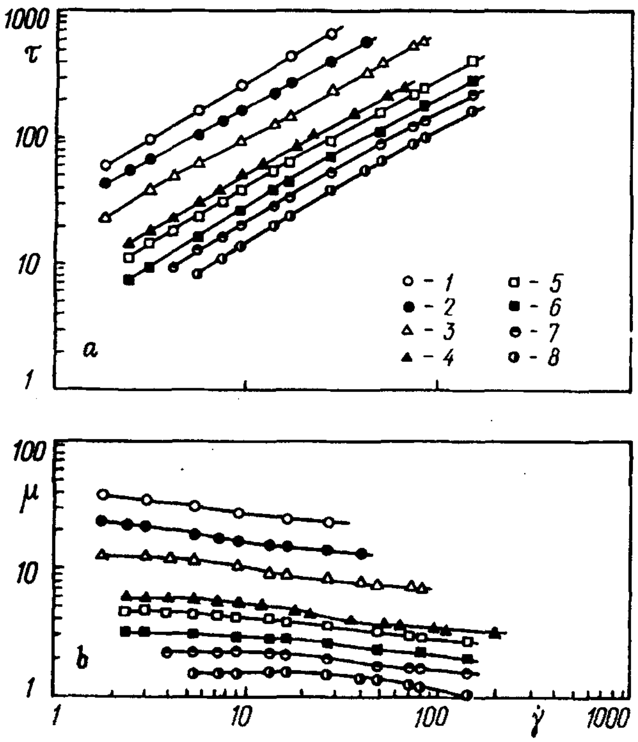


Fig. 2. Measurement results at different temperatures: 1-8) $T = 0$, 5.2, 13.5, 20, 26, 30, 35, 41°C; a) flow curves; b) apparent viscosity versus shear rate. τ, Pa.

$$k = 39.16 \exp(-0.076T). \tag{6}$$

As is seen, with decreasing temperature, the slope of the curves slightly decreases, which is also indicative of increased structure strength. Figure 2b shows the apparent viscosity

$$\mu = \tau/\dot{\gamma} \tag{7}$$

versus the shear rate and temperature. For $T \gtrsim 20$ in the range of small velocity gradients ($\dot{\gamma} \lesssim 10$) the viscosity is virtually independent of $\dot{\gamma}$ and calculated by the formula

$$\mu = 20.93 \exp(-0.064T). \tag{8}$$

At $\dot{\gamma} > 10$ (and in the entire $\dot{\gamma}$ range investigated for temperatures of from 0 to 20°C) the apparent viscosity can be represented by the expression

$$\mu = 36.42 \exp(-0.068T)/\dot{\gamma}^{0.174}. \tag{9}$$

The decrease in viscosity observed with a $\dot{\gamma}$ rise is typical for dispersed systems and can be explained, in the opinion of the majority of authors, by the alignment of particles along the flow and immobilization of the dispersed medium.

In the present work, the suspensions are not stratified, and their hydraulic transport is accomplished in a laminar regime.

Local losses are sufficiently investigated in Newtonian turbulent flows, unlike the cases of the influence of polymers, added in small amounts, which decrease turbulent friction [10]. The works devoted to local losses in laminar flows are few. In [11], local losses are investigated in laminar flows of non-Newtonian pseudoplastic fluids, i.e., aqueous solutions of CMC and PAA of different concentrations. Comprehensive studies have revealed that for

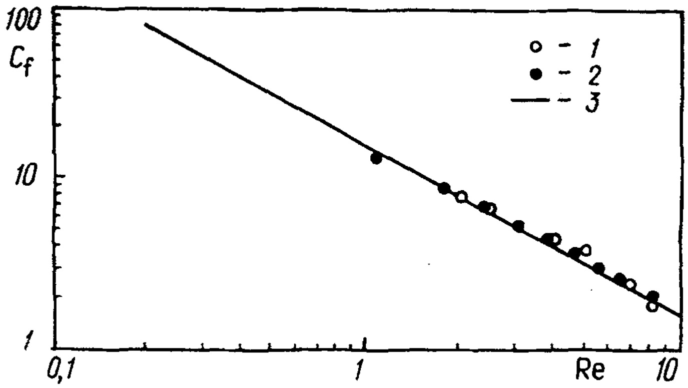


Fig. 3. Flow in the straigth pipe: 1) suspension, 2) glycerol, 3) 16/Re.

Re > 100–150 (the Re numbers are constructed using the effective viscosity) rheological properties do not influence the hydraulic resistances of different facilities.

An analysis of the literature data has revealed the absence of measurement data on local resistances in flows of high-concentration suspensions. Moreover, reliable data on local resistances in Newtonian liquids at low Re values (Re < 50) are also deficient. Therefore, to compute the results obtained in the present work, we also made measurements in a high-viscosity Newtonian fluid, i.e., glycerol. In their analysis, we used the Re number based on the apparent viscosity.

Hydraulic losses were determined experimentally on a setup representing a hydraulic system which incorporated sections of pipes connected in series with different flow areas, as well as a separable section with local resistances caused by bendings, throttle washers, fitting members, etc. The length of the rectangular sections of the pipes was chosen proceeding from the stabilized-flow condition when the inlet effects can be neglected. Considering that the inlet length is evaluated by the expression

$$L_{in}/d = 0.029\,\mathrm{Re}\,, \tag{10}$$

and that in our case the Reynolds numbers are within the range $0.4 < \mathrm{Re} < 30$, the length $L = 3000$ mm proves to be a quite sufficient dimension of the working sections. Pressure losses over the rectangular section and across the sites of local resistances were measured directly during one experiment. For this, Sapfir 22 differential manometers with measurement ranges 0–250 kPa and 0–10 kPa were used. The flow rate was measured by a precalibrated electromagnetic flow meter, model IR-51; the electric conductivity of the suspension was sufficient for its operation. Stacks of pipes with local resistances were mounted on changeable sections. The suspension temperature was measured by a mercury thermometer with an accuracy of 0.1°C at the pipe outlet upon outflowing of the suspension into the receiver tank of the pump. Thrust motion of the suspension was ensured by a single-screw pump of a special design with an electric drive providing smooth speed control of pump rotation. In view of the considerable dissipative losses, a tubular heat exchanger was installed on the suction line.

In the experiments, only a laminar mode of polymer suspension flow in pipelines was realized at low Re numbers.

Figure 3 represents results of pressure drop measurement in suspension flow in 15.7 and 21.3 mm diameter channels generalized in coordinates $C_f = f(\mathrm{Re})$. It should be noted that the data referring to pipes with different cross-sections are in fair agreement, while the resistance law is approximated by the Blasius law

$$C_f = 16/\mathrm{Re}\,, \tag{11}$$

where

$$C_f = 2\tau_w/\rho U_m^2;\ \mathrm{Re} = U_m d\rho/\mu;\ U_m = 4Q/\pi d^2,\ \tau_w = d\Delta P/4L.$$

Local losses are expressed in terms of local hydraulic resistance ξ as

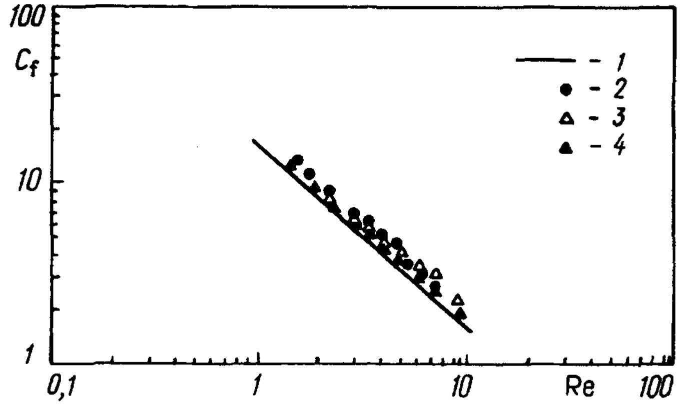


Fig. 4. Flow in the bent pipes: 1) 16/Re, 2-4) 60, 90, 120°, respectively.

$$\Delta P_{\rm loc} = \xi \rho U_{\rm m}/2 . \tag{12}$$

The general formula for determination of the coefficient of local losses in the laminar flow of Newtonian liquids is [12]

$$\xi = A/{\rm Re}^{L} + \xi' . \tag{13}$$

In the low Re range, the quantity ξ' is neglected, $L \sim 1$.

We investigated local resistances at the following places: 1) inlet, outlet; 2) valve; 3) smooth flow turnings by 60, 90, 120°; 4) cylindrical throttle washers with a ratio of cross-sectional areas equal to m = 0.38, 0.45, and 0.64.

Due to centrifugal forces, either secondary flows can develop in the curvilinear sections of pipes (bendings), or the velocity profile in the cross section can be distorted. In this case, the resistance law changes. As a criterion of such a flow for Newtonian liquids, the Din number is

$${\rm Di} = {\rm Re} \sqrt{R_{\rm p}/R_{\rm b}} , \tag{14}$$

where $R_{\rm p}$ is the radius of the flow-passage section of the pipe, $R_{\rm b}$ is the radius of the bend. A comparison of head losses in the straight pipe $\Delta P_{\rm p}$ with those $\Delta P_{\rm b}$ in the bends

$$\Delta P_{\rm b} = \Psi \Delta P_{\rm p} \tag{15}$$

shows that the coefficient Ψ depends on the Din number and rheological properties of the fluid. For Newtonian fluids it is established that $\Psi = 1$ at Di < 10.

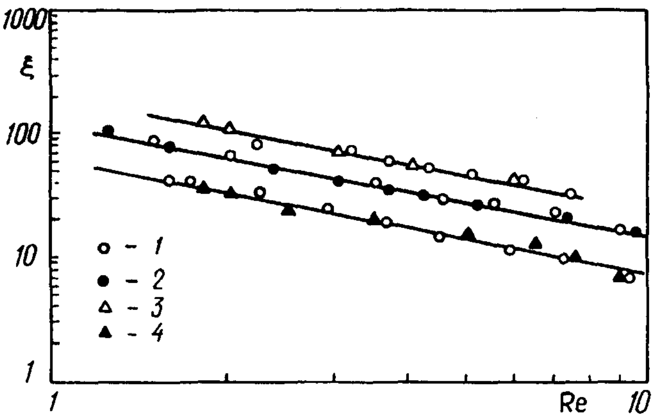
Data on hydraulic resistance determination in curved pipes are given in Fig. 4. As is seen, at low Re numbers the resistance law of the curved pipes remains virtually the same as for rectilinear sections of the corresponding length, i.e., $C_{\rm f} = 16/{\rm Re}$.

Measurement data on local resistances, i.e., valves, throttle washers, at the pipe inlet (sudden narrowing), at the pipe outlet (sudden broadening) are processed in the form

$$\xi = 2\Delta P_{\rm loc}/\rho U_{\rm m}^{2} = f({\rm Re}) , \tag{16}$$

where the Re number is constructed using the apparent viscosity (7) of the suspension.

Of throttle washers (conic, with a double taper, cylindrical) we investigated those with the highest resistance, i.e., cylindrical washers. In measurements, the valve was fully opened. Experimental data in form of the dependence $\xi = f({\rm Re})$ are presented in Figs. 5 and 6. Results of measurements made in a Newtonian fluid, i.e., glycerol and in a suspension are sufficiently well described by the relation



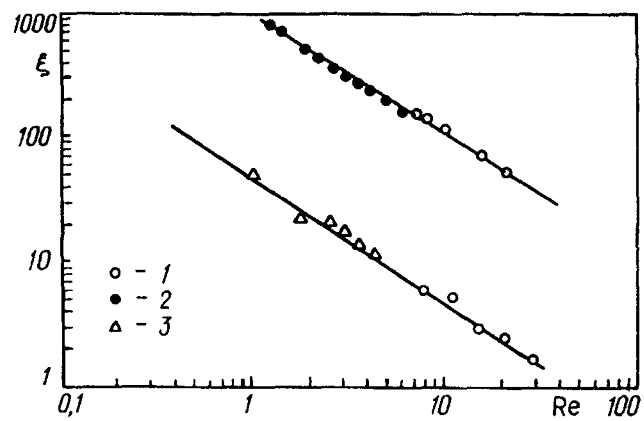


Fig. 5. Coefficient of local resistances of the throttle washers: 1) measurements in glycerin; 2-4) $m = 0.38, 0.45, 0.64$, respectively.

Fig. 6. Coefficient of local resistances: 1) measurements in glycerol, 2) valve, 3) inlet (sudden narrowing).

TABLE 1. Values of the Coefficient A in Formula (17)

Fittings	A	Fittings	A
Throttle washer:		Valve	1000
$m = 0.38$	200	Sudden broadening	47
$m = 0.45$	140	Sudden narrowing	56
$m = 0.64$	90		

$$\xi = A/\mathrm{Re}. \tag{17}$$

Coefficients A for different resistances are given in Table 1.

In [13], for a Newtonian liquid and Re < 100, $A = 70$ is reported for a conic washer with a ratio of cross-sectional areas of, as in our experiment, $m = 0.64$. As is seen from Table 1, for a cylindrical washer with $m = 0.64$ $A = 90$.

Thus, the investigations show that local resistances in the investigated suspensions in the range $0.4 < \mathrm{Re} < 30$ manifest quasi-Newtonian regularities.

NOTATION

τ, shear stress; τ_w, wall shear stress; τ_0, limit shear stress; k, consistency measure; n, index of degree of non-Newtonian property; $\dot{\gamma}$, shear rate, ρ, density; μ, apparent viscosity; d, diameter; ξ, coefficient of local resistances; U_m, mean velocity; R_b, bending radius; ΔP_p, head losses in straight pipe; ΔP_b, head losses in bend; ΔP_{loc}, head losses in local resistances; Di, Din number; Re, Reynolds number; C_f, resistance coefficient.

REFERENCES

1. B. A. Barbanel', É. A. Vasil'tsov, and V. V. Gorbachev, Inventor's Certificate No. 1152634, Byull. Izobret., No. 16 (1985).
2. B. A. Barbanel', É. A. Vasil'tsov, and S. S. Maksimova, Mixing of Flowing Media in Pipelines [in Russian], Moscow (1981).
3. Stable Liquid Polymer Composition, USA Patent No. 383589 (1974).

4. N. A. Pokryvailo, O. Vain, and N. D. Kovalevskaya, Electrodiffusion Diagnostics of Flows in Suspensions and Polymer Solutions [in Russian], Minsk (1988).
5. Z. D. Jastrzebski, I&EC Fund, 6, 445 (1967).
6. G. Antonini, O. Francois, P. Gistais, and A. Touret, in: Proc. of the 6th Int. Symp. Coal. Slurry Combust. and Technol., Orlande (1984).
7. Y. Cohen and A. B. Meltzner, J. of Rheol., 29, No. 3, 67-102 (1985).
8. J. Blaszczyk and R. Petela, Rheol. Acta, 25, 521-526 (1986).
9. Pipeline Hydrotransport of Solid-State Materials [in Russian], Book of Abstracts of the All-Union Scientific-Technical Conference, Moscow (1986).
10. V. V. Chernyuk, Influence of additives, decreasing turbulent friction, on local hydraulic resistances [in Russian], Abstract of the Candidate's Dissertation (Engineering), L'vov (1985).
11. J. Svec, Hydraulicke rotraty a mereni prutoku casove nezavislych nenewtonskych kapalin, Praha (1978).
12. A. D. Al'tshul' and P. G. Kiselev, Hydraulics and Aerodynamics [in Russian], Moscow (1975).
13. B. B. Nekrasov (ed.), Handbook on Hydraulics, Hydraulic Machines and Drives [in Russian], Minsk (1985).