pressure difference, Pa; De, Debourgh number; We, Weissenberg number; Re_f, oscillatory Reynolds number.

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RHEODYNAMICS AND MASS TRANSFER DURING PERIODIC AND
NONUNIFORM CYLINDER MOTION IN POLYMER SOLUTIONS

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Rheodynamics and mass transfer features are studied using periodic and uniform cylinder motion in viscoelastic fluids of the dilute polymer solution type. Estimates are performed of the characteristic time of the solutions.

It has been shown earlier [1] that during cylinder vibrations with low amplitudes (a/d ≫ 1) in viscoelastic fluids of the dilute polymer solution type the secondary flow pattern changes as compared with a Newtonian fluid, resulting in elevation of the intensity of mass transfer (∿ 12-15% in a 100 ppm concentration of a WSR-301 solution).

In contrast to vibrations with low amplitudes where secondary stationary flow play a fundamental part in transfer processes, cylinder vibrations with high amplitudes are accompanied by separate periodic flows [2] and the viscoelastic properties of the fluid can be due to other effects.

Taking account of the complexity of the theoretical analysis of such flows, the main attention was paid to selection of the methodology of the experiment that would permit a study of the flow structure and the mass transfer near the cylinder.

The electrodiffusion method we used in combination with visualization is well recommended for the investigation of separation flows [3].

Visualization of the separation flow near a 5 mm diameter cylinder (a/d = 1.35) performing harmonic vibrations at the frequency f = 1 and 5.5 Hz was carried out on an installa-
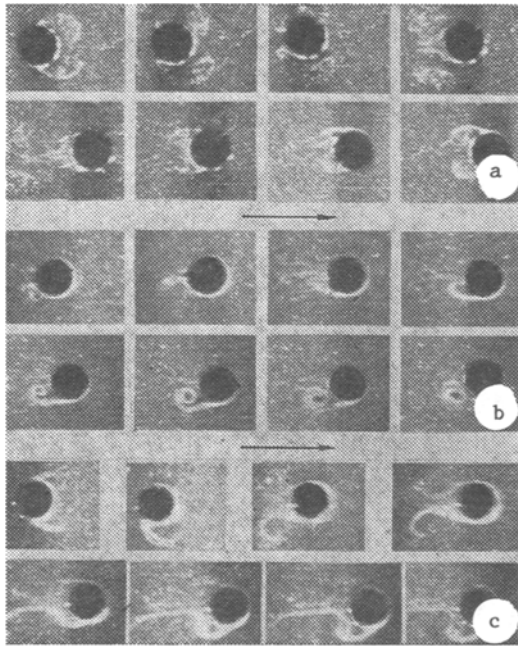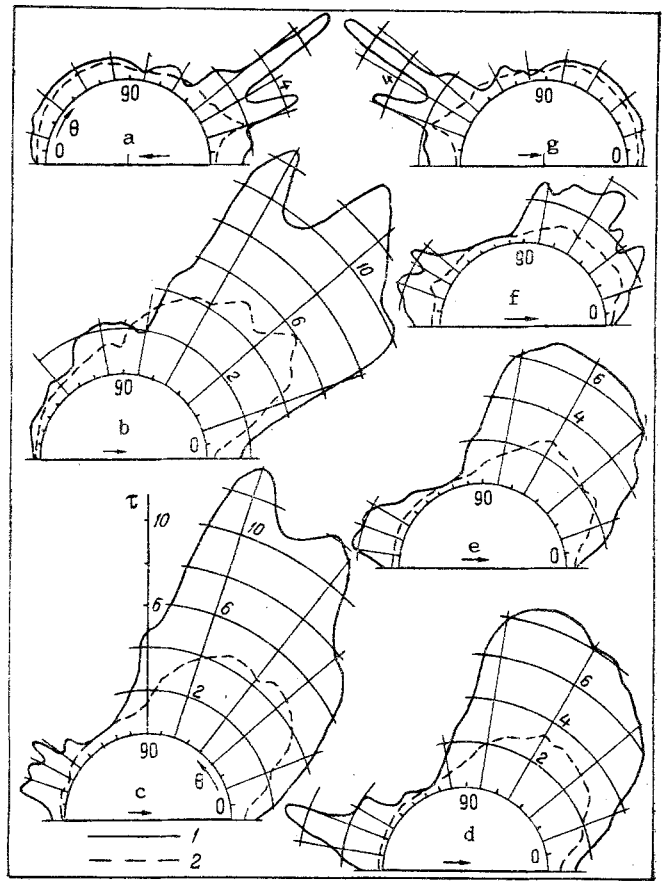
Fig. 1

Fig. 2

Fig. 1. Flow visualization near a vibrating cylinder: a, b) visualization in water, a/d = 1.35, f = 1 and 5 Hz, respectively; c) visualization in the PEO solution WSR-301, c_p = 100 ppm, a/d = 1.35, f = 5 Hz; 1) arrows show the motion direction.

Fig. 2. Results of friction stress measurements on the surface of a vibrating cylinder (f = 5.5 Hz, a/d = 1.4): a) t = 0, time of change in the motion direction to the reverse; b-g) t = 0.11T, 0.16T, 0.22T, 0.33T, 0.44T, 0.5T, respectively; 1) measurements in an electrolyte; 2) measurements in the PEO solution WSR-301, c_p = 100 ppm; 3) arrows display direction of motion. τ, Pa.

tion whose description is presented in [1]. Used for the visualization were 10-μm-diameter magnesium oxide particles. The survey was performed by a fixed movie camera. The local friction stress on the surface and the integrated mass transfer were measured on the same installation by using the electrodiffusion method. In the first case two platinum rectangular local electrodes 0.35 × 4.02 mm and 0.327 × 4.34 mm were mounted diametrically opposite flush with the wall with long side along the generatrix of a 10-mm-diameter cylinder (a/d = 1.4). The instantaneous value of the current was recorded by using a loop oscilloscope for sensor locations at 5° intervals.

An estimate of the electrode inertia [4] disclosed the possibility of using quasistationary relationships between the measured current and the friction stress [4]

$$\tau = \frac{1{,}9 \nu I^3}{F^3 L^2 h^3 c_0^3 D^2} \, . \tag{1}$$

The integrated mass transfer was measured by using cylindrical electrodes of different diameters. An electromagnetic vibrator to whose armature the electrodes were fastened was used as vibrations source in the experiments. The vibrations frequency was given by an audio generator in the 20-80-Hz band. The amplitude could be varied from 0.03 to 2 mm. Equimolar solutions of potassium ferro-ferricyanide (c_0 = 2.5·10^{-2} kmole/m³) with a K_2SO_4 background and with polyethyleneoxide (PEO) WSR-301 admixtures of different concentrations were used as working fluids. It has been shown earlier [5] that the polymer solutions being utilized do not cause any substantial blocking of the electrodes. Viscosity of the solutions was measured on a U-shaped viscosimeter that realizes the VT method of measurements [6] (V
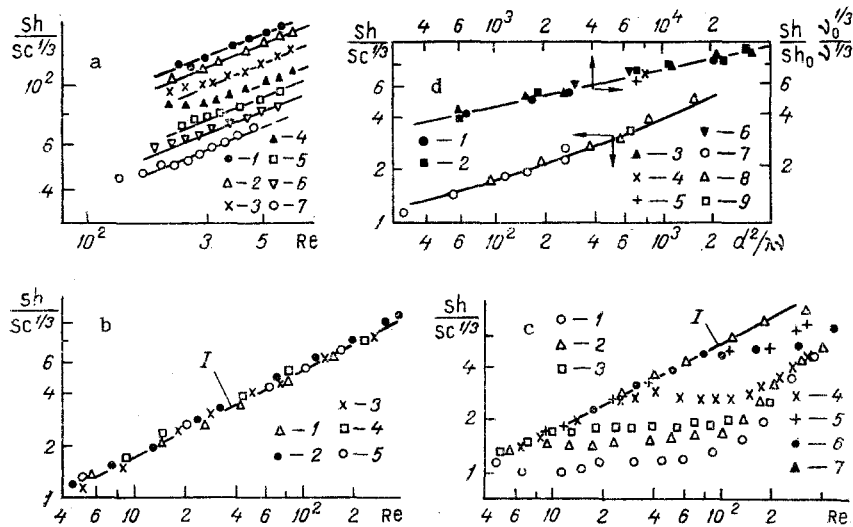
Fig. 3. Results of investigating the mass-transfer: a) mass transfer of a vibrating cylinder, d = 1 mm, a/d = 0.8-2: 1) measurements in an electrolyte; 2-7) measurements in PEO WSR-301 solutions, c_p = 2, 10, 20, 50, 100, 200 ppm, respectively; b) mass transfer for electrolyte flow around a cylinder: 1-4) d = 0.22, 0.39, 1, 2 mm, respectively; 5) experimental data from [22]; I is the approximation (3); c) mass transfer for PEO WSR-301 solutions flowing around a cylinder: 1-5) d = 0.22 mm, c_p = 200, 100, 50, 20, 10 ppm, respectively; 6, 7) d = 1 mm, c_p = 200, 20 ppm, respectively; I is the approximation (3); d) extension of measurement results in PEO WSR-301 solutions: 1-6) mass transfer of a vibrating cylinder; 1-3) d = 1 mm, f = 30, 60, 80 Hz, respectively; 4-6) d = 2 mm, f = 40, 60, 70 Hz, respectively; 7-9) mass transfer for flow around a cylinder, d = 0.22, 0.39, 1 mm, respectively.

is the control volume of the fluid and T is the measurement time). The coefficient of Fe-$(CN)_6^{-3}$ ion diffusion was determined from the transient characteristic of the diffusion current in a fixed medium [7].

In its general features the flow pattern of a Newtonian fluid behind a vibrating cylinder appears as follows. Flow separation starts at the cylinder rear stagnation point on the accelerated motion section, the point of separation moves forward along the surface, and a wake is formed behind the cylinder. A pair of symmetric vortices forms and grows rapidly on the stagnation section behind the cylinder. The vortices attain their greatest size before the cylinder stops and the motion is reversed (Figs. 1a and b).*

The pattern of co-wake formation being observed in a Newtonian fluid is qualitatively in agreement with those known for cylinder motion from a state of rest [8] and for cylinder vibrations with high amplitudes [2].

The influence of the PEO admixtures in the first half-period of the vibrations is weakly expressed. The visualization displayed in Fig. 1 corresponds to the second half-period. The significant influence of the polymer is seen (Fig. 1c). The vortex flow in the wake is strongly suppressed: no intensive vortex is formed at the end of the half-period, and the co-wake zone of the preceding cycle advances slowly to the stern, is dissipated more weakly.

Reduction of the separation flow intensity and of the frequency of Karman vortex collapse in polymer solution behind uniformly moving cylinders was observed in [9]. A rise in flow stability in the wake behind a disc is noted in [10].

Results of measuring the friction stress intensity are displayed in Fig. 2. They agree qualitatively with the visualizations. It is seen that the PEO admixtures result in a reduc-

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* The unclear image of the second vortex on certain photographs is due to inhomogeneity in the distribution of the contrast substance.
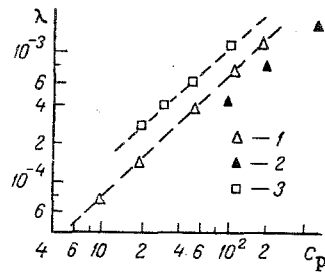
Fig. 4. Characteristic time estimates: 1) $\lambda(c_p)$ obtained from measurements in this paper; 2) data from [20]; 3) data from [19]. λ, sec; c_p, ppm.

tion of the friction stress over practically the whole cylinder surface. The quite significant polymer influence on the frontal domain at the beginning of the half-period (Figs. 2b and c) is associated with the imposition of the flow in the co-wake of the preceding cycle on the main motion. As can be judged by the friction stress measurements, the presence of the polymer results in a substantial reduction in its intensity (Fig. 2a). The point of separation to the end of the half-period is found for $\theta = 100°$ while it is difficult to assess its location for cylinder vibrations in a polyoxide solution since the flow is strongly suppressed in the separation zone.

The hydrodynamics features being observed in the presence of a polymer should evidently influence even the nature of the surface heat transfer to the medium.

As already mentioned, an increase in the mass transfer intensity ($Sh/Sh_0 > 1$) occurs for the cylinder vibrations with low amplitudes ($a/d \ll 1$) in polymer solutions. However, as the vibrations amplitude $\underline{a}$ grows the values of Sh and Sh_0 equilibrate. As $\underline{a}$ grows further, an abrupt reduction in the mass-transfer intensity first occurs (Fig. 3 in [1]) and then for $Re > Re_{cr}$ (not shown in the figure) a dependence of the number Sh on Re, shown in Fig. 3a, is set up. Let us note that as the polyoxide concentration increases the values of Re_{cr} are reduced.

The a/d range in this investigation was 0.8-5. There are no experimental data on cylinder vibrations in Newtonian fluids for such a/d.

It is seen from Fig. 3a that in agreement with the results of visualizations and measurements of the local friction stresses as the PEO concentration increases the mass transfer intensity is reduced and the data can be approximated by the expression

$$Sh = B\,Re^{0.44}Sc^{1/3}, \tag{2}$$

where B is a function of the polymer concentration and the cylinder diameter in the general case. It is clear that the ratio Sh/Sh_0 is independent of the vibration rate $U = a\omega$ for $Re > Re_{cr}$ but depends only on the diameter, viscosity, and a certain parameter characterizing the properties of this solution which depend primarily on the polymer concentration.

Certain common features with the nature of the mass transfer of a vibrating cylinder are disclosed in an investigation of mass transfer under conditions of the stationary flow of PEO WSR-301 solutions around cylindrical electrodes (d = 0.2, 0.39, 1, 2 mm) in the Re range between 2 and $7 \cdot 10^2$ (Fig. 3c). The experimental investigation was carried out by using the electrodiffusion method on an installation whose description is presented in [11]. The test data in the electrolyte solution without the PEO admixture are shown in Fig. 3b. They are approximated by the dependence

$$Sh = 0.52Re^{0.514}Sc^{1/3}, \tag{3}$$

which is in good agreement with the extension of the test data on the heat transfer of cylindrical wires of thermoanemometers in the Re number range from 20 to 10^3 [12].

Results of measurements in electrolyte solutions with polymer admixtures are presented in Fig. 3c. It is seen that up to a certain number Re_{cr} the PEO admixtures do not influence the mass transfer intensity. Starting with Re_{cr}, data on mass transfer deviate from data for $c_p = 0$ and behave analogously to the case with vibrating cylinders, independent of the velocity but dependent only on the diameter, viscosity, and a certain parameter characterizing the properties of this solution. Mass transfer anomalies appear all the more strongly the smaller the cylinder diameter. Thus, for a 2 mm diameter cylinder the sensitivity to the velocity was conserved for all the investigated PEO solutions. Earlier, James, Acosta [13], and James, Gupta [14] detected similar anomalies by investigating the flow and

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heat-transfer characteristics of thin cylindrical sensors of thermoanemometers in polymer solutions of concentrations from 6 to 300 ppm in the Re = 0.1-200 number band. The results of the experiment were extended by a complex $d^2/\lambda\nu$ = Re/We (λ is molecular relaxation time) which characterizes the relationship between the inertia and elasticity forces. The authors of [13] assumed that the drag and heat transfer anomalies occur because of the fact that the boundary layer around the cylinder is thickened in the polymer solutions as compared with water because of the origination of normal stresses. Mashelcar and Marrucci [15] arrived at the same deduction by examining the problem of viscoelastic Maxwell fluid around a cylinder, and showed that the thickness of this layer depends on the fluid properties ν, λ. the drag and heat transfer coefficients are here functions of the complex $d^2/\lambda\nu$. Velocity visualizations and measurements in PEO WSR-301 solutions in the neighborhood of a 0.2 mm diameter cylinder, performed in [16], showed that the cylinder is surrounded by a sufficiently thick zone within which the velocities are almost zero. The convective heat transfer of a 0.05 mm diameter cylindrical electrode was investigated in the 0.01-1 Re number band in [17]. The electrochemical system $K_4Fe(CN)_6/K_3Fe(CN)_6$ with KCl background was used, in which Polyox Coagulant of 50, 100, 200 ppm concentration was dissolved and where independence of the mass transfer coefficient from the velocity was also observed. Starting from the condition that $\bar{U} = \bar{U}_{cr}$ is the "beginning" of the non-Newtonian behavior and $\lambda\bar{U}_{cr}/d \sim 1$ [18] here, the quantity $\lambda \sim 10^{-2}$ sec is determined for solutions of 100-200 ppm concentration. An analogous estimate on the basis of our results yields a λ of the same order. In this connection let us note that a computation [13] of the molecular relaxation time for the Polyox Coagulant solution (M = $5.18 \cdot 10^6$ kg/kmole, $[\eta] = 1.78$ m^3/kg) of 100 ppm concentration yields the value $\lambda = 2.6 \cdot 10^{-4}$ sec. Analysis of the results of our experiments results in the relationship

$$\frac{Sh}{Sc^{1/3}} = Ac_p^\beta, \tag{4}$$

where $\beta = -0.33$; A is a constant dependent only on the diameter. Furthermore, assuming $\lambda \sim c_p^m$, where λ is the characteristic time of the fluid, it can be shown that the data on the mass transfer of cylinders are generalized in the form (Fig. 3d, points 7, 8, 9)

$$\frac{Sh}{Sc^{1/3}} = f(d^2/\lambda\nu), \tag{5}$$

which affords a possibility for determining the form of the dependence $\lambda(c_p)$ in the investigated range of variation of the parameters given by one "benchmark" value $\lambda = \lambda_0$. The value $\lambda_0 = 0.7 \cdot 10^{-3}$ sec, determined in [1] for a PEO WSR-301 solution of 100 ppm concentration, was used for processing the experimental data in the form (5). The magnitudes of λ for other concentrations are presented in Fig. 4. Superposed on this same figure are data of James [19] investigating the PEO FRA solution as well as the data from [20] for the WSR-301 solutions. It is seen from Fig. 4 that the dependence of λ on the polymer concentration is almost linear, which corresponds to assumptions of the molecular theory of real solutions [21].

The lower line in Fig. 3d is a computation using the dependence (21) in [15] that has been obtained under the assumption that the heat flux (in our case the mass flux) proceeds to the cylinder surface through a layer of delayed fluid. The agreement between the experiment and computation data can probably be considered an indirect confirmation of this assumption.

The experimental data on the mass transfer of the vibrating cylinders of 1 and 2 mm are also extended well in the variables $d^2/\lambda\nu$. Used here are the values of λ presented in Fig. 4. The results of the processing are shown in Fig. 3d (points 1-6).

NOTATION

a, vibrations amplitude; f, frequency; $\omega = 2\pi f$, circular frequency; d, diameter; L, h, electrode length and width; c_p, polymer concentration; c_0, depolarizer concentration; ν, viscosity; $[\eta]$, characteristic viscosity; D, diffusion coefficient; λ, molecular relaxation time, the characteritic fluid time; M, molecular weight; F, Faraday number; I, diffusion current; U = $a\omega$, vibration velocity; $\bar{U}$, incident flow velocity; S, area; Θ, angle of separation; B, A, β, m, constants in (2) and (5); Re = $\bar{U}d/\nu$, Re = $a\omega d/\nu$, Reynolds numbers; Sh = Id/Fc_0DS, Sherwood number; $Sh_0 = I_0d/Fc_0DS$, Sherwood number in the electrolyte without polymer admixtures; Sc = ν/D, Schmidt number; Wn = $U\lambda/d$, Wn = $\bar{U}\lambda/d$, Weissenberg numbers; T, period of the vibrations; and t, time.

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HEAT AND MASS TRANSFER BETWEEN THE DISPERSE PHASE AND THE CARRYING

MEDIUM IN A PLANE TURBULENT DISPERSE NEAR-WALL JET

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UDC 66.015.23

Heat and mass transfer in a liquid—liquid and liquid—solid medium are investigated theoretically and experimentally in a jet heat- and mass-transfer apparatus.

The diagram, in principle, of an element of the construction of the jet heat- and mass-transfer apparatus under consideration is represented in Fig. 1. Clamped rigidly in the apparatus housing 1 in the shape of a parallelepiped are horizontal perforated plates 2 overlapping part of the apparatus transverse section and a moving vertical baffle 3 with slots in which horizontal plates are arranged with a certain spacing. The mentioned plates can be utilized as heat transmitting surfaces.