similar reduction in $\omega_{c.s.}$ due to a decrease in the difference in velocities between the drops and the gas being cleaned. This conclusion is consistent with the findings in [1, 2].

In conclusion, we should note that the above-described effects are manifest to a greater degree in the co-current movement of the gas and drops in the direction opposite to that of gravity.

NOTATION

η, cleaning efficiency; P, (ΔP), pressure, pressure drop; z, longitudinal coordinate; ξ, friction coefficient; d, diameter; W, velocity; ρ, density; σ, surface tension; φ, volumetric vapor content; N, number of drops per unit volume; β, angle of inclination of generatrix of cone; G, flow rate; ω, removal coefficient; g, gravitational acceleration; We, Weber criterional number. Indices: ", ', gas, liquid; Σ, total value; d, s, drop, solid particle; m, maximum value; fr, friction; wa, wall; a, acceleration; g, weight component; 0, quantity referred to the inlet section; n, most probable value.

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ELECTRODIFFUSIVE DIAGNOSIS OF THE VISCOELASTIC PROPERTIES OF POLYMER SOLUTIONS ON A ROTATING SPHERICAL ELECTRODE

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This article examines the feasibility of measuring normal stresses from data from electrochemical diagnosis over the surface of a rotating sphere.

The rotation of a sphere in a liquid causes a secondary meridional flow as well as the main circular flow. Such flow is centrifugal for Newtonian fluids, with flow toward a pole and flow back to the region of the equator. In rotational shear flow of viscoelastic liquids, nonisotropic normal stresses are created. These stresses either lower the rate of the centrifugal flow or convert it into centripetal flow. In the last case, the liquid flows over the sphere in the equator region and flows back from the pole region. These effects were first examined by Giesekus [1]. Quantitative calculations of the flow of a viscoelastic second-order fluid about a rotating sphere [1, 2] make it possible to determine the normal stresses on the basis of study of the kinematics of the secondary meridional flows. Such experiments are usually performed by visualization of the flow about a rotating sphere [3]. Since the intensity of the meridional flow decreases very rapidly with increasing distance

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from the surface of the sphere, the results of these experiments are qualitative. Consequently, the use of visualization is limited to strongly elastic and viscoelastic fluids. More reliable for quantitative study of the kinematics of meridional flows are methods of indirectly determinng the wall gradient of meridional velocity on the basis of measurements of the rate of convective heat and mass transfer. The electrochemical method [4] may be the most advantageous of these methods from the point of view of sensitivity and constancy of the initial properties of the fluid. It should be noted that instrumental methods of measuring the difference in normal stresses (such as with a Weissenberg rheogoniometer) are inapplicable in weak polymer solutions at shear rates less than 10^3 sec^{-1}. We will examine the possibility of measuring the difference in normal stresses from data from electrochemical diagnosis of the secondary meridioinal flow about the surface of a rotating sphere. The rheodynamic theory of such flows was developed for fluids for which the following differences in normal stresses occurs in simple shear flow along with the shear stresses τ_{12}:

$$\tau_{12} = \eta\dot{\gamma},\ \tau_{11} - \tau_{22} = \nu_1\dot{\gamma}^2,\ \tau_{22} - \tau_{33} = \nu_2\dot{\gamma}^2. \tag{1}$$

In contrast to more realistic models of viscoelastic media, here we assume that the material coefficients η, ν_1, and ν_2 are constant, i.e., are independent of the shear rate. The approximate solution of the equations of motion is based on the following representations [5]. With sufficiently slow rotation of the sphere in an infinite fluid having a constant viscosity, primary circular flow with the following distribution of angular velocities is established

$$\omega = \Omega (R/r)^3 \sin\Theta. \tag{2}$$

Such a flow is viscometric and in a viscoelastic fluid is accompanied by the creation of a difference in the normal stresses

$$\tau_{\varphi\varphi} - \tau_{\theta\theta} = (\nu_1 + \nu_2)\dot{\gamma}^2,\quad \tau_{rr} - \tau_{\theta\theta} = \nu_2\dot{\gamma}^2. \tag{3}$$

The shear rate field $\gamma(r, \Theta)$, with allowance for (2), is expressed by the relation

$$\dot{\gamma} = -\sin\Theta r\,\partial_r\omega = 3\Omega\sin\Theta\,(R/r)^3. \tag{4}$$

Due to the action of the elastic stresses (3) and inertia ρV_φ^2, secondary meridional flows with corresponding viscous drag are created in the fluid. As a result, the equations of motion for the stream function χ

$$V_\theta = \sin^{-1}\Theta r^{-1}\partial_r\chi,\ V_r = -\sin^{-1}\Theta r^{-2}\partial_\theta\chi \tag{5}$$

can be represented in the form

$$\eta\sin^{-1}\Theta\,[\partial_{rr}^2 + r^{-2}\sin\Theta\partial_\theta\sin^{-1}\Theta\partial_\theta]^2\chi = P_c - P_N, \tag{6}$$

where

$$P_c = -\rho(\operatorname{ctg}\Theta\,\partial_r - r^{-1}\partial_\theta)\,V_\varphi^2 = 6\rho R\Omega^2 (R/r)^5 \sin\Theta\cos\Theta; \tag{7}$$

$$P_N = -(\operatorname{ctg}\Theta\,\partial_r - r^{-1}\partial_\theta)(\tau_{\varphi\varphi} - \tau_{\theta\theta}) - r^{-2}\partial_r r^2\partial_\theta(\tau_{rr} - \tau_{\theta\theta}) = 72\nu_N\Omega^2 R^{-1}(R/r)^7\sin\Theta\cos\Theta; \tag{8}$$

$$\nu_N = \nu_1 + 2\nu_2 \tag{9}$$

(usually, $\nu_N \approx \nu_1$, since $|\nu_2| \ll |\nu_1|$).

The solution of biharmonic equation (6) with the corresponding boundary conditions can be reduced to the following simple form [6]

$$\chi = \frac{\rho\Omega^2 R^5}{8\eta}\left(1 - \frac{R}{r}\right)^2\left(1 - \mathrm{Ab}\left(2 + 4\frac{R}{r}\right)\right)\sin^2\Theta\cos\Theta, \tag{10}$$

where

$$\mathrm{Ab} = \frac{\nu_N}{\rho R^2}. \tag{11}$$

The corresponding profile of the gradient of meridional velocities over the surface of the sphere can be expressed as

$$\dot{\gamma}_m(\Theta) = \partial_r V_\theta|_{r=R} = \frac{1}{4}\Omega\,\mathrm{Re}\,(1 - 6\mathrm{Ab})\sin^2\Theta\cos\Theta, \tag{12}$$

where

$$\mathrm{Re} = \frac{\Omega R^2 \rho}{\eta}. \tag{13}$$

As was shown in [1, 5], in deriving Eq. (10) it is possible to ignore terms of the order $\Omega R^3 \mathrm{Re}^2$. A more detailed analysis for a Newtonian fluid showed that Eq. (10) is satisfactorily accurate for the range Re < 10. A serious limitation in the derivation of this equation is the assumption of constancy of the material coefficients η and ν_N. Thus, an evaluation should be made of the values of $\dot\gamma$ corresponding to values of the material functions $\eta(\dot\gamma)$ and $\nu_N(\dot\gamma)$.

The relation $\eta(\dot\gamma)$ primarily characterizes the structure of the primary circular rotational flow. It is described by Eq. (2) if the viscosity is constant in the range $\dot\gamma < \dot\gamma_V$; γ_V is the maximum value of the shear rate of the equator of the sphere, determined from (4) through the relation

$$\dot\gamma_V = 3\Omega. \tag{14}$$

With a variable $\eta(\dot\gamma)$, the stream function χ for the mean shear velocity $\dot\gamma = \dot\gamma_N$ can be expressed by Eq. (10). Here, it should be considered that the reason for the secondary flows is not the elastic stresses themselves but the nontrivial value of P_N characterizing their nonuniformity. This leads to the following estimate:

$$\dot\gamma_N = \int_V \dot\gamma P_N dV / \int_V P_N dV = 1.3\,\Omega, \tag{15}$$

where the fields of $\dot\gamma$ and P_N from (4) and (8) are integrated over the entire volume V of the fluid.

Attempts have been made to use a rotating sphere to determine the elastic stresses in fluids [3, 8-10]. However, methods of flow visualization were used in each case, and these methods require the use of relatively large spheres. The sensitivity and accuracy of such measurements is therefore limited to large Reynolds numbers Re ~ R^2 and low values of Ab ~ R^{-2}. The electrochemical method is free of these limitations. It is based on the theory of convective diffusion in an approximation of a concentrated boundary layer on axisymmetric electrodes. Within the framework of this approximation, it is possible to ignore diffusion currents over the surface of the sphere and, by considering the thinness of the diffusion layer (Sc >> 1), to simplify the stream function:

$$\chi = \frac{\Omega^2 R^3}{8\eta}\left(1 - \frac{R}{r}\right)^2 \left(\rho R^2 - \frac{1}{6}\nu_N\right) \sin^2\Theta \cos\Theta. \tag{16}$$

The equation of steady convective diffusion here takes the form

$$V_r \partial_r C + \frac{V_\theta}{r}\partial_\theta C = D\left(\partial_{rr} C + \frac{2}{r}\partial_r C\right), \tag{17}$$

where V_r and V_θ are known coordinate functions satisfying the continuity equation:

$$V_r = -\frac{1}{r^2 \sin\Theta}\partial_\theta \chi, \quad V_\theta = \frac{1}{r\sin\Theta}\partial_r \chi. \tag{18}$$

Equation (17) can be written as follows in the variables χ and Θ:

$$DR^{-1}\left[2Af(\Theta)\right]^{-1/2} \sin^{-1}\Theta \partial_\theta C = \partial_\chi \chi^{1/2} \partial_\chi C, \tag{19}$$

where

$$Af(\Theta) = \frac{\Omega^2 R^3}{4\eta}\left(\rho R^2 - \frac{1}{6}\nu_N\right)\sin^2\Theta\cos\Theta,$$

with the boundary conditions

$$\begin{gathered} C = C_0 \ \text{for} \ \chi \to \infty \ \text{or} \ \Theta < \Theta_0, \\ C = 0 \ \text{for} \ \chi = 0 \ \text{and} \ \Theta > \Theta_0. \end{gathered} \tag{20}$$

Solution of the equation of convective diffusion leads to the following expression for the mean densities of diffusion current:

$$I_N = 0{,}4891\,\varphi_E F_m C_0 (D^2\Omega^2 R\rho/\eta)^{1/3}\,|1 - 6\mathrm{Ab}|^{1/3}, \tag{21}$$

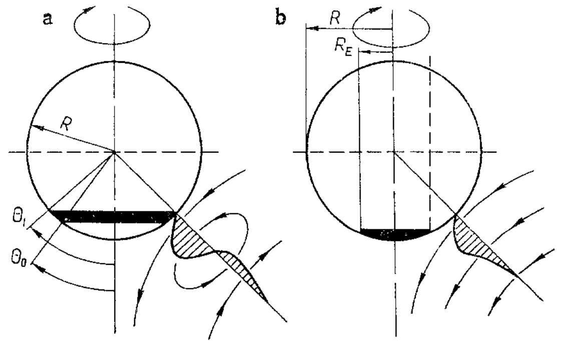

Fig. 1. Configuration of rotating spherical electrodes and diagram of secondary meridional flows: a) rotating spherical electrode with a peripheral sensitive element, centripetal flow at $^1/_6$ < Ab < $^1/_2$; b) rotating pole electrode, centripetal flow at Ab > $^1/_2$.

where

$$\varphi_E = \left[3\int_{\Theta_0}^{\Theta_1} \sin^2\Theta \cos^{1/2}\Theta d\Theta\right]^{2/3} \Big/ \left[\int_{\Theta_0}^{\Theta_1} \sin\Theta d\Theta\right] \tag{22}$$

depends only on the geometry of the working electrode, a diagram of which is shown in Fig. 1 along with the flow regimes. For a Newtonian fluid, Ab = 0, and Eq. (21) is simplified:

$$I_V = 0.4891\ \varphi_E F_m C_0 (D^2\Omega^2 R\rho/\eta)^{1/3}. \tag{23}$$

Tests we conducted [11] with Newtonian equimolar solutions of potassium ferro- and ferricyanide on a rotating spherical pole electrode (cathode) confirmed that the results obtained agree to within 5% with Eq. (23) in the range Re_{cr} < Re < 10. Thus, Eq. (21) can also be considered suitable for viscoelastic solutions – electrolytes – in the indirect determination of ν_N, since all of the other parameters in (21) are found independently. Proceeding on the basis of (21) and (23), we obtain

$$\nu_N = \frac{\rho R^2}{6}\left[1 \pm (I_N/I_V)^3\right]. \tag{24}$$

The minus sign corresponds to the centrifugal regime, 6Ab < 1; the plus sign corresponds to centripetal flow over the surface of the sphere, 6Ab > 1 (here, the flow may be different far from the surface). The orientation of the flow was determined visually in preliminary tests.

An initial series of tests was conducted at the Institute of Heat and Mass Transfer of the Belorussian Academy of Sciences with relatively concentrated solutions of polyethylene oxide (PEO) WSR-301. The value of ν_N for PEO can be measured with a Weissenberg rheogoniometer at large shear rates. Then experiments were conducted on mainly dilute polymer solutions (to 100 ppm) at the Institute of Theoretical Foundations of Chemical Processes of the Czechoslovak Academy of Sciences [12].

A "Reotest II" rotational viscometer was used in the tests. A spherical pole electrode connected to an LP7e polarograph was installed on the spindle of the viscometer. More detailed information on the setup can be found in [11, 16]. We used spheres 2.85, 5, 10, and 20 mm in diameter. Platinum wire electrodes were mounted flush against the surface of the pole of the sphere. The setup allowed multiple-stage regulation of rotational velocity from 0.03 to 25.2 rad·sec^{-1}. Viscosity was measured in a broad range of shear rates with capillary and rotational viscometers. Preliminary tests showed that the viscosity and the coefficient of the normal stresses depend appreciably on the batch of the polymer, the time of its storage, and the method used to prepare the solution. The electrochemically active components of the solution were potassium ferro- and ferricyanide (C = 0.025 kmole·m^{-3}). A 4% addition of K_2SO_4 was made as the background electrolyte. The diffusion coefficient D of the depolarizer was determined with one of the spherical pole electrodes by analyzing the transitional I–t curves under potentiostatic conditions [13] and with a kinematic regime at the forward [11] (Ab < $^1/_6$) or rear [14] (Ab > $^1/_6$) critical point.

A series of experiments was conducted to determine ν_N of the sample of WSR-301 PEO, for which we had data on the measured difference in normal stresses.

Figure 2 shows the dependence of the steady-state densities of diffusion current I on the angular velocity for 10- and 20-mm-diameter spheres. Also shown are values of I_V calculated from Eq. (23). Here, the value of η in (23) was taken from the results of viscometric meas-

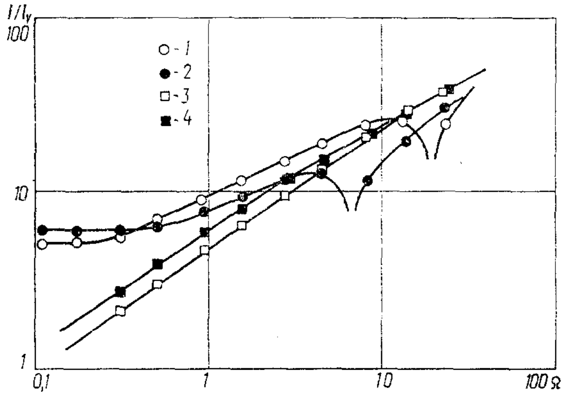

Fig. 2

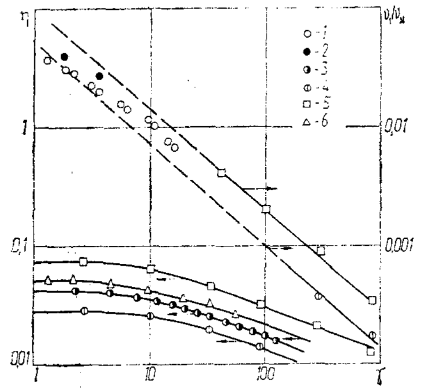

Fig. 3

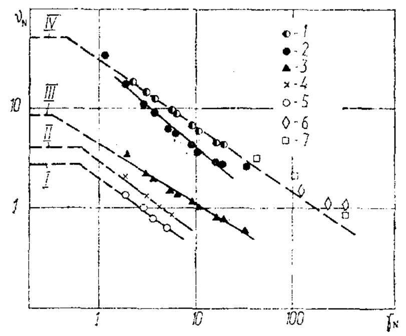

Fig. 4

Fig. 2. Dependence of limiting diffusion current on angular velocity: $I(\Omega)$ for the 10-mm-diameter electrode (1) and 20-mm-diameter electrode (2); $I_V(\Omega)$ for the 10-mm-diameter electrode (3) and 20-mm-diameter electrode (4).

Fig. 3. Rheological characteristics of a 0.35% solution of PEO WSR-301 with EX-additions at 20°C: 1, 2) $\nu_N(\dot{\gamma})$ for a spherical pole electrode 10 and 20 mm in diameter, respectively; 3) flow curve; 4, 5) data from measurement of ν_1 and η with a Weissenberg rheogoniometer for 0.35 and 0.5% solutions of PEO, respectively; 6) values of η for a 0.5% solution of PEO ("old" batch). ν_1, ν_N, mPa·sec²; η, mPa·sec.

Fig. 4. Normal stresses for different solutions of PEO WSR-301: 1) 0.5% solution; 2) 0.5% solution ("old" batch); 3) 0.3% solution; 4) 0.2% solution; 5) 0.1% solution; 6, 7) for comparison, data from rheogoniometric measurements by other authors for a 0.5% solution of PEO. I, II, III, IV) Data calculated from Eq. (26), $\nu_0 = 2\xi_0$, for 0.1, 0.2, 0.3, and 0.5% solutions of PEO. ν_N, mPa·sec²; γ_N, sec⁻¹.

urements of $\eta = \eta(\gamma_V)$, $\dot{\gamma}_V = 3\Omega$. It is apparent from the figure that a decrease in angular velocity is accompanied by a change from the centrifugal regime [test points 1 and 2 are located below the data for $I_V(\Omega)$] to the centripetal regime [test points 1 and 2 are accordingly located above $I_V(\Omega)$]. This change in regimes was confirmed by visual observations. The substantial decrease in current densities seen in Fig. 2 for both spheres corresponds to the region of values of Ω, where

$$\nu_N = \frac{1}{6}\rho R^2. \tag{25}$$

The values of ν_N from Eq. (25) can be analyzed by using only part of the data shown in Fig. 2. These are the data corresponding to the region of creeping flow Re < 10 and for which the effects of free convection are still weak, i.e., there is agreement with the conclusions made in [11]. Results of determination of ν_N are shown in Fig. 3 together with data on viscosity. Also shown for comparison are data for a solution of WSR-301, C = 0.35%, obtained with a Weissenberg rheogoniometer. With allowance for the limited sensitivity of the rheogoniometer, the data were obtained at relatively high shear rates compared to our case. Extrapolation to the region of small values of $\dot{\gamma}$ showed (Fig. 3) that they agree well. The use of smaller spherical electrodes made it possible to study the viscoelastic properties of more dilute polymer solutions. Figure 4 shows results of measurements of ν_N for solutions of PEO WSR-301 with concentrations of 0.5, 0.1, 0.2, and 0.3%. Also shown for comparison are data from electrodiffusive and rheogoniometric measurements of the coefficients of the difference in normal stresses for a PEO solution with C = 0.5%.* The agreement is good in this case as well. Here, an "older" batch of PEO (difference of three years) was used. It was characterized by lower values of viscosity than in the previous instance (see Fig. 3) and the coefficients ν_N and ν_1 shown in Fig. 4. It is not possible to compare our data with other measurements in the region of low shear rates due to the lack of such measurements. However, a qualitative comparison can be made for $\dot{\gamma} \to 0$ by using the method of determining the initial coefficient of the normal stresses ξ_0 proposed by Malkin [15] and based on the approximate relation

$$\xi_0 = \frac{2n}{\pi(n+1)} \frac{\eta_0}{B}, \tag{26}$$

where n, η_0, and B are determined on the basis of the measured relation $\eta(\dot{\gamma})$ (η_0 is the maximum Newtonian viscosity; B is the maximum value of $\dot{\gamma}$ corresponding to the condition $\eta = \eta_0$). The resulting calculated values of $2\xi_0 (\nu_0 = 2\xi_0)$ agree qualitatively with the values of ν_0 obtained by extrapolation of the results of electrodiffusive measurements of $\nu(\dot{\gamma})$ to the region $\dot{\gamma} \to 0$ (see Fig. 4).

It should be noted that a further decrease in the diameter of the sphere could, first, significantly increase the sensitivity of the method and, second, expand the range of its application to higher values of shear rate. However, it will be necessary to develop an appropriate rheodynamic model in order to more correctly apply the method to fluids with significantly variable material coefficients η, ν_1, and ν_2.

NOTATION

C, concentration of depolarizer, kmole·m^{-3}, and polymer, ppm; D, diffusion coefficient of depolarizer, m^2·sec^{-1}; r, Θ, φ, spherical coordinates; R, radius of sphere, m; R_E, radius of electrode, m; $\dot{\gamma}$, shear rate for the primry viscometric flow, sec^{-1}; ν_1, ν_2, ν_N, coefficients of the normal stresses, Pa·sec^2; ρ, density, kg·m^{-3}; η, viscosity, Pa·sec; Ω, angular velocity, rad·sec^{-} ; I, limiting diffusion current, A·m^{-2}; I_V, I_N, theoretical values of current I for viscoelastic and Newtonian fluids; $Re = \Omega R^2 \rho/\eta$, Reynolds number; n, flow index.

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FLOW AND HEAT TRANSFER OF AN ANOMALOUSLY VISCOUS FLUID IN THE GAP BETWEEN ROTATION AND STATIONARY DISKS WITH NONUNIFORM PRESSURE ABOUT THE PERIMETER

V. M. Shapovalov, N. V. Tyabin, and L. M. Beder

UDC 532.135:536.24

The problem of bypass flow of a liquid under the influence of nonuniform pressure about the perimeter is solved.

One of the more promising pumps for transporting melts of polymers and high-viscosity liquids is the so-called circular pump [1]. It has several technicoeconomic advantages over conventionl screw pumps, particularly high efficiency. The pressure about the perimeter of a circular pump is nonuniform, which results in bypass flow of the liquid in the space between the body and the end of the rotor. It is interesting to evaluate the size of this flow, since it affects the overall efficiency of the pump. Also, analysis of this type of flow may prove useful in the design of precision-metering spur-gear pumps, for which stability of flow rate is very important. The end seal can be regarded as a disk–disk system in which the liquid is subjected to intensive shear strains. A flow diagram is presented in Fig. 1. The top disk (pump body) is stationary, while the bottom disk (pump rotor) rotates with an angular velocity ω. We will ignore the hydrodynamic effect of the shaft. A bridge separating the intake and delivery zones is located at the point $r = R$, $\varphi = 0$. The bridge has negligibly small angular dimensions and its hydrodynamic effect can be ignored. The velocity field is a three-dimensional shear field.

Considering the condition $h \ll R$, we assume that creeping flow is realized in the gap, and the forces of gravity and inertia can be ignored. Here, $\partial P/\partial z \approx 0$, and there is no flow in the z direction. With allowance for these assumptions, the following boundary-value problem is formulated:

$$\frac{\partial P}{\partial r} = \frac{\partial}{\partial z}\left(\mu \frac{\partial v_r}{\partial z}\right), \tag{1}$$

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