BOUNDARY LAYER SEPARATION ON A CIRCULAR CYLINDER IN A NON-NEWTONIAN ELASTICOVISCOUS FLUID FLOW

A. V. Luikov, Z. P. Shul'man, and B. I. Puris

Inzhenerno-Fizicheskii Zhurnal, Vol. 14, No. 1, pp. 17–28, 1968

UDC 532.517.2:532.135

The results of an experimental investigation on the separation of a non-Newtonian elasticoviscous fluid flow over a circular cylinder are reported. A new effect has been detected, namely, an unusually pronounced delay in separation due to the addition of polymers to the solution.

Introduction. The problem of the flow of non-Newtonian fluids has recently received considerable attention. This is because such fluids are complex systems with more general laws of hydrodynamics. Rheodynamic investigations are of practical importance for the chemical industry and the creation of new polymer materials. It should also be noted that the hydrodynamics of modern high-speed aircraft, should, strictly speaking, be based on the relations for rheological systems, since atmospheric air at altitudes above 9 km has shown rheological properties.

In most studies of purely viscous non-Newtonian fluids the so-called power law is used to characterize the internal friction stress. The analysis of such systems is based on Newton's law of internal friction with a correction, in the form of an empirical exponent n, introduced (modified Newton's law):

$$p_{ik} = -p_0 \delta_{ik} + k \left| \frac{1}{2} \dot{\varepsilon}_{mr} \dot{\varepsilon}_{rm} \right|^{\frac{n-1}{2}} \dot{\varepsilon}_{ik}. \qquad (1)$$

From the thermodynamics of irreversible processes we know that Newton's law of viscous flow corresponds to the region of validity of the linear Onsager relations.

One of the authors proposed [1] a generalized relation between the fluxes I_i and the thermodynamic forces X_k that is valid for fluid systems with different rheological models:

$$I_i = L_i^{(r)} \dot{I}_i + \sum_k (L_{ik} X_k + L_{ik}^{(r)} \dot{X}_k). \qquad (2)$$

From this relation, for example, it is possible to obtain the well-known Oldroyd formula [2], proposed for the description of a viscoelastic fluid with zero given stress ($L_i^{(r)} = -\tau_r$, $L_{ik}^{(r)} = \lambda_r$, $L_i = \eta$):

$$p_{ik} = \eta \dot{\varepsilon}_{ik} + \lambda_r \left(\frac{d\dot{\varepsilon}}{dt} \right)_{ik} - \tau_r \left(\frac{dp}{dt} \right)_{ik}. \qquad (3)$$

Here, p_{ik} and $\dot{\varepsilon}_{ik}$ are the deviators of the stress and strain rate tensors; η, λ_r, τ_r are constants of the material: η is the steady-state shear viscosity; λ_r is the delay period characterizing the rate of exponential decrease of shear on sudden removal of the shear stresses; τ_r is the stress relaxation period associated with the instantaneous cessation of shear flow. These constants are determined by the viscosity of the continuous phase, and the volume concentration and modulus of elasticity of the disperse phase. Rheological law (3), which is physically meaningful only if the inequality $\tau_r > \lambda_r \geq 0$ is satisfied, includes as a special case the classical model of a viscoelastic Maxwell liquid ($\lambda_r = 0$).

The essential difference between laws (1) and (3) is that in the former under the action of shear the rheological system displays a single fundamental property, i.e., it represents a purely viscous fluid with a modified Newton's law, while in the second the properties of a Newtonian fluid and an imperfectly elastic solid are combined (second and third terms on the right side of Eq. (3) which characterize the instantaneous and delayed elasticity).* From the rheological standpoint there are no fundamental distinctions between an elastic solid and a fluid; the difference consists in the values of the stress relaxation and elastic aftereffect periods. In the first case the shear stress relaxation period τ_r is extremely large, while in the second it is negligibly small on the usual time scale.

Constitutive equation (3) is confirmed by experimental data on the flow of structured systems such as emulsions, polymer solutions, and suspensions of elastic particles. The suspended elastic elements (droplets, flexible macromolecules, etc.) deform under the action of shear stresses and accumulate elastic strain energy. In accordance with [3], in the presence of a steady-state shear flow unequal normal stresses inevitably develop in the fluid (3). The nonzero differences of the normal stresses along and across the streamlines lead to the apperance of a Weissenberg effect [4].

Thus, Oldroyd's law explains, at least in first approximation, new physical effects which cannot be predicted on the basis of the classical Newtonian concept of viscosity. Model rheological systems satisfying (3) are easily obtained introducing polymer additives into a Newtonian liquid. In particular, we used as model liquid an aqueous solution of the sodium salt of carboxymethyl cellulose (Na-CMC). The elastic elements are formed by the polymer macromolecules with additional immobilization of the solution by "solvation" sheaths. The deformation of such an element in the presence of a velocity gradient is not in-

---

*If the coefficient of viscosity is large ($\eta \to \infty$), we obtain Hooke's law of elasticity $p_{ik} = G \varepsilon_{ik}$, since $\tau_r = \eta/G$, where G is the shear modulus. For further details see [1].

stantaneous since the macromolecule resists distortion. The time required to change the macromolecule configuration is determined by the relaxation period and depends on the dimensions, shape, and flexibility of the chain. The mechanical behavior of such a solution should, in principle, be described by such generalized relations as (2) and (3).

Kotaka et al. investigated the viscoelastic properties of Na-CMC solutions with a "parallel-disk" rotary instrument. Figure 1 presents the distribution curves for the rise of the liquid in vertical piezometers mounted along the radius of the stationary disk for a 1.97% (by weight) solution at 28° C. Even at relatively small shear rates on the order of 10 $\sec^{-1}$ the viscoelastic properties are very influential. For shear rates of 10^3 $\sec^{-1}$ the viscoelastic stress p_V becomes higher than the shear stress p_S. The data of Fig. 2, taken from [5], show that p_V and p_S increase more rapidly at lower Na-CMC concentrations.

Ernst [6] has recently noted that in turbulent flows of aqueous Na-CMC solutions in circular tubes at $\varepsilon = (0.5-3.5) \cdot 10^3$ $\sec^{-1}$ the viscoelastic properties are strongly manifested even at concentrations of 0.1%.

We have studied a new effect probably associated with the influence of the viscoelastic properties on the separation of the boundary layer from the surface of a circular cylinder in a flow.

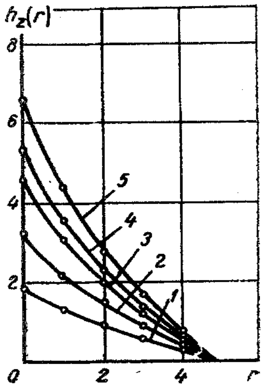

Fig. 1. Distribution of the liquid rise in vertical piezometers (cm) mounted along the radius of the stationary disk (cm) for a 1.97% (by weight) solution, as a function of shear rate: 1) 5.52 rpm; 2) 17; 3) 33.3; 4) 48; 5) 84.

History of the problem. Bluff bodies in the uniform flow of a Newtonian fluid at Re > 1 exhibit separation of the boundary layer. For an infinitely long circular cylinder Hiemenz [7] calculated the angular coordinate of the stationary position at the separation point: $\Theta_0 = 82°$ (Θ is the central angle reckoned from the forward stagnation point). Hiemenz used the measured pressure distribution on the contour of a cylinder placed in a uniform flow of water. The potential flow velocity derived from the Bernoulli equation accounts for the countereffect of the boundary layer and coincides closely with the theoretical law $U = 2U_\infty \sin\Theta$ up to $\Theta = 40°$. In accordance with experiment, Hiemenz's formula establishes a pressure minimum at a point with $\Theta = 70°$ instead of at $\Theta = 90°$ as required by the classical theory of an ideal fluid.

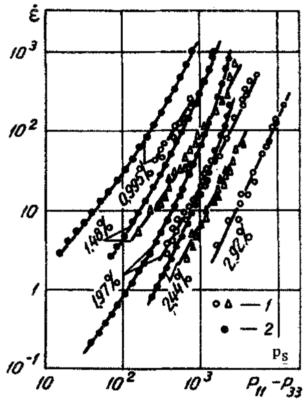

Fig. 2. Shear rates versus stress p_S and $p_{11} - p_{33}$ (dyne/cm^2): 1) normal stress 2) shear stress.

Subsequently, it was found that the separation point is conservative and does not depend on the Reynolds number, i.e., on the diameter of the cylinder d, the free-stream velocity U_∞, and the nature of the Newtonian fluid [8]. In later years numerous experiments also found that the central angle lay approximately between 80 and 90° irrespective of the Reynolds number. At about the same time [9] the Eiffel effect was experimentally detected. This is the sudden drop in the total drag coefficient of bluff bodies by a factor of 3–5 at Reynolds numbers of the order of 10^5. The Eiffel effect, which has been carefully studied on cylinders and spheres, is a phenomenon of a general character and may occur in association with separated flows over any surface. In the usual explanation, with an increase

Table 1

Basic Characteristics of Flow System

C, %	$\nu_{\text{eff. max}} \cdot 10^6$ m^2/sec	$(k/\rho)\,10^6$ m^2 n−2	n	Re_{eff}			
				$U_\infty = 0.45$, m/sec	$U_\infty = 0.318$, m/sec	$U_\infty = 0.153$, m/sec	$D \cdot 10^9$, m^2/sec
0	0.92	0.92	1	10663	7535	3625	1.01
0.5	3.98	5.124	0.96	2465	1742	838	1.9
1.0	13.96	28.057	0.88	703	497	239	1.75
1.5	38.28	95.04	0.83	256	181	87	1.44

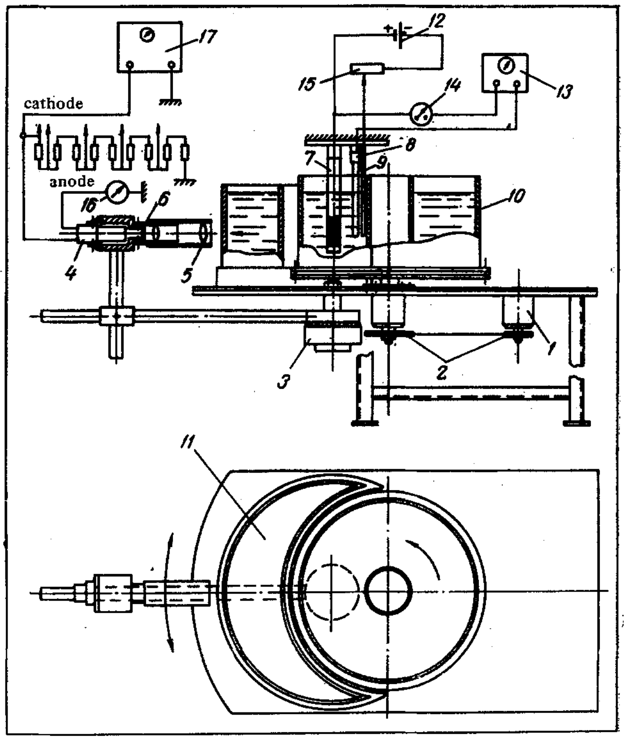

Fig. 3. Diagram of the experimental setup: 1) RD-09 electric motor; 2) pulleys; 3) traverse mechanism; 4) FEU-35 photomultiplier; 5) lenses; 6) slit; 7) anode; 8) calomel electrode; 9) cathode; 10) rotating chamber; 11) stationary tank; 12) dc source; 13) vacuum voltmeter; 14) milliammeter; 15) rheostat; 16) microammeter; 17) stabilized dc source.

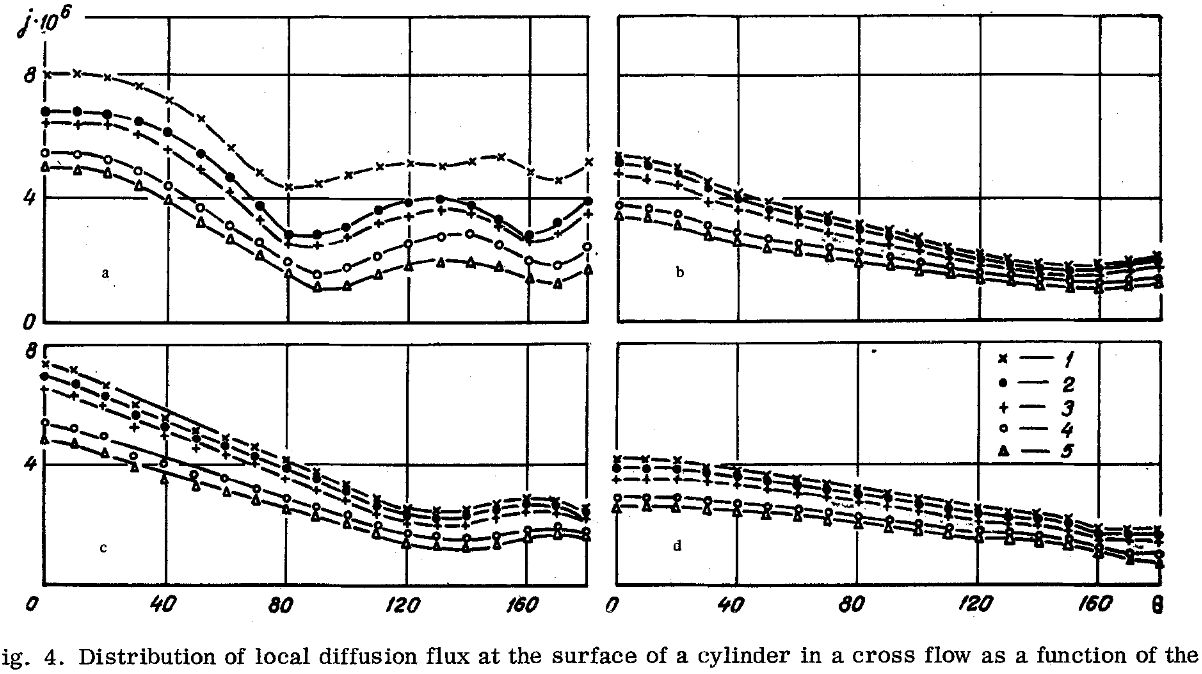

Fig. 4. Distribution of local diffusion flux at the surface of a cylinder in a cross flow as a function of the generalized Reynolds number: a) 1) Re = 10 550; 2) 9550; 3) 7450; 4) 4470; 5) 3580; C = 0%; b) 1) Re = = 2159; 2) 1935; 3) 1505; 4) 885; 5) 703; C = 0.5%; c) 1) Re = 504; 2) 448; 3) 342; 4) 193; 5) 151; C = 1%; d) 1) Re = 172; 2) 152; 3) 114; 4) 63; 5) 49; C = 1.5%.

in the Reynolds number and the degree of free stream turbulence the transition line in the separated laminar boundary layer gradually approaches the separation line and, finally, at some instant reaches the wall. In view of the intense molar momentum exchange in the turbulent boundary layer the retarded masses of fluid increase and separation is displaced downstream to a new, almost stationary position $\Theta_0 = 105^\circ$ [10]. As a result of the increased coverage of the cylinder contour the pressure losses (form drag) in the total drag balance are sharply reduced. Prandtl's special experiments on spheres [11] and those of Fage [10] on cylinders convincingly confirmed that the sharp fall in drag coefficient is associated with the rearward displacement of the separation line. By artificially creating turbulence on a bluff-body boundary layer it was possible to advance drag "crisis" and create flow conditions favorable from the standpoint of a reduction in hydrodynamic losses. On the other hand, laminarization of the boundary layer, which is so favorable for reducing friction drag on streamlined shapes, may lead, in the case of bodies characterized by flow separation, to the opposite result, i. e., to an increase in drag in the critical region.

For a long time a number of investigators studied methods of artificial laminarization of the boundary layer, primarily mechanical ones (injection, suction, concurrent motion of the wall, etc.).

In 1948 Toms [12] and I. T. El'perin [13] independently proposed adding polymers to water as a means of reducing turbulence in pipes and channels of the separationless type. We now have a considerable amount of experimental and theoretical information regarding the effect of polymer additives on friction drag. The most fundamental results have been obtained in the USSR by G. I. Barenblatt et al. [14, 15]. These authors have noted the possible effect of polymer additives on the separation position on circular cylinders in a cross flow. The work of this school combines effective hydrodynamic methods with a sensitive microphysical approach.

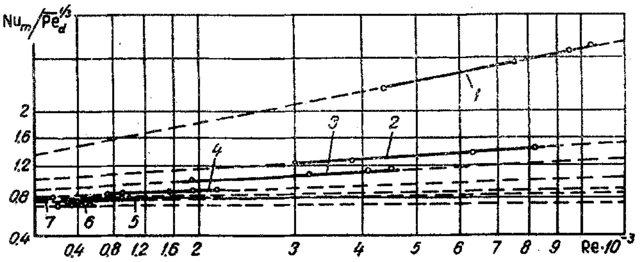

Fig. 5. Over-all mass transfer property as a function of the pseudoplasticity parameter: 1) C = 0; 2) 0.1; 3) 0.25; 4) 0.5; 5) 0.75; 6) 1.0; 7) 1.5.

Experimental method. So far the effect on the form drag of adding polymers to a low-molecular liquid has not been investigated. There are certain, purely qualitative, indications that in the case of an elongated body of revolution of the ogival type an advantage is to be gained only at very low polymer concentrations, an increase in concentration being accompanied by a sudden rise in the drag [16]. At the same time, the friction drag of a plate in a longitudinal flow falls continuously with increase in polymer concentration.

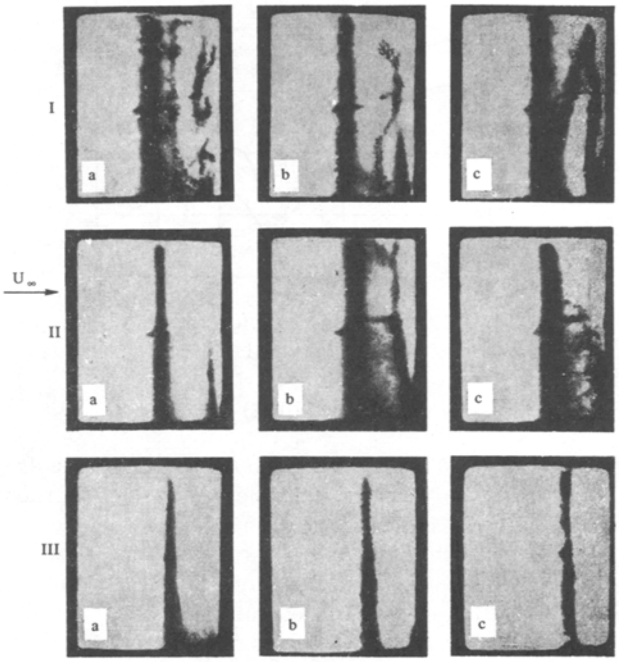

Fig. 6. Visualization of the transverse flow in an elasticoviscous pseudoplastic fluid over a circular cylinder: I) C = 0%, n = 1: a) Re_{eff} = 10 663; b) 7535; c) 3625; II) C = 0.5%, n = 0.96: a) Re_{eff} = 2465; b) 1742; c) 838; III) C = 1%, n = 0.88; a) Re_{eff} = = 703; b) 497; c) 239.

So far, only measurements of the integral drag characteristics by the gravimetric method or drag calculations using the actual pressure distribution over the flow contour have been done for cylinders and spheres in non-Newtonian high-molecular solutions. At the same time, many important physical aspects have gone unnoticed. In particular, the effect of polymers on the separation point and the boundary layer regimes of bluff bodies has not been explained. This question is fundamental in the hydrodynamics of viscous fluids.

We have conducted such experiments on cylinders placed in an aqueous solution of sodium-carboxymethyl cellulose with very small concentrations of electro-

Table 2

Parameters of Empirical Formula (5)

C, %	0	0.1	0.25	0.5	0.75	1.0	1.5
A	0.33	0.34	0.345	0.43	0.498	0.5	0.534
m	0.19	0.16	0.15	0.1	0.073	0.06	0.078

chemiluminescent substances (ECL). Na-CMC is a polyelectrolyte with a weakly alkaline reaction. The low-molecular ECL additives do not affect seriously the pH of the solution, nor did they cause any degradation of its mechanical properties [5].

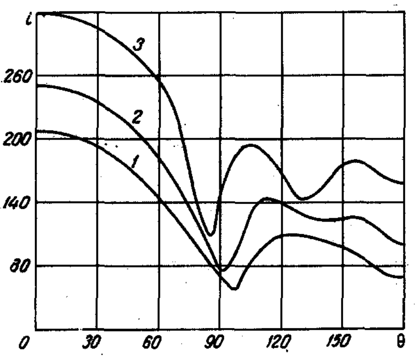

Fig. 7. Local mass transfer for a cylinder in a cross flow of Newtonian liquid (aqueous electrolyte) according to N. Pokryvailo's data: 1) $\mathrm{Re}_{\mathrm{eff}} = 240$; 2) 400; 3) 740.

The idea of the method [17] is as follows. If two stationary platinum electrodes are placed in a moving, weakly alkaline electrolyte containing H_2O_2 ions and luminol, a blue luminescence is observed at the anode. Its intensity at any point on the catalytic surface of the anode is strictly proportional to the local ionic current. At the same time, we obtain a sharp, highly contrasted visualization of the most important and interesting details of the hydrodynamics (separation length, transition region, wake) of the flow around the anode without introducing additional perturbations into it. A description of the electrochemical system is given in [17], where the separation on cylinders, cones, and inclined plates (angle of attack 3 and 13°) in a cross flow of a Newtonian fluid was investigated. There it was shown that electrochemiluminescence is excited in a region near the wall that is much thinner than the boundary layer (width of the order of several wavelengths of light), i. e., practically on the anode itself. The experiments were conducted at a certain interelectrode potential value, chosen to ensure the most favorable external circuit conditions for visual observation and photoelectric registration of the effect. Then the stationary ECL reaction takes place in the diffusion region. The limiting current regime is characterized by an almost zero concentration of H_2O_2 ions diffusing to the anode. The convective diffusion process ceases to depend on the kinetics of the electrochemical reaction, without affecting the hydrodynamics, since the transverse mass flux density is 10^{-7} kg/m^2 · sec.

The experimental setup (Fig. 3) consisted of a plexiglas vessel 10 in the form of a circular cylinder ($d_c = 350$ mm, $h_c = 150$ mm) rotated about a vertical axis by the continuous electric drive 1. The linear velocity of the fluid relative to the anode could be regulated in the range from 1 to 100 cm/sec. Anode 7, in the form of a platinum cylinder d = 21.8 mm, was placed in the solution at a distance from the walls calculated to exclude undesirable hydrodynamic interference effects and secondary unsimulated influences. Measurements showed a uniform velocity in the flow approaching the cylinder. Photomultiplier 4 registered the intensity of the luminescence on each part of the anode surface. By means of traverse arm mechanism 3 the entire optical system could be smoothly rotated about the axis of the cylindrical anode so that its luminescent surface always remained in the focal plane in the course of a continuous circuit. The photocurrent was measured with a sensitive microammeter. The experimental data were checked by integrating the local values of the photocurrent. In each experiment this integral should coincide with the total electronic current in the external circuit correct to the same constant multiplier determined by calibration (apparatus constant). The potential between the solution and the anode was measured with a standard saturated KCl-calomel electrode.

The experiments covered the range of Reynolds numbers $(0.2\text{–}10) \cdot 10^3$, and U_∞ was varied from 15 to 50 cm/sec. The polymer concentrations were C = = 0, 0.1, 0.25, 0.5, 0.75, 1, 1.5%. A certain increase in the light absorption of the solution with increase in concentration was taken into account. With the same apparatus the relation between the attenuation of the light and the polymer content of the solution was determined.

By means of a capillary viscometer we independently recorded the rheological flow curves of the investigated solutions in the shear rate range $(0.2\text{–}5.0) \cdot 10^3\ \mathrm{sec}^{-1}$, corresponding to the mass transfer experiments. The flow curves were described by a power equation. The rheological parameters of the solutions and the values of the diffusion coefficients are presented in Table 1.

Effect of polymer additives on the nature of the flow. Control experiments with a Newtonian ECL solution were conducted to determine the apparatus constant and to compare the data obtained with the classical results. The diffusion flux distributions at the surface of the cylinder for various Reynolds numbers are given in Fig. 4. Furthermore, the experimental data was compared with the well-known empirical formula of McAdams [18], which is widely used in calculating the total heat and mass transfer of cylinders in a cross flow:

$$\mathrm{Nu}_m = (0.35+0.56\ \mathrm{Re}^{0.52})\ \mathrm{Pr}_m^{\ 0.3}. \qquad (4)$$

The agreement (Fig. 5) proved to be good (within 1–2%).

The separation point for all Reynolds numbers was stable in the range $80 \leq \Theta_0 \leq 90°$. The same result was obtained visually (photos in Fig. 6). The curves in Fig. 4 are for solutions with Na-CMC additives. A new result was obtained—the separation line is displaced very sharply downstream almost to the rear stagnation point. Thus, for a 1% additive concentration the position of the separation line, determined visually (Fig. 6) and from the distribution of local j-fluxes (Fig. 4), lies on the generator with $\Theta_0 = 155°$. As the elasticoviscous and pseudoplastic properties of the solution are reinforced, the local diffusion flux curves gradually fall, becoming increasingly flatter.

The parabolicity of the $j = f(\Theta)$ curves on the forward surface, familiar in connection with Newtonian fluids, progressively degenerates into an almost linear dependence. Consequently, the cylindrical ECL-reaction surface gradually becomes more and more equally accessible for ion diffusion. There is a radical redistribution of the roles of the various factors controlling the diffusion process in the boundary layer. As a result, the dependence of Nu_m on Re gradually weakens (Table 2). The following expression is an acceptable correlation of the experimental data as a whole:

$$\mathrm{Nu}_m/\mathrm{Pe}_{md}^{1/3} = A\,\mathrm{Re}^m. \tag{5}$$

The observed effect cannot be attributed to an increase in ν_{eff} with increase in polymer concentration and a corresponding reduction of $\mathrm{Re}_{\mathrm{eff}}$. Experiments with a Newtonian solution were conducted in the range $\mathrm{Re}_{\mathrm{eff}} = 200-1000$. In this case the separation point did not go beyond the azimuth 110°. Similar results were obtained by N. Pokryvailo [19], who conducted his experiments by another method and with other Newtonian solutions (Fig. 7), and by Grassman [20], and others, using smooth and rough cylinders.

It is not yet possible to give a rigorous explanation of the new fact reported above. However, a possible explanation may be based on the mechanisms of viscoelastic behavior of non-Newtonian solutions.

In the preseparation region, where the shear rates are low, the mechanism of pseudoplasticity should manifest more weakly than the viscoelastic one. Here, the elastic energy accumulated in the preceding sections of the layer is gradually liberated and leads to a redistribution of momentum in the flow. Owing to this "additional" elastic aftereffect momentum the fluid particles may move further downstream against the positive longitudinal pressure drop. An important part in the prolongation of the boundary layer may be played by the increased (as compared with the lateral and transverse) Weissenberg stress along the streamlines. Then the layer, as it were, presses itself against the cylindrical surface. Finally, it is possible to introduce Oldrody's boundary effect hypothesis [21], based on the concept of effective adhesion.

Thus, an analysis of the experimental data obtained reveals the following:

1) A new effect has been observed, namely, a marked delay in separation of the boundary layer on the cylinder and displacement of the separation line far beyond the midsection at relatively low polymer concentrations in the Newtonian solution.

2) The position of the separation line of the laminar boundary layer of a pseudoplastic viscoelastic fluid depends on the free-stream velocity and is shifted downstream somewhat as the velocity falls.

3) With increase in polymer concentration there is a marked change in the intensity and character of the eddy motions near the surface of the cylinder beyond the separation line. Powerful smoothing, first of the small-scale, then of the large-scale eddy structure is observed and the flow becomes less and less disturbed.

4) The laws of convective mass transfer have been quantitatively investigated on bluff bodies in a non-Newtonian elasticoviscous and pseudoplastic fluid flow. The effect of polymer additives on the diffusion mass transfer has been studied.

We are grateful to the Director of the Thermoaerodynamics Laboratories, Corresponding Member of the Academy of Sciences Belorussian SSR B. M. Smol'skii for helping to organize this research.

NOTATION

p_0 is the isotropic pressure component; ρ is the density; $\eta_{\mathrm{eff}} = k|\dot{\varepsilon}_{mr}\dot{\varepsilon}_{rm}/2|^{(n-1)/2}$ is the effective viscosity in the modified Newton's law (1); ε_0 is the shear strain; $\dot{\varepsilon}$ is the shear rate; k is the consistency coefficient in (1); L_i and L_{ik} are the phenomenological coefficients in (2); n is the non-Newtonian behavior exponent in (1); δ_{ik} is the "unit" tensor, Kronecker delta; $U(\Theta)$ is the local value of velocity at the outer edge of the boundary layer; d_c and h_c are the diameter and height of rotating cylindrical vessel; d is the diameter of cylindrical anode; C is the concentration of polymer solution in bulk phase; $j(\Theta)$ is the local value of diffusion flux; D is the molecular diffusion coefficient; $\mathrm{Re}_{\mathrm{eff}} = U_\infty d/\nu_{\mathrm{eff}}$ is the effective Reynolds number; $\mathrm{Re} = U_\infty^{2-n} d^n/k/\rho$ is the generalized Reynolds number; $\mathrm{Pr}_m = \nu_{\mathrm{eff}}/D$ is the Prandtl number; $\overline{\mathrm{Nu}}_m = \overline{j}d/c_\infty D$ is the (mass transfer) Nusselt number averaged over the surface; $\mathrm{Pe}_{md} = U_\infty d/D$ is the (mass transfer) Peclet number.

REFERENCES

1. A. V. Luikov, IFZh [Journal of Engineering Physics], 9, no. 3, 1965.
2. J. G. Oldroyd, Proceed. Roy Soc., Lond., **A202**, 345, 1950; **A218**, 172, 1953.
3. J. G. Oldroyd, Rheology, **1**, New York, 1956.
4. K. Weissenberg, Proceed. 1-st Intern. Rheol. Congr. Amsterdam, 1948.
5. T. Kotaka, M. Kurata, and M. Tamura, Journ. of Appl. Physics, **30**, no. 11, 1959.
6. W. Ernst, AAIA Journ., **5**, no. 5, 1967.
7. Hiemenz, Dissertation, Göttingen, 1911, Dinglers Polytechn. Journ., **326**, 321–324, 1911.
8. S. Goldstein (editor), Modern Developments in Fluid Dynamics, Vol. 1 [Russian translation], Gosinlitizdat, Moscow, 1948.
9. Eiffel, Comptes Rendus de l'Ac. des Sciences, **155**, 1597–1599, 1912.
10. L. G. Loitsyanskii, Mechanics of Fluids and Gases [in Russian], GITTL, Moscow, 1957.
11. L. Prandtl, Gottingen Nachrichten, s. 177–190, 1914, Journ. Roy. Aero. Soc., 31, 730, 1927.
12. B. A. Toms, Proceed. 1-st Intern. Rheol. Congr., 135–141, 1948.
13. I. T. El'perin, USSR patent no. 169955 with priority from 6 December 1954. Of Byul. Kom. Izobr, i Otkr. pri Sov. Min. SSSR, no. 7, 1965.
14. G. I. Barenblatt, I. G. Bulina, and V. P. Myasnikov, PMTF [Journal of Applied Mechanics and Technical Physics], no. 3, 1965.
15. G. I. Barenblatt, I. G. Bulina, Ya. B. Zel'dovich, V. N. Kalashinkov, and G. I. Sholomovich,

PMTF [Journal of Applied Mechanics and Technical Physics], no. 5, 1965.

16. E. W. Merril, K. A. Smith, and R. Y. C. Chung, AIChE Journ., 12, no. 4, 809, 1966.
17. B. Howland, G. S. Springer, and M. G. Hill, Journ. Fluid Mech., 24, part 4, 697–704, 1966.
18. W. H. McAdams, Heat Transmission [Russian translation], Metallurgizdat, 356, 1961.
19. N. A. Pokryvailo, Author's abstract of Candidate's dissertation, Minsk, 1967.
20. P. J. Grassman, Trüb. Chem. Ing. Techn., no. 8, 529, 1961.
21. J. G. Oldroyd, Proceed. 1-st Intern. Rheol. Cong. Scheveningen, part II, 130, 1949.

12 June 1967

Institute of Heat- and Mass-Transfer
AS BSSR, Minsk