QUESTION OF THE EFFECTS OF POLYMER ADDITIVES

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The possible mechanism for drag reduction is discussed on the basis of an analysis of experimental data on the influence of polymer additives on heat and mass transfer and rheodynamics.

As is known, small quantities of certain polymers dissolved in a liquid are capable of altering the nature of the turbulent flow substantially. The friction drag is here reduced noticeably even at concentrations on the order of several millionths [1]. Not only near-wall turbulent flows, but also jets and rotational flows exhibit such behavior. The diversity of the manifestation of this effect is associated with the physicochemical peculiarities of polymer solution structure.

According to the data in [2-7], polymer molecules in solution can form a structure of the aggregate or associate type. A powdery polymer particle consists of a large number of packs. On falling into water the particle gradually dissociates into the original packs, which immobilize the water and are transformed into active associates. Under further dissolution, the associates dissociate into separate macromolecules [2]. The process of dissociation into structural packs and molecular aggregates occurs more rapidly upon plastification of the polymer by glycerine, for example.

It is shown in [5] that a change in the hydrodynamic efficiency of a polymer in time depends on the structural rearrangement of the macromolecules in the solution, as is verified by light-scattering measurements performed after different time intervals, starting with the time of preparation of the solution. The maximum dimension of the formation after 3 h of holding the solution was 2.8 μm. The presence of polyoxyethylene particles containing several thousand molecules in the solution is confirmed in [6].

Results of microscopic observations of solutions of a sodium salt of carboxymethyl cellulose (Na—CMC) in water are presented in [7] which directly verify the presence of supermolecular formations therein. A polarization microscope was used for the microscopic investigations. Observations were performed for both an immobile solution and during its flow along a capillary. The transverse dimension of the formation is 50-200 μm, while the longitudinal dimension reaches 1000 μm in some formations.

At present there is no single viewpoint about the crux of the drag reduction effect by polymer additives. The most widespread viewpoint is that hydraulic drag reduction is associated with attenuation (quenching, suppression) of turbulence. According to other observations, polymer additives in the form of particles in dilute suspensions or in gas suspensions either do not at all influence turbulence energy significantly [8-10], or even magnify it [11-13] for a noticeable reduction in drag. A qualitative analogy can be mentioned, which is that the nature of the flow of polymer solutions at low Reynolds numbers is mightily identical to the nature of the flow of a "pure" fluid at high Re (a fuller velocity profile, thinning of the boundary layer, reduction of the friction drag coefficient, pulling separation on poorly streamlined bodies, etc.). Let us examine this question in greater detail.

In our opinion, elongated particles or macromolecules can produce perturbations in flows with Reynolds number very much less than Re_{cr} for a pure medium. The magnitude of Re_{cr} for a solution turns out to depend not only on the flow characteristics but also on the molecule size and configuration and on microstructural formations of associate type. This is verified by the authors' data on the mass transfer of a longitudinally streamlined plate for different concentrations of the non-Newtonian additive (Na—CMC). The method of investigation is

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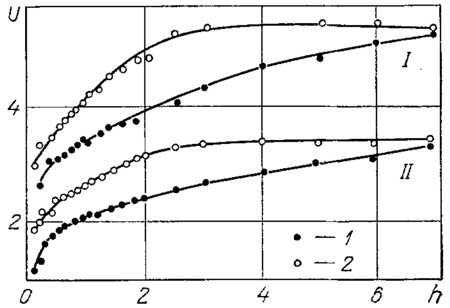

Fig. 1. Velocity profiles in the boundary layer of a body of revolution with ∅35 mm and length 700 mm at the x = 550 mm section for polyoxyethylene solutions: I) U = 5.3 m/sec; II) U = 3.45 m/sec; 1) C = 0; 2) $C = 5 \cdot 10^{-5}$.

described in [14]. The transition from the laminar to the turbulent mode of mass transfer is established by the mass flux distribution on the wall, and the magnitude of Re_{cr} is here reduced to 325. Analogous results are also obtained in [15-20].

Measurement data on the hydrodynamic friction of water with slight polymer additives of polyoxyethylene, guarana tar, and Na–CMC are presented in [15, 17, 20]. By using an induction pressure sensor, the origin of turbulence was determined. The first notable pulsations for the polyoxyethylene solution with 10^{-5} concentration were clearly recorded for Re = 1350, while they were at $Re_{cr} = 1200$ for Na–CMC in a 0.75% concentration, where the flow crisis was determined by two independent methods: by the spreading of a colored jet and by the break in the curve of the dependence of the pressure drop on the discharge.

Velocity profiles measured by using a Doppler laser anemometer in the boundary layer of a longitudinally streamlined body of revolution of 35-mm diameter and 700-mm length are represented in Fig. 1. The polymer additives noticeably influence the velocity distribution and produce the filled profile characteristic for turbulent flow.

The "drag crisis" is well known for poorly streamlined bodies, i.e., the sharp reduction in the total drag coefficient upon achieving Reynolds numbers on the order of 10^5. This phenomenon, which has been studied carefully in cylinders and spheres, is general in nature, and can occur for any separation flows. Its standard interpretation is based on the fact that as the Reynolds number or degree of turbulence of the free stream grow, the transition point in the boundary layer will gradually approach the line of separation and, finally, turns out on the wall. Then because of a more intensive molar transfer, entrainment of fluid masses decelerated by counterpressure occurs by a pulse in the now already turbulent boundary layer, and the separation is shifted downstream. Earlier onset of the drag crisis is evoked successfully by artificial turbulization of the flows around poorly streamlined bodies. Turbulence noticeably reduces the drag coefficient because of the displacement of the line of stream separation in the root part and the restoration of the pressure on the rear surface of the body.

Mass transfer in transverse non-Newtonian fluid flow around a cylinder and drag of a sphere (Figs. 2-4) are accompanied by new effects.

The minimum on the distribution curve for the mass fluxes along the streamlined cylinder surface is shifted from an 83° azimuth to 135° [21]. Intensification is observed of the local (Fig. 2) and total (Fig. 3) cylinder mass transfer. The maximum drag reduction was achieved in tests with spheres (Fig. 4) in polyox solutions of 0.0075% concentration and was about 50% for the numbers Re = 10^4-10^5. The additional introduction of Na–CMC in this solution in quantities 0.01-1.5% yielded a noticeable reduction in the drag coefficient in a broader range of numbers Re (10^2-10^5). The investigations were performed by the method described in [21, 22].

By analogy with the flow around an axisymmetric body, estimates of the boundary-layer thickness in the flow around plates show that the boundary-layer thickness diminishes to approximately half at a 3-m/sec velocity at the section X = 550 mm, for example. Then a free stream velocity on the order of 100 m/sec would be required to obtain a velocity profile for

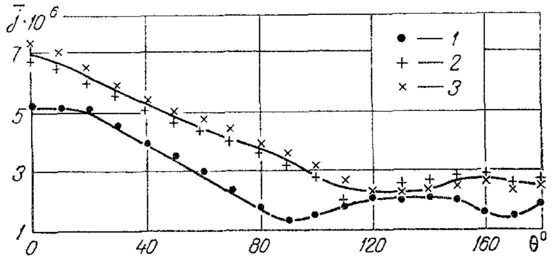

Fig. 2. Distribution of local diffusion flows on the surface of a transversely streamlined cylinder: 1) C = 0%; Re = 3580; 2) C = 0.1% Na-CMC; Re = 3790; 3) C = 0.5% Na-CMC; Re = 2160.

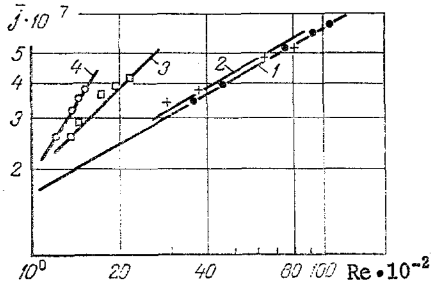

Fig. 3

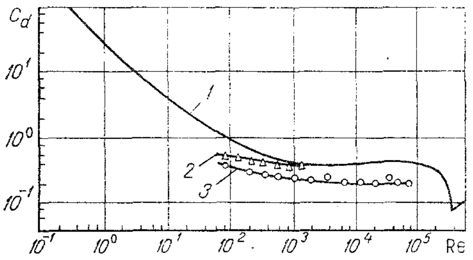

Fig. 4

Fig. 3. Total mass transfer characteristics of a transversely streamlined cylinder as a function of the pseudoplasticity parameter: 1) C = 0%; 2) C = 0.1% Na-CMC; 3) C = 0.5% Na-CMC; 4) C = 0.75% Na-CMC.

Fig. 4. Dependence of the sphere drag coefficient on the Reynolds number for polymer solutions of different concentrations: 1) C = 0; 2) C = 10^{-2}-1.5% Na-CMC; 3) C = 0.0075% WRS-301 + 10^{-2}-1.5% Na-CMC.

a water flow similar to that observed in the polymer solutions. In the case of flow around a cylinder this would correspond to Reynolds numbers of 10^5-10^6 and a domain of flow crisis, boundary-layer turbulization, to abrupt drag reduction and pulling of separation.

The analogy noted above seems paradoxical at first glance since turbulent flows of both dilute solutions and of homogeneous fluids can be considered physically as flows containing large-scale regular structures in the general case.

The polymer additives probably produce a definite transformation of the large-scale structures localized in a thin domain near the solid wall, where the transformation is such that it will contribute to diminution of the hydrodynamic drag of the bodies. This is indicated by the significant increase in the longitudinal and transverse velocity pulsations in the Na-CMC solutions during the flow around a sphere (Fig. 5), the intensification of heat and mass transfer [23] at the numbers Re = $(0.3\text{-}4)\cdot 10^3$ (see Figs. 3 and 4), and also the high-speed moving pictures of artificial caverns in a WSR-301 polyox solution of concentration 0.05% and in water during flow around a d = 12 mm disk at a velocity $u \approx 20$ m/sec, $\lambda = 0.12$.

The cavern surface is not smooth, but has the form of a periodic structure with a 2-3-mm wavelength in the case of pure water, and a 6-9-kHz frequency. Polyox additives noticeably alter the cavern boundary and the size and nature of its closure. The cavern is elongated, the wavelength grows to 4-5 mm, and the frequency is reduced to 4-5 kHz. Results of investigations on the stability of coherent structures on the boundary of an artificial cavern are in good agreement with the data in [24] on an investigation of the vortex street in the turbulent wake behind a cylinder.

The general considerations we expressed are confirmed by measurements of the drag, the pressure distribution, the velocity pulsations, and the pressure at the surface of a trans-

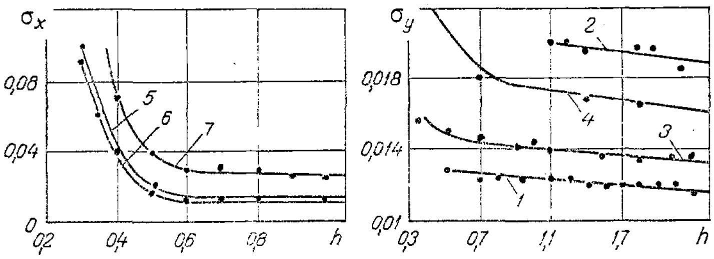

Fig. 5. Rms values of the longitudinal and transverse velocity pulsations in the flow around a sphere at a point located at a 45° angle: 1) C = 0; 2) C = 0.05% Na-CMC; 3) C = 0.01% polyoxyethylene; 4) C = 0.02% Na-CMC; 5) C = 0; 6) C = 0.01% polyoxyethylene; 7) C = 0.05% Na-CMC.

versely streamlined circular cylinder and in the root region [25]. The influence of polymer degradation was studied, i.e., the microstructural reduction on the drag, separation, wake width, and amplitude—frequency characteristics of the pulsation field. Moreover, suspensions of equally dense spherical and rodlike particles (with elongation to 100) were used. It is shown that all the new phenomena detected are determined mainly by the particle geometry and size.

It follows from the results of [25] that a polymer subjected to degradation will evoke an earlier onset of the drag crisis, will magnify velocity and pressure pulsations in the separation domain, i.e., lower Re_{cr}, which correlates well with our investigations and results [26], where it is shown that the drag crisis of a cylinder sets in for numbers Re ≈ 100 in Na—CMC solutions, i.e., a polymer of low molecular weight.

Therefore, the nature of the influence of polymer additives on the heat and mass transfer, turbulence, drag, etc. depends substantially on the kind of polymer, its molecular weight, and the structure of the solution, i.e., as can be assumed, on the dynamic stability and form of coherent large-scale structures transformed by the polymer additives.

NOTATION

C, solution concentration; j, local value of the diffusion flux, $kg/m^2 \cdot sec$; $Re_{cr} = UX_{cr}/\nu$, critical Reynolds number; U, free stream velocity, m/sec; $Re = U^{2-n}d^n/k/\rho$, generalized Reynolds number; d, cylinder diameter, mm; k, consistency index; n, index of non-Newtonian behavior; σ_x, σ_y, rms values of longitudinal and transverse velocity component pulsations; h, distance from the sphere surface, mm; λ, cavitation number.

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