EFFECT OF POLYMER ADDITIVES ON THE LARGE-SCALE STRUCTURE OF THE VELOCITY FIELD IN THE BOUNDARY REGION OF A SPHERE

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An experimental study was made of the effect of polymer additives of different molecular weight on certain characteristics of the velocity field in liquid flow about a sphere.

It is believed [1-7] that polymer additives stabilize flow in the boundary region and thereby reduce drag. On the other hand, results presented in [8] indicate that polymer additives have a destabilizing effect. It was noted in [9] that polymer additives stabilize flow only directly at the wall, destabilizing flow in the rest of the region. The results in [10-12] indicate an increase in the turbulence energy level in the presence of polymer additives, leading to a marked reduction in drag. Similar results were obtained in [13] in measuring the structure of turbulent submerged jets. In [12], a dehydrated solution of polyoxyethylene, by intensifying pulsations of velocity and pressure in the separation region, resulted in an earlier attainment of critical drag, i.e., a reduction in Re_{cr}.

It is known that the angle of the separation line reckoned from the forward critical point $\Theta_{sep} = 81°$ for a circular cylinder [14]. The introduction of Na–carboxymethylcellulose into a liquid flowing transversely about a cylinder leads to critical drag at very low Reynolds numbers (of the order of 10^2) and displacement of the separation line into the after region [15] up to $\Theta_{sep} = 135°$. As already noted, velocity and pressure pulsations increase in this case.

Thus, the available empirical data indicate that the character of the effect of polymer additives on the processes of heat exchange and drag and the structure of the turbulence depends substantially on the type of polymer, its molecular weight, and the structure of the solution. However, the data do not make it possible to unambiguously connect a reduction in drag with flow stabilization accompanying the introduction of polymer additives. In this regard, it is of considerable interest to investigate the effect of different polymer additives on the average and fluctuation velocities and, in particular, on the transformation of large-scale regular structures of the flow field.

Shown below are the results of visual observations of measurements made with a laser anemometer of certain statistical characteristics of the velocity fields in the boundary region in the flow of water, a solution of polyoxyethylene, and Na–carboxymethylcellulose about a sphere. The tests with the polymers were done both by dissolving the additives over time throughout the entire volume and by supplying prepared solutions through a smooth slit 0.6 mm wide. Figure 1 shows the working body, a sphere 35 mm in diameter. The concentration of the polyoxyethylene solution was 10^{-4}–$2\cdot10^{-5}$ in studying the entire volume and $5\cdot10^{-4}$–$5\cdot10^{-5}$ in the case of delivery of the solution through the slit. The concentration of the Na–CMC solution was $3\cdot10^{-3}$ in the case of injection (through the slit) and $5\cdot10^{-4}$–$2\cdot10^{-4}$ in the other case.

The tests were conducted in a closed-type hydrodynamic channel of 3500 liters capacity at flow rates of 1.4–3 m/sec. A uniform velocity profile in most of the cross section of the working channel was ensured by guide blades, located at the inlet to the working part of the system, and a 50-fold constriction. The channel cross section was 150×200 mm. The laser, an optical system, and a DISA55L-type LDA photomultiplier were located near the transparent side windows of the channel on a coordinate table. Located above the channel was a device

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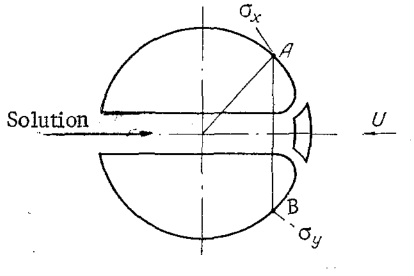

Fig. 1

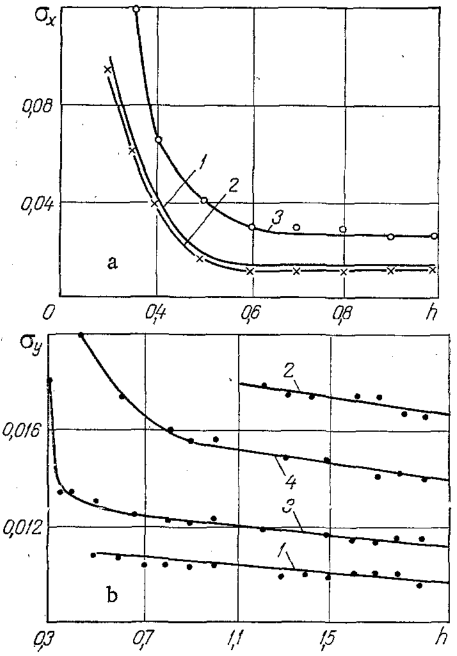

Fig. 2

Fig. 1. Schematic diagram of the working body and the measured characteristics.

Fig. 2. Profiles of rms pulsations: a) longitudinal (1—water; 2—POE, C = 0.01%; 3—Na—CMC, C = 0.02%) and b) transverse component of velocity at $\alpha = 45°$, U = 1.14 m/sec (1—water; 2—Na—CMC, C = 0.05%; 3—POE, C = 0.01%; 4—Na—CMC, C = 0.02%).

for installing the models; it was designed to move the top cover of channel, along with the hydrodynamic balance and test body secured to the cover.

We used the standard measurement procedure contained in the instructions for the measuring apparatus to obtain two components of the velocity of the turbulent flow. In accordance with this method, it is sufficient to perform three measurements at each point, rotating the plane of the probing beams through three fixed values of the angle α. The accuracy of the measurements of σ_x was improved by positioning the beams in a plane tangent to the sphere at point A. We measured the magnitude of the transverse pulsation σ_y without measuring the positioning angle when we moved the beams to point B. The visual observations in the boundary region of the sphere were made as polymer solution was fed into the boundary layer. About 1% milk was added to the solution as a dye. The observations of the structure of the boundary layer were made in controlled light, here using a stroboscope specially developed by the Institute of Heat and Mass Transfer (Academy of Sciences of the Belorussian SSR) for this purpose. For photographing, bias lighting was supplied both from a constant light source and from a flashing light with pulses of 10^{-4} sec, illuminating only the middle plane of the model. The photographs were taken at a speed of $4 \cdot 10^3$ frames/sec, making it possible to clearly observe the development of structures in the boundary layer.

Figure 2a, b shows the results of measurements of the distribution of rms values of transverse and longitudinal velocity pulsations through the thickness of the boundary layer. These results were obtained for the whole volume, and they pertain to one rate of flow over the body. We see an increase in the level of the pulsations both in the longitudinal and transverse components of velocity in the Na—CMC solutions. At the same time, the level of the longitudinal pulsations shows almost no change in the polyoxyethylene solutions at Re = $4 \cdot 10^{-4}$, while the transverse pulsations increase by 20%. Here, it is interesting to note that an increase in the Reynolds number to $1.3 \cdot 10^5$ is accompanied by a 50% increase in the level of longitudinal pulsations in the polyoxyethylene solutions compared to the pulsation level in the flow of the pure liquid about the body. Similar results were obtained when the polymer solutions were fed into the boundary layer.

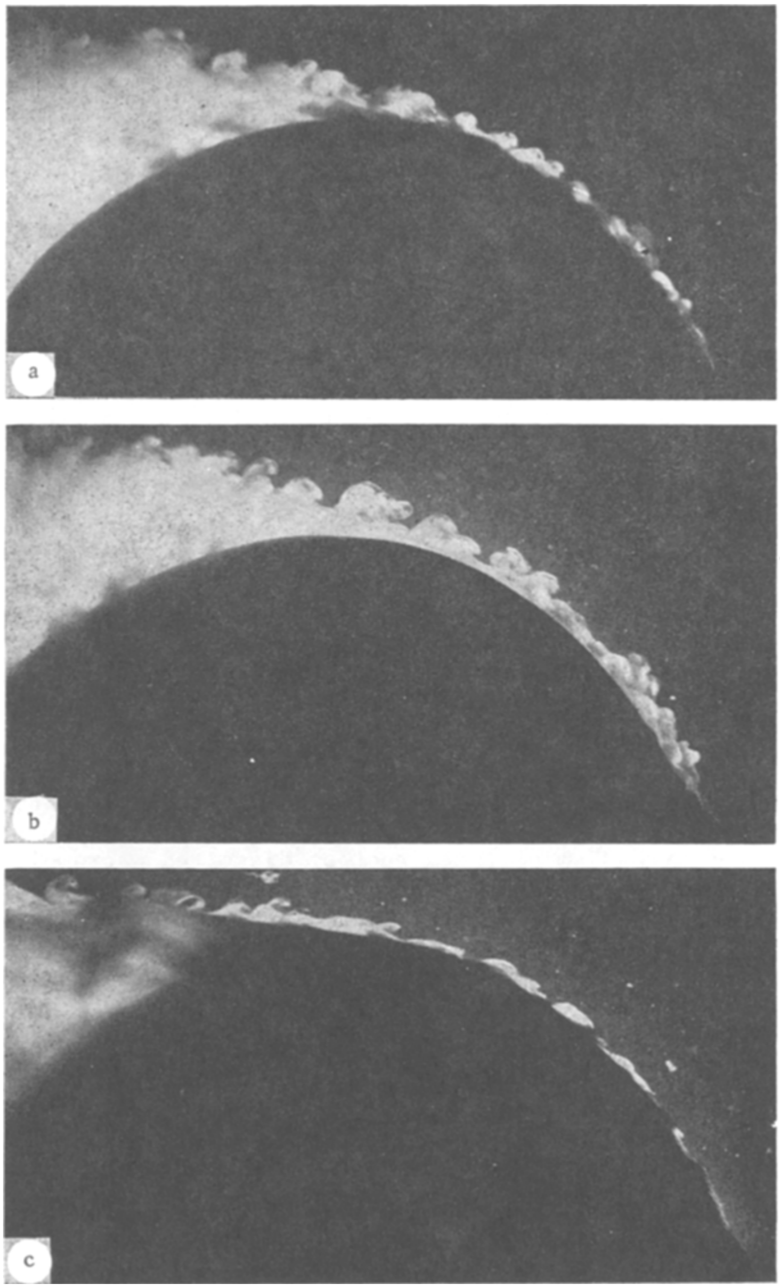

Fig. 3. Visualization of flow in boundary region in flow about a sphere (Re = $4 \cdot 10^4$) with injection of: a) water into water; b) Na–CMC (C = 0.3%) into water; c) POE (C = 0.002%) into a POE solution of the same concentration. Injection rate 0.3 m/sec, U = 1.14 m/sec. Scale 6:1.

Visual observations of the boundary layer of the sphere show that physically turbulent flows of solutions and homogeneous liquids may generally be regarded as flows containing regular large-scale structures (Fig. 3a-c) with roughly circular cross sections in a vertical plane parallel to U in the case of a pure liquid. In the case of flow of the Na–CMC solution about a body, the regular eddies become larger but retain their shape. In the case of the polyoxyethylene solution, the eddies are transformed into an ellipse with a major axis oriented in the flow direction. This is evidently connected with the capacity of polyoxyethylene to form fibers oriented in the flow direction and acting to impede the development of lateral transport. At first glance, this seems to contradict the above-noted increase in the intensity of the velocity pulsations. However, if we keep in mind that the addition of polymers leads (as a result of deformation of macromolecules) to an increase in effective viscosity only in the outer part of the boundary layer [16] — leaving the layer unchanged in the viscous sublayer — it becomes clear that the eddies in the outer part of the layer increase in size simultaneously with a cancellation of Reynolds stresses. Cancellation of Reynolds stresses, in turn, leads to displacement of the point at which there is a change in the slope of the average velocity upward from the wall. This results in a thickening of the viscous sublayer and a reduction in the drag associated with the body. The enlargement of the viscous sublayer leads to an increase in the scale of the eddies in the sublayer, which leads to an increase in velocity pulsations. Here, the small-scale pulsations which "feed" Reynolds stresses are suppressed. This means that turbulence in the viscous sublayer consists mainly of pulsations of the flow as a whole [17], so we should expect that σ_x/U = const, as was observed in our tests.

The completed studies established the presence of a certain connection between the transformation of regular structures and the introduction of polymer additives, leading to a substantial reduction in drag associated with submerged bodies. The presence of such a connection indicates that the drag of the body might possibly be controlled by controlling the large-scale structures.

NOTATION

U, velocity of incoming flow; d, diameter of sphere; ν, kinematic viscosity; Re_{cr}, critical Reynolds number; $Re = dU/\nu$, Reynolds number based on the diameter of the sphere; σ_x, σ_y, rms values of pulsations of longitudinal and transverse components of velocity; C, concentration of polymer solution; h, distance from wall, mm.

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