HOT-WIRE ANEMOMETER STUDY OF THE STRUCTURE OF POLYMER SOLUTIONS

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When added to a turbulent liquid certain soluble high-molecular polymers are capable of sharply reducing the drag [1, 2]. This effect is evidently associated with the formation in the solutions of large associations of polymer macromolecules and solvent molecules, which behave as rigid particles in relation to the high-frequency turbulent fluctuations [3-5].

These particles occur in different ways, either by the swelling of dry particles of powdered polymer or as a result of the disruption of the continuous network formed by the macromolecules after the polymer dissolves. A network is observed in connection with such polymers as polyoxyethylene; guar gum, on the other hand, does not form a continuous network.

The presence of particles in the solution leads to a screening of Pitot tubes, consisting in a lowering of their readings when their diameter is comparable with the particle diameter [5, 6]. There are reports of anomalous readings obtained from hot-film anemometers in polymer solutions [6, 7].

Experiments have shown that the hot-body anemometer can be successfully used as an association indicator in weak polymer solutions. In the experiments we used a constant-temperature anemometer made by DISA Electronik with wire and film probes. We investigated solutions of polyoxyethylene with a molecular weight of $4 \cdot 10^6$. The probe was mounted in the potential pore of the stream flowing from a cylindrical nozzle 4mm in diameter; the thermostat pump was used to pump the test liquid through the nozzle along a straight tube 10 mm in diameter and 150 diameters long. The liquid circulated through a closed loop. The experiments were conducted at a constant temperature of 20° C. The jet exit velocity was varied from 0.17 to 2 m/sec and monitored. with a piezometer introduced in front of the nozzle. The anemometer output signal was recorded on a N102 oscillograph with a N135-06 galvanometer (effective frequency band 0-600 Hz).

The oscillograms in Fig. 1 represent the output signal of the anemometer obtained at a nozzle exit velocity of 2 m/sec, which corresponds to a Reynolds number of 3200 in the supply tube. Oscillogram 1 was obtained for pure water. The addition of solid particles (aluminum powder) leads to impacts against the sensitive element of the probe, which were registered on oscillogram 2. The next traces were obtained for a polyoxyethylene solution with a concentration of $3 \cdot 10^{-5}$ by weight. Oscillogram 3 was obtained 30 sec after the jet began to flow. This curve is not very different from oscillogram 1, since at that point the polyoxyethylene solution was in the elastic phase. However, during the flow process the network is broken up into individual associations, which disturb the velocity field near the probe. These disturbances increase for a certain time and then decrease as the associations are reduced in size. The growth of the disturbances is observed in oscillograms 4, 5, 6, 7, and 8 recorded 2, 4, 6, 10, and 16 min, respectively, after the solution began to flow. Then the disturbances decrease, as indicated by oscillograms 9, 10, and 11 recorded after 60, 180, and 240 min, respectively. During all this time the frequency of the fluctuations is observed to increase. Disturbances are almost absent from oscillogram 12 recorded 540 min after flow began. The rms fluctuations σ (mV) at various times t (min) were as follows:

t = 0.5	2	4	6	10	16	60	180	240	540	Water
σ = 19	13.5	19	21	28	30	20	14	13	11	9.3

There is a good correlation between our data and those published in [5].

The oscillograms in Fig. 1 were obtained for a turbulent flow in the supply tube. As soon as the Reynolds number in that tube fell below a critical value, the fluctuations almost completely disappeared from the oscillograms. Disappearance of the fluctuations can be achieved by establishing a laminar flow regime in the supply tube either by reducing the flow velocity or by replacing the tube with a tube of larger diameter (in our case 44 mm) while retaining the same nozzle exit velocity and nozzle diameter. The explanation may be that in the laminar flow and hence in the laminar core of the jet the associations, which are evidently long, flexible, threadlike structures moving along the streamlines, flow over the probe almost without disturbing the velocity field around it. Only occasional associations that have somehow lost their orientation along the streamlines touch the sensitive element of the probe, which is registered as individual blips on the oscillogram.

In the case of turbulent flow in the supply tube and the potential core of the jet the orientation of the associations under the influence of the turbulent eddies may be quite arbitrary; irregular knots and tangles of associations may be formed. For this reason and owing to the transverse velocity fluctuations, a smooth flow over the probe is excluded. The associations strike the sensitive element of the probe and disturb the velocity field around it, which is registered by the anemometer.

It was observed that in the case of a turbulent flow in the supply tube the probe, whose sensitive element was a platinum wire 5 μ in diameter, broke down after not more than 2-3 min of operation. At the same time, in the case of a laminar flow (in both cases the nozzle

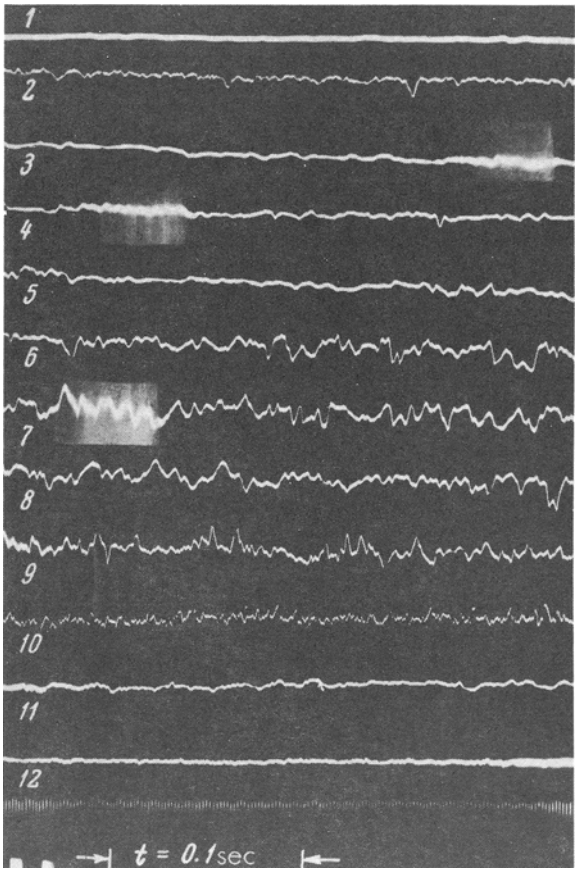

Fig. 1

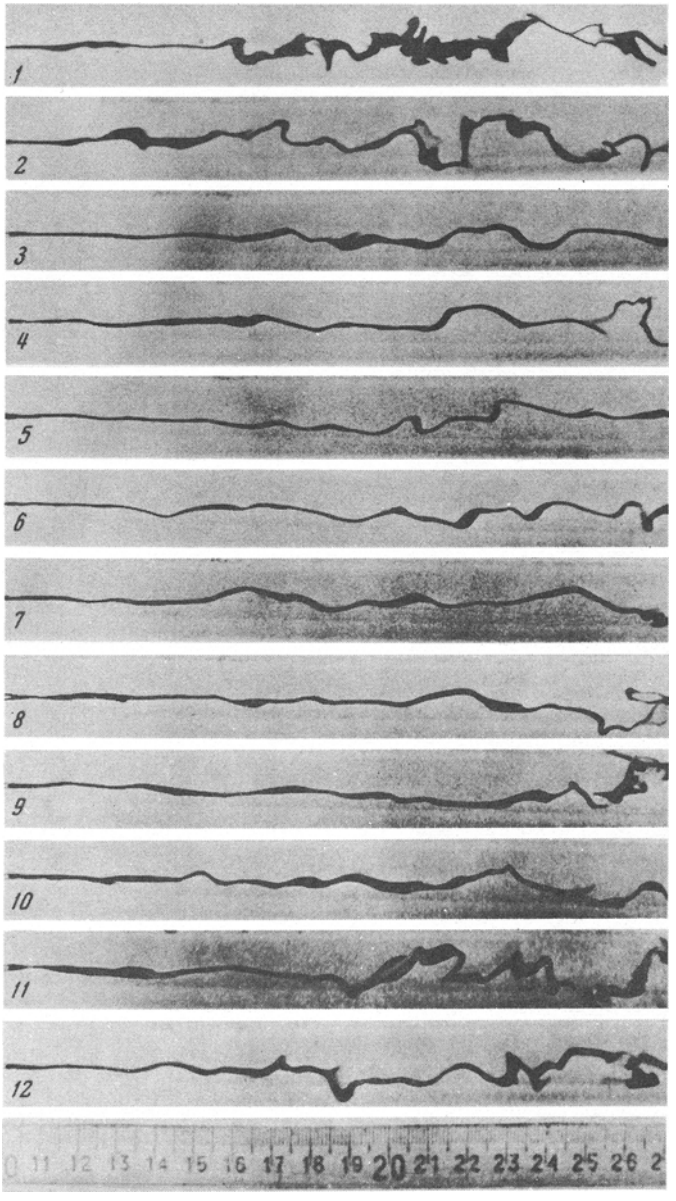

Fig. 2

exit velocity remained constant; the regime was varied by changing the diameter of the supply tube) the probe operated normally for more than 2 hr. In the case of a turbulent flow along the supply tube the platinum wire was entirely coated with gelatinous deposit up to 1 mm thick. In the case of laminar flow the diameter of the wire remained almost unchanged. After 2 hr it did not exceed 6–7 μ. At the same time, there are certain objections to this interpretation. It may be that the fluctuations are not associated with the presence of associations in the solution but are ordinary turbulent fluctuations intensified by the addition of a polymer. This explanation of the results, although unlikely since polymer additives, in reducing the drag, lower the level of turbulence in pipe flow [8], made it necessary to conduct additional experiments. In these the probe was mounted in the tube through which the liquid flowed. A small jet of dye was introduced into the flow. The intensity of turbulent diffusion of the dye was compared with the anemometer readings.

For this purpose we used a glass tube 23.5 mm in diameter and 56 diameters long. As in the previous experiments, the liquid was forced through the system by the thermostat pump. The anemometer probe was installed at the end of the tube. The dye was fed into the flow 53 cm from the beginning of the tube. All the experiments were conducted at a constant flow velocity along the tube of 16 cm/sec, which corresponds approximately to $R = 3.5 \cdot 10^3$.

The photographs in Fig. 2 show the mixing of the dye in a flow of water (photo 1) and in a polyoxyethylene solution of concentration $3 \cdot 10^5$ at various instants of time after the flow began (photos 2–12). The table gives the time at which the photograph was taken (t, min), the mean values of the output signal (v, volts) registered by the anemometer, and the relative intensity of the fluctuations $\bar{\sigma}$ in percent. The corresponding oscillograms of the anemometer output signals are presented in Fig. 3.

As follows from the above data, the addition of a polymer to a water flow leads to a decrease in the level of turbulent diffusion of the dye and, hence, in the level of turbulence. On the other hand, the anemometer registers an increase in the level of the fluctuations, which can be uniquely associated with additional disturbances of the velocity field near the probe by the molecular associations. The minimum diffusion of the dyed jet is closely correlated with the maximum fluctuation level. Subsequently, the diffusion again increases, and the fluctuation level declines. All this is in good agreement with the results and interpretation of the previous experiments.

Our experiments confirm the possibility of using a hot-wire anemometer for investigating the structure of dilute polymer solutions and in particular for establishing the presence of associations in them. At the same time, they indicate definite limitations on the use of the hot-wire anemometer for measuring velocity fluctuations and the tur-

	Water	Polyoxyethylene solution, concentration $3 \cdot 10^{-5}$										
t	—	2	4	6	8	10	15	20	30	60	90	120
v	8.8	8.4	8.6	8.9	8.9	8.9	8.9	8.9	8.9	8.8	8.8	8.7
σ	0.535	0.441	0.419	0.449	0.562	0.609	0.629	0.610	0.606	0.591	0.568	0.552

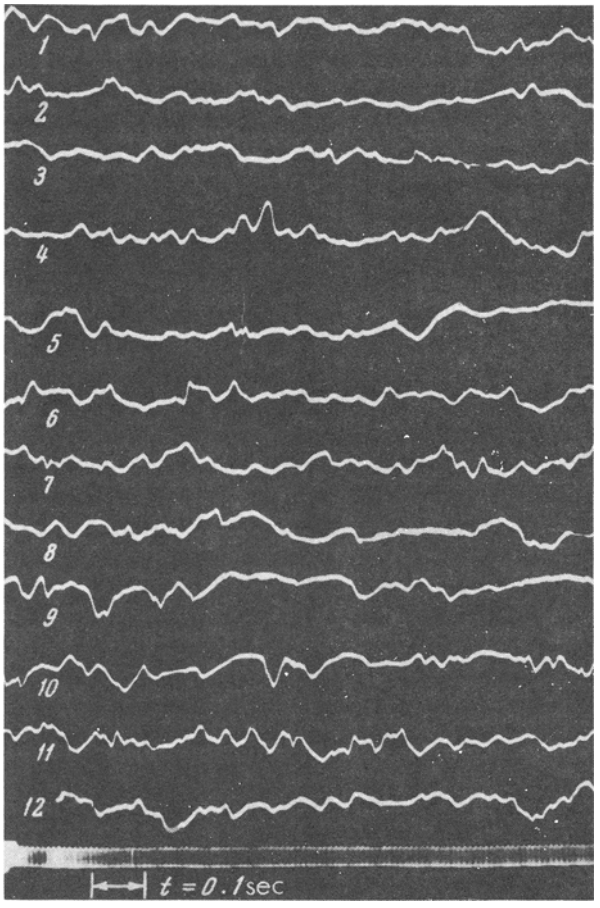

Fig. 3

bulent fluctuation spectrum in flows of dilute polymer solutions containing large viscoelastic associations. When such solutions flow over the probe, the resulting fluctuations of the anemometer output voltage are evidently caused both by velocity perturbations and by fluctuations of the thermal conductivity. The existence of a certain possible difference in the thermal conductivities of the associations and the surrounding liquid can be judged from the fact that the anemometer calibration curves are flatter for an elastic polyoxyethylene solution than for water. In the process of degradation of the solution the calibration curve becomes steeper, gradually approaching the curve for water. This change in the calibration curves with the state of the solution also creates certain difficulties in connection with the use of hot-wire anemometers.

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