EFFECT OF POLYMER ADDITIVES ON PROPAGATION OF TURBULENCE FRONT

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A study is made of the propagation of a turbulent region formed by vibrations of plates with holes in solutions of polyoxyethylene and guar resin. Polymer additives are found to appreciably affect the motion of a turbulence front.

Extensive experimental studies have been made in recent years concerning the effect of small polymer additions on turbulence and turbulent friction as well as on heat and mass transfer under conditions of boundary flow of fluids. A few hundred of such studies have been made. The effect of dissolved polymers on free turbulence has been studied to a much lesser extent.

Several studies [1-5] have been published which deal with the effect of polymer additives on turbulence in the stream behind meshes. An appreciable effect was noted, most of those studies reporting an attenuation of the turbulence intensity and one of them [4] reporting its amplification.

Turbulent immersed jets were considered in other studies [6-13]. There, polymer additives were shown to be capable of noticeably alter the motion of fluid in a turbulent jet. This hydrodynamic effect of polymers can be here either positive or negative, depending on the form of the polymer and on its concentration in the solution as well as on the degree of degradation of the latter. For instance, the velocity at the jet axis can decrease downstream at an either slower or faster rate than in the case of a Newtonian fluid. The excess temperature follows an analogous trend during discharge of a hot jet of polymer solution [10]. There also have been studies made concerning the turbulent structure in immersed jets of polymer solutions [11-13].

Another study [14] has dealt with the trail behind a body in a fluid with polymer additives. There, too, a hydrodynamic effect of small additions of dissolved polymer was observed.

Two other studies [15, 16] have dealt with propagation of a turbulent cloud in a polymer solution by a stirrer with two oppositely rotating helical blades. In that case there were observed a less intense seeding of turbulence and a stronger attenuation of free turbulence in polymer solutions than in Newtonian fluids.

An interesting case of free and zero-shear, in the mean, turbulent flow is propagation of a turbulent region formed by a mesh vibrating in a stationary fluid. In the case of a Newtonian fluid, generally stratified with respect to density, such a turbulent motion was considered from the standpoint of geophysical applications [17]. No study has ever been made of such a turbulent motion in a fluid with polymer additives.

In this experiment equipment made available by Voropaev [18] was used. This equipment consisted of a vessel made of thick acrylic glass 31 × 31 cm in the plan view and 53 cm high (Fig. 1). Turbulence was generated by means of perforated plates 30 × 30 cm large and 0.4 cm thick. The holes in these plates were arranged in a criss-cross pattern. Two such plates were used in the experiment. One of them had holes $d = 0.49$ cm in diameter spaced 0.6 cm apart center-to-center, the other had holes $d \approx 1$ cm in diameter spaced 1.3 cm apart center-to-center.

The perforated plates were mounted horizontally on a vertical rod which an electric motor through a crankshaft set in vibrations about its own axis. The vibration frequency was measured with a frequency meter. The frequency in this experiment was 2.65 ± 0.05 Hz.

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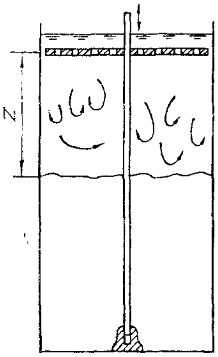

Fig. 1. Schematic diagram of experimental apparatus.

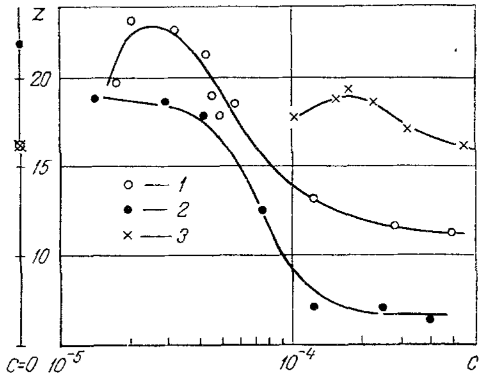

Fig. 2. Depth of penetration of turbulent region z (cm) in time t = 800 sec after beginning of experiment, as function of the polymer concentration c: 1, 2) in solutions of polyoxyethylene; 3) in solutions of guar resin; diameter of holes in plate d: 1, 3) 0.49 cm; 2) 1.0 cm.

The vibration amplitude was 1 cm. At standstill the plate was immersed in the fluid to a depth of ≈ 3 cm.

After the plate had been set in vibrations, there appeared in its vicinity a turbulized layer which then gradually penetrated deeper into the fluid. This layer was made visible by a dye, a phenolic indicator soluble in water. Just before the experiment, a small amount of a hot solution containing 0.01% of this dye and a polymer in the proper concentration was carefully spread over the surface of the fluid. Millimeter scales were fastened to the vessel on two opposite walls and a tape measure was also used for determining the depth of penetration of the turbulence front. The latter did not constitute an even surface and, therefore, its depth was established as an average one only. The depth of turbulence penetration determined in this way was accurate within 0.5 cm. Time intervals were measured with a stopwatch.

The object of the experiment was to study the change of depth of turbulence front penetration as a function of time in water and in aqueous solutions of linear high-molecular polymers: WSR-301 "Polyox" polyoxyethylene and J2-FP guar resin. The solutions were prepared by dilution of original solutions with a 0.5-1% concentration. Distilled water was used as solvent. The temperature of the fluid in this experiment fluctuated within the 19-23°C range.

The experiment has revealed that dissolution of small amounts of polymer in the fluid causes the mode of propagation of the turbulence region to change appreciably. Under the influence of polymer additives this motion can become either faster or slower, as is evident

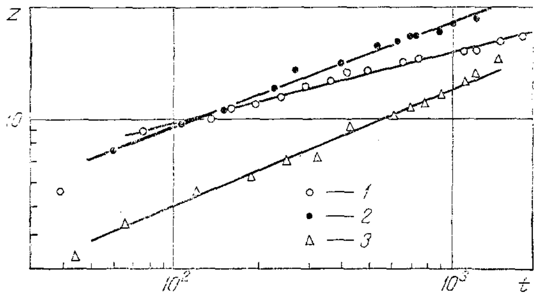

Fig. 3

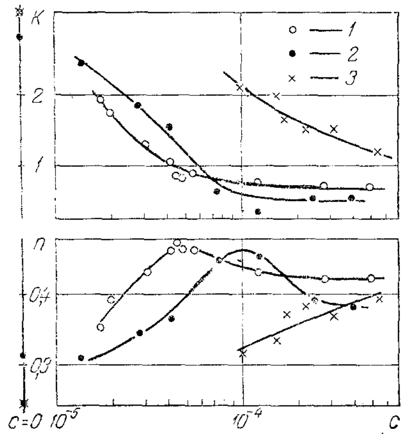

Fig. 4

Fig. 3. Depth of penetration of turbulence front z (cm), as function of time t (sec) during development of turbulent region generated by plate with holes d = 0.49 cm in diameter: 1) in water; 2) in solution with $1.75 \cdot 10^{-5}$ polyoxyethylene concentration; 3) in solution with $5 \cdot 10^{-4}$ polyoxyethylene concentration.

Fig. 4. Dependence of coefficient K ($\mathrm{cm \cdot sec^{-1}}$) and exponent n on the concentration n of polymer in solutions. Notation the same as in Fig. 2.

in Fig. 2. The data obtained on turbulization by the plate with holes 0.49 cm in diameter indicate that a polymer in small concentrations causes the turbulence front to move deeper into the fluid faster, on the average, than it does in water. Increasing the polymer concentration slows down the motion of the turbulence front.

In the case of turbulence generated by the plate with holes 1.0 cm in diameter the turbulence front moved within a certain time less deep in the solutions than in pure water, over the entire given range of polymer concentrations.

The experimental relations z = z(t) can, except for their short initial range, be closely approximated with a power function (Fig. 3)

$$z = Kt^n. \tag{1}$$

The graph in Fig. 3, plotted to a log—log scale, depicts some of these experimental relations. In agreement with relation (1), the points on this graph cluster around straight lines.

The graph in Fig. 4 depicts the dependence of K and n on the polymer concentration in the solution, according to calculations on the basis of experimental data.

The data obtained in this study reveal an appreciable effect of dissolved polymer on the propagation of the turbulence region at polymer concentrations conparable with those used for reducing skin drag during flow. The drag reducing effect and the effect noted in this experiment have still another common feature, namely an asymptotic behavior as the polymer concentration in the solution increases. According to the graphs in Figs. 2 and 4, in polyoxyethylene solutions an increase of the polymer concentration beyond a certain level will not appreciably alter the mode of propagation of the turbulence front. In the range of lower concentrations, on the other hand, an increase of the polyethylene content will cause the coefficient K to decrease and the exponent n to first increase to a maximum and then decrease to an ultimate level.

In solutions of guar resin an increase of the polymer content will also cause the coefficient K to decrease and the exponent n to increase, but neither the maximum n nor the ultimate n were reached at concentrations up to c = $5.5 \cdot 10^{-4}$ and evidently higher concentrations are needed for this.

An analysis of the data obtained with a larger characteristic dimension (larger diameter of holes in the plate) suggests that increasing this dimension requires also increasing the polymer concentration for non-Newtonian effects of comparable magnitudes to occur with different hole sizes. In order to realize the maximum exponent n with a plate with larger holes, for instance, it is necessary also to make the polymer concentration higher than it is with a plate with smaller holes. The non-Newtonian behavior follows an analogous trend in other hydrodynamic situations such as, for example, flow of polymer solutions through pipes.

In examining the propagation of the front of a turbulent region generated by vibrating perforated plates, one must consider two processes governing the flow. These processes are turbulization near the plate and diffusion of turbulence with entrainment of quiescent fluid into turbulent motion.

Polymer additives can influence both processes. The possibility of polymer additives strongly affecting the entrainment mode in which quiescent fluid is set in turbulent motion has to be with the appearance of very thin layers of fluid between large turbulent vortices near the turbulence front [19], where the local shearing rates can reach levels sufficiently high for altering the character of motion so as to make it non-Newtonian.

NOTATION

z, depth of penetration of the turbulence front; t, time; c, mass concentration of polymer in the solution; d, diameter of holes in the plate; K and n, coefficient and the exponent in the power-law relation describing the depth of penetration of the turbulence front as a function of time.

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EXPERIMENTAL INVESTIGATION OF A TURBULENT JET IN TURBULENT CROSS FLOW

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The characteristics of an axisymmetric turbulent jet propagating in a cross flow with a high degree of turbulence are investigated experimentally.

There is a fairly large number of papers devoted to experimental investigations of the development of turbulent round jets in a cross flow [1-6]. These investigations are of interest because a flow of this type is often encountered in technology. The theoretical solution of the problem presently involves great difficulties because of the complex three-dimensional character of the flow in such jets.

The flow structure of a turbulent round jet entering a right-angle cross flow was investigated in detail in [4]; for the most part, the initial, formative section of the jet was investigated. As in all other known experimental work, the transverse flow described in the above paper had a low level of turbulence, 0.3-0.4%. However, in various jet devices where flow of this type occurs, the cross flow is highly turbulent.

The present article provides the results of an experimental investigation of the characteristics of a round turbulent jet propagating in a cross flow whose turbulence level has been increased to 10%. The experiments were performed by means of the experimental device used in [4]. The turbulence level of the cross flow is increased by means of a mechanical turbulator, equipped with a two-row cylinder lattice with the rows moving in opposition. The turbulator is installed at the outlet from the nozzle of a wind tunnel. The description and characteristics of the turbulator are given in [7].

The axis of the jet entering the cross flow at a right angle is located at a distance of 115 mm from the second row of the turbulator lattice. The field of the mean and the pulsating velocities are completely equalized here, while the turbulence intensity in the cross flow is virtually isotropic and approximately equal to 10%. According to L. N. Ukhanova's measurements, the longitudinal integral scale of turbulence was approximately equal to 10 mm at the section of the jet nozzle, while the transverse scale amounted to 5-6.5 mm.

The jet is produced by means of a profiled nozzle with an outlet diameter of 19.5 mm. The cutoff end of the nozzle is mounted flush with the surface of a screen positioned parallel to the flow in the operating section in the wind tunnel below its axis at a distance of 128 mm from it. Drainage of the screen around the jet is provided for investigating the pressure distribution. The thickness of the boundary layer, measured at the screen in front of the nozzle in the absence of the jet at cross flow velocities of 5 and 15 m/sec, was approximately equal to 7 mm.

The air for producing the jet is supplied from a compressor through a receiver. The air discharge was constant in all experiments, while the mean outflow velocity of the jet was equal to $u_0 = 72.5$ m/sec. The Reynolds number, calculated on the basis of this velocity and the outlet diameter of the nozzle, was equal to $0.94 \cdot 10^5$.

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