SOME PECULIARITIES OF THE EFFECT OF POLYMER ADDITIVES ON WALL TURBULENCE

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Results are offered of an experimental study of the effect of polymer additives on the spectral and correlation characteristics of wall pressure pulsations, occurring with flow over both smooth and rough boundaries.

At the present time, together with numerous studies of the effect of polymer additives on hydrodynamic resistance, there have appeared studies which present data on the behavior of the pulsation characteristics of velocity and pressure in the presence of high molecular weight additives [1, 2].

Progress in this field has been held back by certain difficulties which arise with use of traditional methods of hydrodynamic measurement in flows of dilute polymer solutions. In this connection the use of miniature acoustical pressure sensors to study the effect of polymer additives on the spectral and correlation characteristics of wall pressure pulsations is of interest.

Study of the effect of polymers on wall pressure pulsations is also of direct interest in investigation of acoustical phenomena in a controlled boundary layer.

We offer below some results of an experimental study of pressure pulsations in the flow of dilute polyethylene oxide solutions in both smooth and rough surfaced tubes. These results are then compared with data from hydrodynamic measurements. The latter were made by the method of "stroboscopic" flow visualization, developed earlier by the authors of [3].

The studies were performed in low noise hydrodynamic channels of the gravitational type. Measurements of spectral and correlation characteristics of the pressure pulsations were made in a channel with interior working section 2×7 cm^2. A channel with an interior section 1×1 cm^2 was used to study the profile of averaged and pulsation velocities simultaneously with the pressure pulsation spectral characteristic measurements.

All measurements were made at the end of the working sections, where a completely established flow existed. A granular rough surface was formed on the wide walls of the large channel with most probable particle size of $2.5 \cdot 10^{-2}$, $4.0 \cdot 10^{-2}$, and 0.12 cm. In experiments with the small channel the rough surface was deposited on two opposite walls. Polymer solutions at concentration levels of 0.0005 to 0.01% were studied. Wall pressure pulsations were recorded by miniature piezosensors with active surface diameter 1.6 mm, installed flush with the channel wall.

The characteristic effects of polymer additives on spectral characteristics of wall pressure pulsation were noted by the present authors in [4]. Here we will merely mention some general principles of the phenomenon.

The pressure drop measurements performed indicated that reduction of resistance is observed in flow over both a smooth and a rough surface. Simultaneously with the resistance decrease, there occurs a reduction in the spectral levels of wall pressure pulsations, especially noticeable in the high frequency range, less so at low frequencies.

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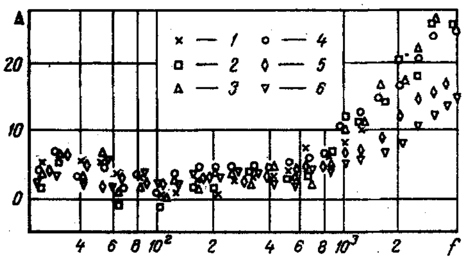

Fig. 1

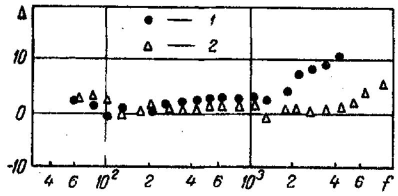

Fig. 2

Fig. 1. Reduction of spectral levels of wall pressure pulsation for flow of polymer solutions of concentration: 1) 10^{-4}; 2) $5 \cdot 10^{-5}$; 3) $2.5 \cdot 10^{-5}$; 4) $1.25 \cdot 10^{-5}$; 5) $6 \cdot 10^{-6}$; 6) $2.5 \cdot 10^{-6}$. Δ, dB; f, Hz.

Fig. 2. Reduction of wall pressure pulsation for 1) fresh, 2) degraded solutions; Δ, dB, f, Hz.

The effect of the polymer additives on pressure pulsation was evaluated by the difference in spectral pressure pulsation levels in 1/3 octave bands for flow of water $L_1(f)$ and polymer solution $L_2(f)$ ($\Delta = L_1 - L_2$).

It developed that both the pressure pulsation level decrease effect and the hydrodynamic resistance decrease effect were dependent on polymer concentration level. There is some optimal concentration value, beginning at which further increase does not affect the spectral and correlation characteristics of pressure and velocity pulsation in the flow or the hydrodynamic resistance. Experimental data for one flow rate and smooth channel walls are shown in Fig. 1. We note that at the optimum concentration level for polyethylene oxide ($5 \cdot 10^{-5}$) the pressure pulsation in the high frequency range is reduced by 1-2 orders. In the low and middle audio frequency range the pressure pulsation is reduced by a factor of 1.5-2 (approximately 6 dB).

Considering the spectral effects, we may note the existence of a characteristic frequency, corresponding to the commencement of active influence of the polymer additive on the spectrum. The absolute value of this characteristic frequency depends on the flow rate and its parameters. All the effects described occur with single time use of the polymer solution.

It is known [5] that solutions of certain polymers which reduce resistance well are sensitive to degradation both by action of shear flows and due to aging.

The effect of polymer degradation on the wall pressure pulsation reduction property is of interest. Figure 2 shows the results of spectral measurements for freshly prepared 0.001% polyethylene oxide solution, and for the same solution after passage through a centrifugal pump. As before, the results are presented in the form of differences in spectral levels. It can be seen that the effect of the centrifugal pump led to a loss of polymer effectiveness. The frequency f, characterizing the commencement of active reduction in high frequency pressure pulsation shifts to the right on the frequency axis. It is also natural that the hydrodynamic resistance reduction decreases significantly with the degraded polymer (from 67% to 20%).

We note that for flow over a rough surface the effect of solution degradation appears still more strongly. Thus, for a 0.005% polyox solution sent through a centrifugal pump a decrease in pressure pulsation was observed only in the extreme high frequency portion of the spectrum. The corresponding reduction in hydrodynamic resistance comprised only 4%.

We will turn to the results of hydrodynamic measurements. As noted above, these measurements were performed by the flow visualization method. It developed that the character of the polymer effect in flow in smooth and rough tubes was similar; the average velocity gradient near the wall decreased under the influence of the polymer; it increased in the intermediate region, and decreased again at the core of the flow. Axial velocity pulsations underwent practically no reduction, and the maximum in the distribution of these pulsations across the channel section shifted from the channel wall in the direction of the flow core. The greatest effect of the polymer additives was on transverse velocity fluctuations. Figure 3 presents data characterizing the distribution of mean square transverse velocity component pulsations over the channel section for flow over smooth and rough surfaces for a flow rate u = 100 cm/sec. The y coordinate in all cases was measured from the channel wall without consideration of the roughness introduced. It may be seen that in the smooth channel at the flow core the value of the mean square transverse velocity

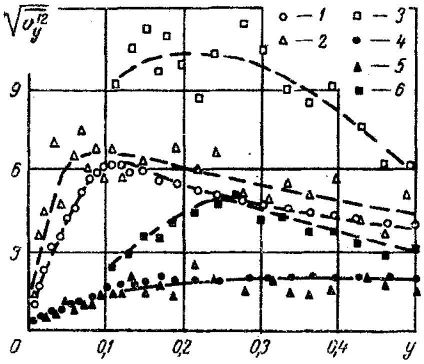

Fig. 3

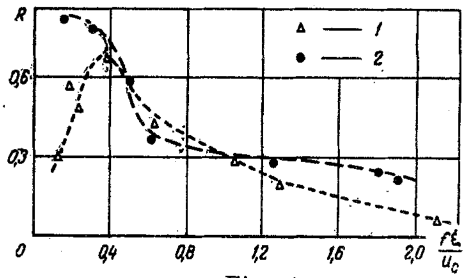

Fig. 4

Fig. 3. Profile of mean square pulsations of transverse velocity component. Smooth channel: 1) water; 4) polymer solution. Roughness, $2.5 \cdot 10^{-2}$ cm; 2) water; 5) polymer solution. Roughness, 0.12 cm; 3) water; 6) polymer solution. v, cm/sec; y, cm.

Fig. 4. Module of mutual pressure pulsation power spectrum: 1) water; 2) polymer solution.

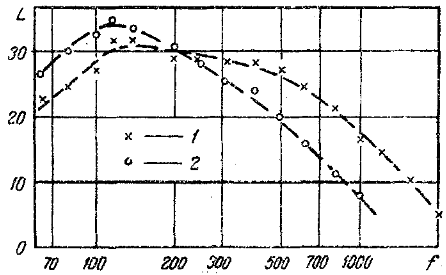

Fig. 5. Wall pressure pulsation spectra: 1) water; 2) polymer solution.

pulsation v_y' is reduced by a factor of two, and in the inner section of the flow, by a factor of 5-6. In the channel with the finer roughness, the reduction is still greater. The value of the mean square axial and transverse velocity pulsations in this channel for flow of the polymer solution proved to be the same as for the smooth channel.

Measurements of the average velocity profile showed that the polymer additives cause an increase in the dimensions of the wall region of the boundary layer. In connection with this, the mode of complete manifestation of roughness is not observed even for $kv_*/\nu > 100$ (according to the results of hydrodynamic measurements).

It was noted earlier that measurements were made with the purpose of studying the effect of polymer additives on the mutual pressure pulsation power spectrum, i.e., on spacetime correlation. Figure 4 shows data on measurement of the mutual power spectrum for the case of pure water and polymer solution with concentration 0.005% over a surface with roughness of $4 \cdot 10^{-2}$ cm.

It is known that the presence of roughness on the walls leads to a more rapid degeneration of turbulence in the boundary layer. We note that the quantity kv_*/ν for the pure water flow in our case proved to be greater than 160, and consequently, the total roughness manifestation regime occurred. However, as is evident from the results of Fig. 4, the presence of a polymer led to decrease in the degeneration rate of large scale turbulences, which is connected with the increase in the wall region of the boundary layer and the change in the flow regime-manifestation of roughness.

For coarse surfaces the liquid flow is characterized by intense turbulization on individual roughness elements. For dense packing of the roughness elements, as was shown in [6], the form of the pressure pulsation spectrum is distinguished by the presence of some characteristic frequency, connected with the formation of turbulence paths on individual roughness elements. It is interesting that upon introduction of polymer additives the pressure pulsation level at this frequency increases somewhat, although the high frequency pressure pulsation decreases significantly (Fig. 5). This effect may be explained by the fact that in the polymer solution only fine scale turbulent structures are suppressed. The results obtained qualitatively support the photographs shown in Fig. 6. The picture of flow around an 0.2 cm ledge (Re $= 4 \cdot 10^{-3}$) by water and a polymer solution was made with a single exposure. As is evident, with addition of the polymer, the fraction of coarse scale turbulence in the wake increases, while that of fine scale turbulence decreases.

Figure 7 shows results of mutual pressure pulsation power spectra for flow over a coarse roughness. In contrast to the case of $4 \cdot 10^{-2}$ cm roughness, the polymer did not cause significant change in the form of

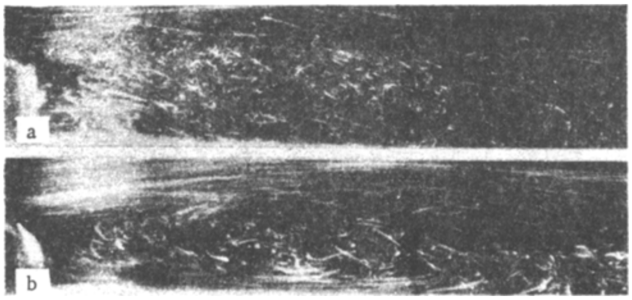

Fig. 6. Flow around a ledge: a) water; b) polymer solution.

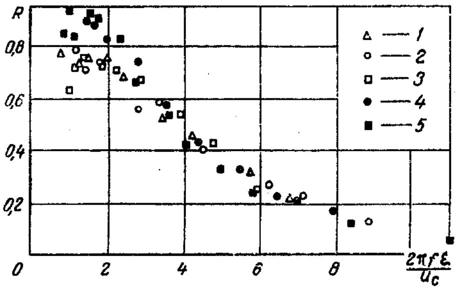

Fig. 7. Module of mutual pressure pulsation power spectra: 1, 2, 3) water, various sensor locations; 4, 5) the same for polymer solution.

the spectrum. Hydrodynamic measurements showed that with flow of the polymer solution over coarse rough surfaces the resistance reduction effect decreased, and the effect of extinguishing transverse velocity pulsations was less significant (the maximum reduction was by less than a factor of four).

The experimental data obtained permit certain conclusions on the mechanism of reduction in hydrodynamic resistance in the case of a rough surface. If the height of the roughness elements is comparable with the magnitude of the enlarged wall region in the polymer solution, the decrease in resistance is connected with a change in the flow mode (transition from the complete roughness manifestation mode to a transitional one). In the case of coarse roughness the reduction is due basically to extinction of fine scale components of the turbulent wake, broken away from roughness elements.

In conclusion it may be noted that the introduction of small additions of high molecular weight substances into a turbulent water flow leads to a reduction in the spectral levels of wall pressure pulsation for flow over both smooth and rough surfaces. This result agrees well with the data obtained on the effect of polymer additives on the transverse component of velocity pulsations, which, as is well known, introduces a significant contribution to the level of wall pressure pulsations. The results of correlation measurements indicate a change in the mode of manifestation of roughness in flow of a polymer solution in a channel. A polyethylene oxide solution subjected to mechanical destruction continues to lower the pressure pulsation level in the high frequency portion of the spectrum, although it exerts practically no effect on hydrodynamic resistance.

NOTATION

$L_1(f)$, $L_2(f)$ are the spectral levels of pressure pulsation in water and polymer solutions;
Δ is the pressure pulsation level reduction;
f is the pulsation frequency;
k is the height of a roughness element;
$v* = \sqrt{\tau_w/\rho}$;
τ_w is the wall shear stress;
ρ is the density of water;
u_c is the turbulent vertex transfer velocity;
ξ is the spatial distribution of sensors in direction of flow;
R is the correlation coefficient;
v_y' is the transverse component of velocity pulsation;
ν is the kinematic viscosity of water.

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