SOME SPECTRAL AND PULSATION CHARACTERISTICS OF A HORIZONTAL GAS–LIQUID STREAM

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The problem of the experimental determination of the spectral characteristics of the two-phase flows was the subject of [1-5], in which it was shown to be possible to identify the mode of flow of a gas–liquid stream from the character of the frequency distribution of the spectral density of the pulsations.

The aim of the present report is an investigation of the spectral and pulsation quantities of a gas–liquid stream in a wide range of variation of the parameters. At present there are no data in the literature on the distribution of the relative intensity of pulsations of wall friction of a horizontal gas–liquid stream.

The experiments were carried out on the installation of [6]. The working channel had a length of 6 m and an inner diameter of 19 mm. The temperature of the gas and liquid at the channel entrance was kept equal to 25°C and the gas was preliminarily humidified. All the measurements were made in a cross section removed from the point of entry of the liquid by a distance of 200 diameters, where the flow can be assumed to be stabilized lengthwise [6]. The liquid was supplied to the channel through an annular slit when measuring the frictional energy spectra and through a T-shaped mixer when determining the relative intensity ε_τ of the frictional pulsations. To investigate the spectral and pulsation characteristics we used the electrodiffusion method [1, 4, 6] which permits the obtainment of reliable data on the magnitude of the average (presented in [6]) and pulsation values of the wall shear stress. As the working liquid we used 0.5 N sodium hydroxide and 0.01 N potassium ferri- and ferrocyanide solutions in distilled water. The faces of platinum plates 0.02 × 0.2 mm in size, set flush with the pipe wall, served as the sensitive elements of the friction detector.

The energy spectra $S_\tau(\omega)$ and the correlation function $R(\Delta\tau)$ were determined on a Ural 14D computer, while the relative intensity $\varepsilon_\tau = \sqrt{\overline{\tau'^2}}/\bar{\tau}_w$ of the pulsations of wall friction were determined instrumentally.

The measurement system is presented in Fig. 1. The signal from the electrodiffusion friction detector 1 was amplified and transformed by the electrodiffusion converter (EDC) 2, whose frequency characteristic curve is linear in the region of 0-10 kHz [7]. The signal from the EDC was fed to an analog-to-digital converter 3 (F-733 ADC) and then passed through an optical decoupling unit 4 and was recorded on magnetic tape by the computer 5. Before recording, the signal was examined on a spectrum analyzer 6, determining f_{max} and f_{min}.

The spectral density $S_\tau(\omega)$ of the input signal was determined from the spectral density $S_I(\omega)$ of the detector current through the functions of [8, 9], $S_\tau(\omega) = S_I(\omega)/|H(\omega_*)|^2$, where $|H(\omega_*)|^2 = [(9 + 0.54\omega_*^2)^2 + 0.027\omega_*^3]^{-1/2}$ is the modulus of the frequency characteristic of the friction detector [1, 10] and $\omega_* = 2\pi f(\mu l^2/\bar{\tau}^2 D)^{1/3}$ is the dimensionless frequency. This equation of the theory of steady-state random processes [8, 9] was used in [1, 4] to obtain the turbulent characteristics of two-phase flows in the high-frequency region. The algorithm suggested in [1, 4] was applied, using a fast Fourier transfer [11].

To confirm the reliability of operation of the detectors and measurement apparatus we measured the frictional spectra in a stream of pure liquid. The resulting experimental dependences, in dimensionless coordinates, of $\psi = S_\tau(\omega)\, w_0'/d\bar{\tau}'^2$ on $\varphi = f(\omega)d/w_0'$ for Re' = 9000 and 54,000 agree well with the results of the experiments of [1, 4, 12], conducted using the electrodiffusion method, as well as with thermoanemometric measurements near a pipe wall [13].

Energy spectra of pulsations in wall friction for a reduced liquid velocity $w_0' = 0.25$ m/sec are presented in Fig. 2. The detector was located on the lateral generatrix. The stratified mode ($w_0'' = 0.5$ m/sec) corresponds to a spectrum (curve 1) with a maximum near

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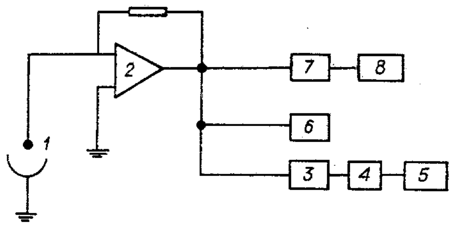

Fig. 1

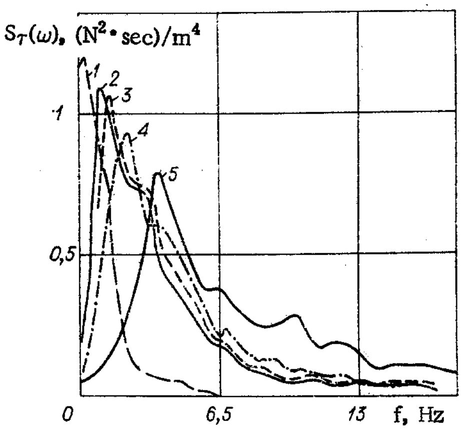

Fig. 2

zero. The spectra of this mode decline monotonically. Spectra with a maximum at the zero frequency were also obtained in [5] in an analysis of velocity pulsations in the gaseous phase of a separate mode.

The plug modes (curves 2: $w_0'' = 3$ m/sec; 3: $w_0'' = 5.3$ m/sec; 4: $w_0'' = 7$ m/sec) have spectra with clearly expressed maxima at a frequency $f \approx 1$-2 Hz; some periodicity is observed in the autocorrelation functions, indicating the presence of a periodic component in the random process.

In the projectile mode of flow (curve 5: $w_0'' = 14.7$ m/sec) the spectrum is broadened owing to the elevation of its high-frequency part. With an increase in the gas velocity the frequency corresponding to the maximum value of $S_\tau(\omega)$ increases, while the maximum itself decreases. In the projectile mode of flow additional maxima appear in the frictional spectra at f = 6-10 Hz. This means that the principal maximum corresponds to the passage of the projectiles, while the additional maxima correspond to secondary vortices arising during the destruction of projectiles.

In Fig. 3 we present frictional spectra for a gas velocity $w_0'' = 40$ m/sec and liquid velocities $w_0' = 0.25$ m/sec (Fig. 3a) and $w_0' = 0.1$ m/sec (Fig. 3b). Recordings of the electrodiffusion current for the same velocities are also presented here. The distribution of principal maxima of the spectral density in the disperse-annular modes evidently corresponds to large-scale waves, while the additional maxima correspond to capillary waves (Fig. 3a). It is seen from Fig. 2 that the energy-bearing part of the spectrum falls at low frequencies. Therefore, the quantity ε_τ in the separate, bubble, and projectile modes can be determined instrumentally [14], without calculating the frictional spectra. In this case the error in determining the quantity ε_τ for $\omega_* < 1$ (the region of quasisteadiness of H^* with ω_*) will be no higher than 7% [1].

The relative intensity of the pulsations in wall friction was determined from the dependence

$$\varepsilon_\tau = 3\sqrt{\overline{I'^2}}/\bar{I}.$$

The average value of the current I at the EDC output was measured by a V-2-23 integrating voltmeter 8 while the mean-square value $\overline{I'^2}$ was measured by a quadratic voltmeter (see Fig. 1), described in [14]; the averaging time was 100 sec.

The quantity ε_τ was measured at reduced liquid velocities $w_0' = 0.25$, 0.5, 2, and 3 m/sec. This corresponded to Reynolds numbers Re' = 4500, 9000, 36,500, and 54,000, calculated from the viscosity, the reduced liquid velocity, and the channel diameter. The flow-rate volumetric gas content β varied from 0 to 0.999 for $w_0' = 0.25$ and 0.5 m/sec; at these β the following modes of flow existed in the channel: bubble, plug, projectile, and disperse-annular. At $w_0' = 2$ and 3 m/sec, β varied from 0 to 0.9, which corresponded to the bubble, projectile, and disperse modes of flow.

Because of the fact that the horizontal two-phase flow is asymmetric relative to the channel axis, the quantity ε_τ was measured at several points (1: upper generatrix; 3: lower generatrix) along the perimeter of the pipe. This was accomplished by rotating the working section about the axis.

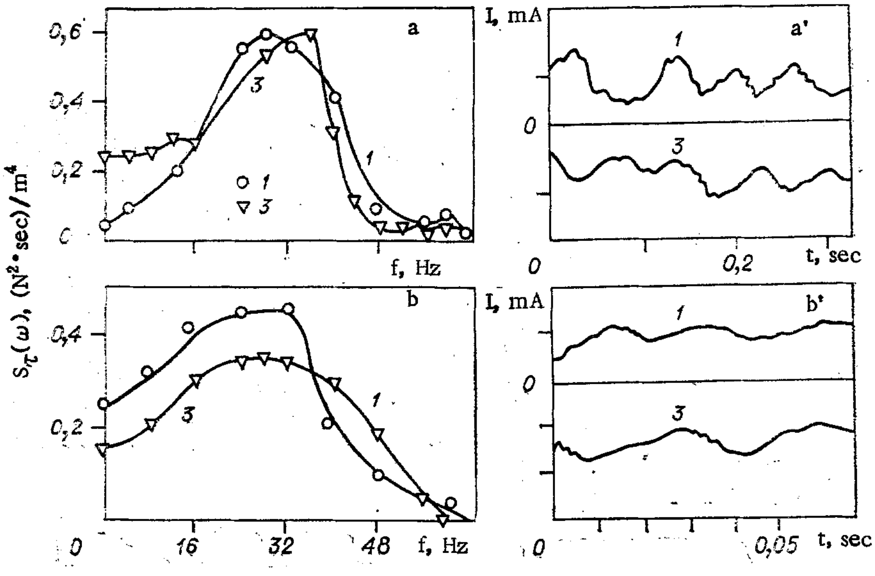

Fig. 3

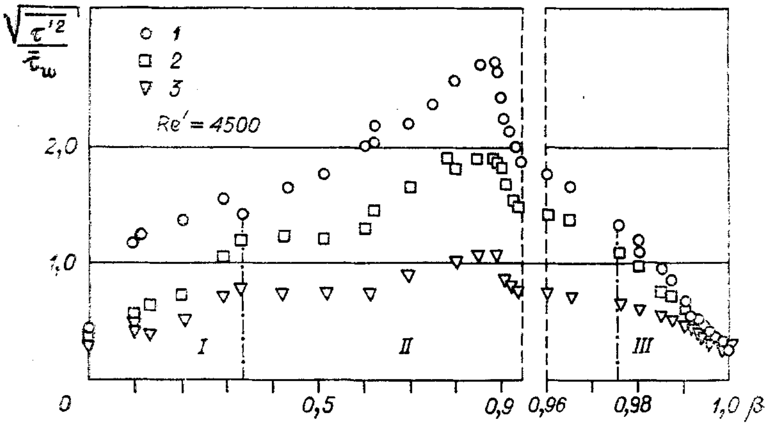

Fig. 4

The results of a measurement of the quantity ε_τ as a function of β for a reduced liquid velocity $w_0' = 0.25$ m/sec are presented in Fig. 4. With an increase in the gas content, ε_τ grows from the value corresponding to one-phase flow, reaches a maximum value in the projectile mode, and then decreases. The dependence of ε_τ on β is not monotonic. In all modes one observes a dependence of ε_τ on the position of the detector. At β = 0-0.3 (the region of the bubble mode I) bubbles of different sizes move near the upper pipe generatrix. For a detector on the upper generatrix (points 1) the quantity ε_τ grows considerably faster than for detectors on the lateral (points 2) and lower (points 3) generatrices. In the range of β = 0.3-0.6 the quantity ε_τ grows slowly (points 2 and 3), and then its sharp growth occurs (points 1 and 2), which corresponds to the projectile mode. With a further increase in the gas flow rate (with Re' = const) the relative intensity ε_τ of the frictional pulsations decreases; here it was observed visually that the connectors between projectiles are broken and the gas plugs merge and form a gas core. A liquid film of varied thickness flows along the channel walls; the quantity ε_τ at the upper generatrix differs from ε_τ at the lower one by about 40%. The values of the relative intensity of the frictional pulsations at the upper and lower generatrices are equalized when a reduced gas velocity $w_0'' \geqslant 70$ m/sec is reached, i.e., stabilization of the film thickness over the perimeter of the pipe sets in.

For a Reynolds number Re' = 36,500 and β = 0-0.45 (Fig. 5) a bubble mode was realized in the working section. In this mode of flow the gas bubbles are distributed relatively uniformly over a pipe cross section. In the process of motion the bubbles can collide with each other and merge, and the fragmentation of large bubbles into smaller ones by turbulent

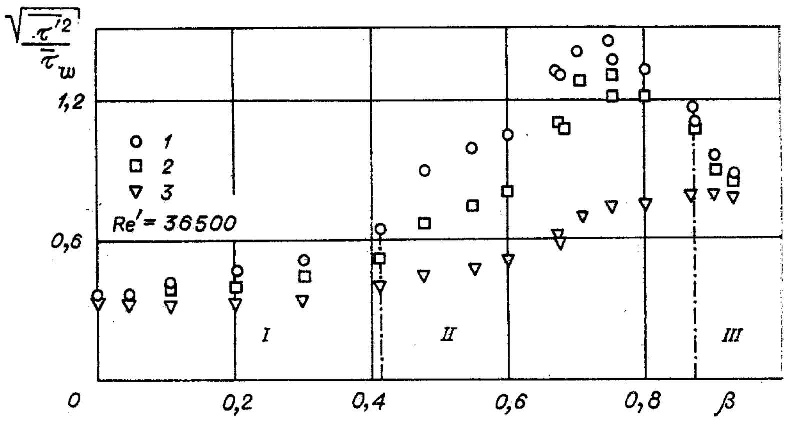

Fig. 5

pulsations occurs at the same time. In the bubble mode the relative intensity of frictional pulsations is low (Fig. 5). A further increase in the gas flow rate leads to the process of bubble merging predominating over the fragmentation process, and there is an increase in the sizes of the gas inclusions. Some of them occupy almost the entire cross section and have a projectile shape. The maximum pulsations of the gas and liquid flow rates were observed in the projectile mode (β = 0.45-0.9). It should be noted that the layering of the quantity ε_τ over a cross section at a constant value of β (in the range of β = 0-0.85) decreases with an increase in the liquid flow rate. Thus, the results obtained show that with an increase in the volumetric flow-rate gas content the quantity ε_τ grows, and this growth is the stronger, the smaller the Reynolds number. The effect of a strong increase in the relative intensity of the frictional pulsations at small Re' can be explained by the fact that the gas bubbles approach very close to the upper generatrix of the pipe. At low velocities of the carrier phase (the liquid) the relative motion of the gaseous phase near the upper wall of the channel is great, which leads to an increase in the value of $\sqrt{\overline{\tau'^2}}$; the increase in the mean value $\bar{\tau}_w$ happens less intensely. In developed turbulent flows (Re' $\geqslant$ 36,500) the relative velocity of motion of the gas bubbles is manifested less strongly, since it is small compared with the velocity of the carrier phase.

The visual observations and the data pertaining to ε_τ show that three modes of flow can be distinguished: I) bubble, II) projectile, III) disperse-annular (see Figs. 4 and 5).

It is interesting to note that the behavior of the quantity ε_τ in horizontal and vertical [4] pipes differs both qualitatively and quantitatively.

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INFLUENCE OF TARGET ORIENTATION ON THE ENERGY ACCOMMODATION COEFFICIENT FOR NITROGEN IONS

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The energy accommodation coefficient is one of the most important parameters describing interaction of particles of an incident stream with a body surface. Knowledge of this parameter is a basic requirement in determining the aerodynamic characteristics of, and of the heat transfer to bodies in free-molecular flow. Data is sparse for the energy accommodation coefficients of particles in the energy range ∼1–100 eV [1], and therefore α_i is often assumed to be near 1, although this condition does not hold in practice for most working gases. Also missing in the literature is the required volume of information on accommodation coefficient as a function of the orientation of the exposed surface relative to the velocity vector of the incident stream.

The present article presents α_i as a function of the orientation of some target materials in a high-speed ($u_\infty = 10$ km/sec) stream of partially ionized nitrogen. The experimental investigations were conducted in a gasdynamic plasma facility in a flow of rarefied plasma, generated in an accelerator with ionization of the working substance by means of an electron beam. A schematic diagram of a source of this type was given in [2].

The accelerated stream of ions of intensity $j_\infty \approx 10^{15}$–10^{17} ions/cm^2·sec was directed into the working chamber in which the residual gas pressure was $\sim 7 \cdot 10^{-7}$–$1 \cdot 10^{-6}$ torr. The measurements were made with a working chamber pressure of $\sim (0.87\text{-}1.6)\ 10^{-5}$ torr.

The energy accommodation coefficient of the nitrogen ions was measured with a planar hot wire anemometer probe, in the form of a disk $\delta = 0.12$ mm with a working surface of diameter 3.5 mm, to the back face of which were attached the current leads and a thermocouple. The lateral surface of the sensor, the thermocouple, and the current leads were insulated from contact with the plasma by means of a ceramic tube.

The volt–ampere characteristics $\log \dot{I}_e = f(V)$ had a sharply pronounced straight-line section. This allowed us to determine the electron temperature to be $T_e = 3.5$–4.7 eV by the conventional method [3].

The plasma potential φ_0 was determined by the second derivative method, and also from the electronic part of the probe characteristic, drawn on a semilogarithmic scale. This gave quite high accuracy in measurement of the energy W_i of ions of the stream transferred by the particles to the plasma–layer interface. The values obtained agree satisfactorily with values of W_i calculated on the assumption that the accelerating potential is equal to

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