Laplacian; $\Delta_1 = r(\partial/\partial r)(1/r)(\partial/\partial r) + (\partial^2/\partial x^2)$, second-order differential operator; $A = \varkappa_j t_*/\rho c_p R_j^2 = 2\ (\mathrm{We})^{1/2}/\mathrm{Pe}$; $t_* = (\rho R_j^3/\sigma)^{1/2}$, time scale; $\mathrm{We} = v_j^2 \rho R_j/\sigma$; $S = (\partial\sigma/\partial t)(T_j - T_s)/\sigma$; $l^2 = \gamma/\mathrm{Oh} + k^2$; $\beta^2 = \gamma/A + k^2$; I_n, modified Bessel function of order n; $\partial T_0/\partial x$, temperature gradient along the jet; σ, surface tension; ν, kinematic viscosity; k, wave number; v_j, mean velocity of the jet; ρ, density of the liquid; R_j, initial radius of the jet; $u_0(r)$, initial velocity profile; $\mathrm{Ma} = R_j(\partial\sigma/\partial T) + (\partial T_0/\partial x)/\sigma$; P, pressure perturbation; $\gamma = \gamma_r + i\omega$; Oh, Onezorg number.

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EXPERIMENTAL INVESTIGATION OF THE EFFECT OF THE SIGNAL-TO-NOISE RATIO ON THE CHARACTERISTICS OF FORCED CAPILLARY DISINTEGRATION OF A JET

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Dependences of the signal-to-noise ratio in a jet in the case of forced capillary disintegration of the jet (FCDJ) on the excitation signal, the mean jet velocity, the velocity distribution in the jet, and the jet diameter are derived. It is shown that, for equal excitation amplitudes, the signal-to-noise ratio in the case of FCDJ depends on the jet diameter and the velocity profile. A relationship between the relative scatter of diameters of the droplets formed as a result of FCDJ and the signal-to-noise ratio is derived.

The phenomenon of forced capillary disintegration of a liquid jet (FCDJ) is the basis of one of the most promising methods of generating an ordered flow of monodisperse (i.e., having similar dimensions) macroparticles. Such flow is finding increasingly wide application in technology and new techniques [1-3]. The basic advantages of this method include a high degree of monodispersity (a quantity which is the reciprocal of the coefficient of particle size variation), a considerable generation frequency, and a small angular divergence of the particle flux generated.

One of the most important problems in designing generators of monodisperse droplets characterized by a high degree of monodispersity is the provision of a maximum signal-to-noise ratio in the disintegrating jet. In the final analysis, this ratio determines the characteristics of the droplets generated, such as the standard deviation of sizes and velocities, the angular divergence, and the presence or absence of associated drops.

It should be mentioned that, until now, no attempt was made to determine experimentally the signal-to-noise ratio in the case of FCDJ. This is probably due to the difficulties in separating and recording the intensities of the many noise sources in the generator that are due to random frame vibrations, wall roughnesses in the outflow channel, relaxation of the velocity field in the jet, etc. The noise in the frequency band corresponding to the maximum gain increases the fastest, causing the jet to disintegrate into droplets.

For the criterion of the signal-to-noise ratio in FCDJ, we propose to use the ratio of the length L_j of the jet segment that has not disintegrated at a fixed level of the excitation

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signal to its mean length $\hat{L}_{jS}$ in spontaneous disintegration. This approach is based on the fact that the length of the nondisintegrating jet segment $\hat{L}_{jS}$ in spontaneous disintegration constitutes a natural "detector" of all internal and external noise level sources in the system.

By analogy with the relationships for the length of the nondisintegrating jet segment in the case of FCDJ [4], we write an expression for the mean length of the jet in spontaneous disintegration,

$$\hat{L}_{jS} = \frac{v_j}{\gamma} \ln\left(\frac{R_j}{\hat{\delta}_{0S}}\right),$$

where R_j is the radius of the unperturbed jet.

The noise level, as well as the amplitude of the initial perturbations responsible for FCDJ, can be measured with respect to the logarithm of the $\hat{\delta}_{0S}/R_j$ ratio (δ_0/R_j, respectively):

$$\ln\left(\frac{\hat{\delta}_{0S}}{R_j}\right) = -\frac{\gamma}{v_j}\hat{L}_{jS}.$$

Then, the difference between the logarithms of the δ_0/R_j and $\hat{\delta}_0/R_j$ values determines the signal-to-noise ratio in the jet:

$$\ln\left(\frac{\delta_0}{R_j}\right) - \ln\left(\frac{\hat{\delta}_{0S}}{R_j}\right) = \ln\left(\frac{\delta_0}{\hat{\delta}_{0S}}\right).$$

Considering that 1 dB = $10\log((\delta_0)/\hat{\delta}_0)$, we write the expression for the signal-to-noise ratio in the liquid jet in the following form:

$$G[\text{dB}] = 4{,}3\ln\left(\frac{\delta_0}{\hat{\delta}_{0S}}\right).$$

This makes it possible to determine experimentally the value of G with respect to the difference between the length of the nondisintegrating jet segment L_j in FCDJ and the mean length $\hat{L}_{jS}$ in spontaneous disintegration of a jet outflowing from the generator nozzle with the same mean velocity v_j in the absence of the FCDJ excitation signal:

$$G = 4{,}3\ln\left(\frac{\delta_0}{\hat{\delta}_{0S}}\right) = \frac{4{,}3\gamma}{v_j}(\hat{L}_{jS} - L_j). \tag{1}$$

We have investigated experimentally the effect of various factors – the conditions of disintegration excitation, the characteristics of the liquid to be dispersed, and the parameters of the generator nozzle – on the noise-to-signal ratio of the jet in FCDJ.

The experiments were performed with distilled water, a mixture of water and glycerin, and ethyl alcohol, which have the following characteristics at T = 20°C:

water: viscosity, $\eta = 1.05\cdot10^{-3}$ Pa·sec; surface tension, $\sigma = 0.0073$ N/m; density, $\rho = 10^3$ kg/m^3;

aqueous solution of glycerin: viscosity, $\eta = 10.96\cdot10^{-3}$ Pa·sec; surface tension, $\sigma = 0.0648$ N/m; density, $\rho = 1.141\cdot10^3$ kg/m^3;

ethyl alcohol: viscosity, $\eta = 1.22\cdot10^{-3}$ Pa·sec; surface tension, $\sigma = 0.023$ N/m; density, $\rho = 790$ kg/m^3.

The liquid to be dispersed was first purified by filtration through a filter where the pore diameter was equal to 20 μm.

Piston generators with vibrating nozzles were used for FCDJ excitation. The outflow channels in the generator nozzles were prepared by using tantalum disks with a thickness of 400 μm. The channels were provided with conical inlets which had convergence angles of 30-60°, rectangular outlet edges, and a unity ratio of the length to the outlet orifice diameter, $L_N/D_N = 1$. Glass channels with rectangular inlet and outlet edges, characterized by $L_N/D_N \gg 1$, were used in a number of experiments.

For determining the signal-to-noise ratio, we measured the length of the nondisintegrating segment L_j of the jet, the mean outflow velocity of the liquid v_j, and the disintegration time $t_d = L_j/v_j$ as functions of the excitation signal, defined by the dynamic pressure $P_\sim$ in the generator near the outflow channel. The increment in the rise of axisymmetric disturbances in the jet γ, used for calculating G by means of expression (1), was determined by using the dependence of the disintegration time t_d on $\ln P_\sim$.

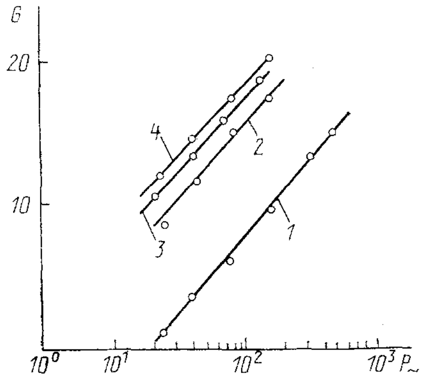

Fig. 1

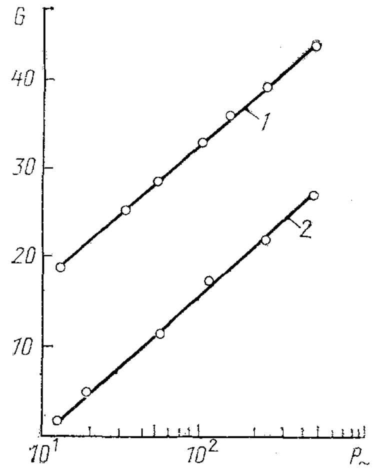

Fig. 2

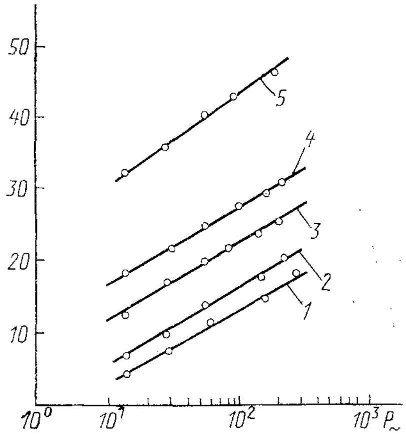

Fig. 3

Fig. 1. Signal-to-noise ratio in the jet G in the case of FCDJ as a function of the excitation signal $P_\sim$ and the mean jet velocity v_j. The water is deionized; $D_N = 50 \cdot 10^{-6}$ m, $L_N/D_N = 1$; 1) $v_j = 2.6$ m/sec; 2) 5.3; 3) 9.6; 4) 12.3. The values of G are given in decibels.

Fig. 2. Dependence of G on $P_\sim$ for different liquid velocity distributions in the jet. Ethyl alcohol, $v_j = 5.7$ m/sec and $D_N = 200$ μm. Curve 1 corresponds to a fully developed Poiseuille profile, $L_N/D_N = 54$; curve 2 corresponds to a velocity profile close to a uniform one, $L_N/D_N = 1$.

Fig. 3. Dependence of G on the $P_\sim$ value and the diameter of the outflow channel in the FCDJ generator nozzle D_N. Deionized water; $L_N/D_N = 1$, Re = 1000; 1) $D_N = 300$ μm; 2) 200; 3) 100; 4) 50; 5) 30.

The dynamic pressure was measured by means of a semiconductor pressure sensor with a constant amplitude–frequency response throughout the measurement frequency range, from 500 Hz to 50 kHz.

The length of the jet segment that had not disintegrated L_j was measured by means of a microscope, which was moved along the jet on the optical stage by means of a micrometric screw. The jet was illuminated with a strobotac synchronized with the disintegration frequency and provided with a device for changing the observation phase. The error in determining L_j in measurements based on this method was equal to ±5 μm. The method described in [5] was used for a more accurate determination of L_j. The beam of an argon laser was focused on the jet so that the beam diameter was approximately equal to the jet diameter. A magnified image of the jet was projected by means of an objective onto the diaphragm mounted in front of a photomultiplier. Since the jet of an optically transparent liquid constitutes a natural cylindrical lens, its shadow image has in its middle a light strip whose size is of the order of $0.1D_j$. The essence of the method consists in separating by means of the diaphragm the transparent region of the jet image and projecting it on the photocathode of the photomultiplier (an FÉU-85 photomultiplier was used). The photomultiplier signal was transmitted through a preamplifier to an integral discriminator and a scaling device, connected to a microcomputer by means of a KAMAK system. The FCDJ generator was moved vertically by means of a micrometric screw. This system made it possible to record with a high accuracy (of the order of ±1 μm) the length L_j of the jet segment that had not disintegrated, as the scaling device records pulses at the droplet formation frequency at the location of disintegration.

The mean liquid velocity in the jet v_j was found with respect to the liquid discharge, which was determined by weighing with an accuracy to 0.1%, while the mean velocity of monodisperse droplets in the jet was measured by using the flight time method.

The mean length of the nondisintegrating jet segment in spontaneous disintegration $\hat{L}_{jS}$ is found with respect to the position of the maximum of the $(1/N)(dN/dz)$ function, where N is the photomultiplier counting rate, and z is the coordinate along the jet.

Figure 1 shows the signal-to-noise ratio G for water ($D_N = 50$ μM) as a function of the dynamic pressure in the generator $P_\sim$ for different mean values of the outflow velocity v_j. It is evident that the value of G increases somewhat with an increase in v_j. This increase

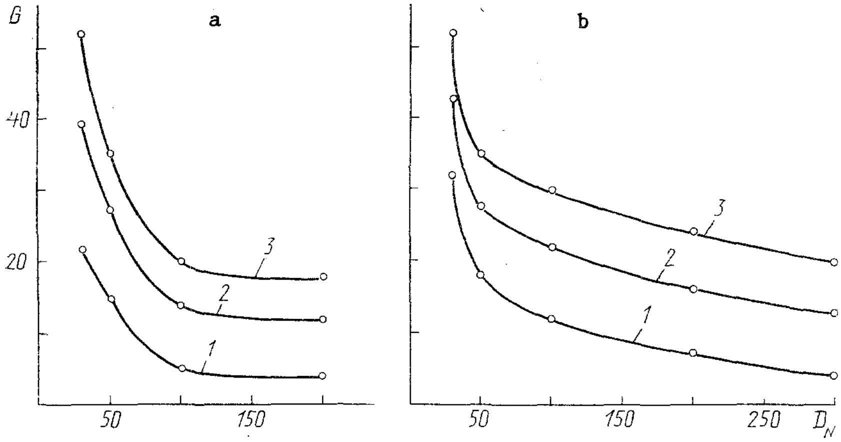

Fig. 4. Dependence of G on D_N for distilled (a) and deionized (b) water; L_N/D_N = 1. Curve 1 corresponds to the excitation signal $P_\sim$ = 10 Pa; 2) 100; 3) 500. The values of D_N are given in micrometers.

continues until v_j reaches values corresponding to a Reynolds number of ~2000, i.e., up to the point where the laminar character of the flow is disturbed. A considerable reduction in G was also observed with a decrease in v_j to a value below v_j^{min}, which was especially pronounced for nozzles with small D_N values. This is connected with the wetting of the nozzle's outside surface by the liquid, which causes distortion of the velocity field in the jet as it emerges from the outflow channel. Naturally, this distortion of the field (deviation of a velocity profile close to a uniform one, which is characteristic for channels with a small value of L_N/D_N) is more strongly pronounced as D_N diminishes, which explains the difference observed.

The effect of nonuniformity of the jet velocity profile in FCDJ on the value of G can be estimated by using the results of experiments where generator nozzles with sharply different L_N/D_N values are used, which are shown in Fig. 2. It is evident that, all other conditions being equal, the signal-to-noise ratio for a fully developed velocity profile in the jet (L_N/D_N = 54) is lower by almost 10 decibels in comparison with a uniform profile (L_N/D_N = 1). It should be mentioned that this is also confirmed by the increase in L_j as the ratio L_N/D_N increases for a constant value of $P_\sim$, which we observed earlier [4].

Figure 3 shows the dependences of G on $P_\sim$ for different diameters D_N of the outflow channel for the same value L_N/D_N = 1 and a mean jet velocity v_j for which the Reynolds number is equal to Re = 100. The data obtained indicate that the value of G rises with a reduction in the jet diameter, which can be explained by an increase in the ratio of the surface tension force responsible for FCDJ to the inertial force.

The sharp increase in G for D_N = 30 μm is connected with the development of dynamic surface tension during short times of jet surface existence. This is readily seen in comparing the experimental dependences of G on D_N for distilled (Fig. 4a) and deionized (Fig. 4b) water. In the first one, the rise in surface tension occurs with longer times of surface existence (disintegration times), which manifests itself in an "earlier" (for D_N = 100 μm) change in the character of the relationship between G and D_N with a decrease in D_N.

The standard deviation of droplet sizes in forced capillary disintegration of a jet outflowing from nozzles with different outflow channel diameters was measured by using the method of image analysis, which entailed an error not worse than ±0.1% throughout the entire measurement range. The method is based on using a pulsed coherent light source and a multichannel optical analyzer for recording the images of droplets, combined with a personal computer. An LGN-502 argon laser was used as the light source. Its radiation was modulated by means of an opticoacoustic modulator (OAM), which made it possible to produce coherent radiation pulses with a duration of 100 μsec for illuminating the droplets. The light pulses were synchronized with the droplet formation frequency by means of an electronic circuit.

In measuring the standard deviation of droplet dimensions, the PZS linear receiver of an OMA sensor head was positioned perpendicularly to the direction of the flow of macroparticles, and the light pulses were produced at the moment the receiver was intersected by the droplet diameters.

TABLE 1. Dependence of the Standard Deviation of the Diameters of Droplets Formed due to FCDJ δD and $\delta D/D$ on the Diameter of the Outflow Channel D_N and the Signal-to-Noise Ratio G for the Excitation Signal Amplitude $P_{\sim}$ = 100 Pa

D_N, µm	G, dB, for $P_{\sim}=100$ Pa	δD, µm	$(\delta D/D)$, %
100	22	0,8±0,4	0,2±0,15
200	16	0,9±0,4	0,2±0,1
300	13	1,1±0,3	0,2±0,1
400	10	2,2±0,3	0,3±0,05
500	—	2,7±0,3	0,3±0,05

The exposure time of the OMA sensor head was set at 200 msec, which ensured accumulation of the images of $2\cdot10^2$ to $2\cdot10^3$ droplets during the exposure time in the frequency range used (1-50 kHz). The data obtained were converted to decimal code and were recorded in the magnetic-disk accumulator of the computer for subsequent processing.

The optical system was calibrated and adjusted by using a precision scale-coordinate grid, placed at the location of the jet. Glass light fibers with diameters close to the diameters of the droplets under investigation were used for determining the instrumental line of the system.

The standard deviation values of the droplet sizes δ_D were determined by means of the expression

$$\delta D = \sqrt{\delta D_e^2 - \delta D_i^2},$$

where δD_e is the standard deviation of the particle diameters, measured with respect to the half-width of the differential distribution, and δD_i is the instrumental line of the system, defined by the diffraction divergence of the laser beam and the quality and setting of the optical system. The results of individual measurements were summed, so that the total statistical measurement data corresponded to the recording of not less than 10^4 droplets.

The results obtained in measuring the standard deviation of droplets are given in Table 1. It is evident from the table that, for equal excitation signals $P_{\sim}$, the coefficients of variation of the droplet dimensions increase with the jet thickness (the diameter of the outflow channel D_N) in proportion to the reduction in the signal-to-noise ratio as D_N increases. This indicates that the criterion for estimating the signal-to-noise ratio in the jet that is proposed here is actually related to the standard deviation of the droplets formed, which is a most important characteristic of FCDJ.

The results obtained are of great importance in designing generators of monodisperse particles for various applications.

NOTATION

η, viscosity; σ, surface tension; T, temperature; ρ, density of the liquid to be dispersed; L_j, length of the nondisintegrating part of the jet in FCDJ; $\hat{L}_{jS}$, mean length of the nondisintegrating part of the jet in spontaneous disintegration; v_j, mean jet velocity; t_d, disintegration time; D_N, diameter of the outflow channel; δ_D, standard deviation of the particle dimensions; $P_{\sim}$, dynamic pressure in the generator chamber; γ, increment in the rise of perturbations of the jet surface; δ_0, amplitude of the initial FCDJ disturbance; δ_{0S}, mean amplitude of the initial jet perturbations in spontaneous disintegration.

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