LITERATURE CITED

1. V. N. Stasenko, "Use of a shadow instrument for determination of the characteristics of turbulence," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1970).
2. S. R. Stefanov, A. M. Trokhan, and Yu. D. Chashechkin, "Investigation of the turbulent pulsations of the refractive index of water using Töpler instrument," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1971).
3. L. M. Soroko, Principles of Holography and Coherent Optics [in Russian], Nauka, Moscow (1971).
4. Yu. I. Kopilevich, "Connection between the characteristics of the signal of a shadow instrument and the spectrum of the turbulence," Zh. Prikl. Mekh. Tekh. Fiz., No. 6 (1975).
5. T. L. Ho, "Coherence degradation of Gaussian beams in a turbulent atmosphere," J. Opt. Soc. Am., 60, No. 5 (1970).
6. V. N. Tatarskii, "The propagation of waves in a turbulent atmosphere" [in Russian], Nauka, Moscow (1967).
7. G. Korn and T. Korn, Handbook on Mathematics [in Russian], Nauka, Moscow (1974).
8. A. S. Gurvich, N. S. Time, L. S. Turovtsev, and V. F. Turchin, "Reconstruction of the spectrum of turbulent pulsations in the atmosphere from optical measurements," Izv. Akad. Nauk SSSR, Fiz. Atmos. Okeana, No. 5 (1974).
9. V. F. Turchin, V. P. Kozlov, and M. S. Malkevich, Using Methods of Mathematical Statistics for Solving Incorrect Problems, Usp. Fiz. Nauk, No. 3 (1970).

EXPERIMENTAL STUDY OF DYNAMICS OF GAS BUBBLES IN A TURBULENT JET

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In investigating the scattering of ultrasound by turbulent jets for noncontacting flow diagnostics, the effect of gas bubbles of various sizes must be taken into account. The problem of the evolution of the bubble distribution function in the jet is also of certain interest.

A number of experimental papers have appeared on the study of the free-gas content in still water and in a disturbed volume of liquid. Gavrilov [1] describes a method for determining the free-gas content based on a measurement of the attenuation of ultrasound.

In this method the gas content is estimated from the expression

$$K_l = 6{,}3 \cdot 10^5 n(R_0) R_0^3,$$

where K_l is the attenuation factor in dB/m; $n(R_0)$ is the number of bubbles per cm^3 of liquid; and R_0 is the radius of a bubble.

We find the gas-bubble distribution function by using the tabulated values [2] of the absorption cross section σ for bubbles of various sizes. Since the composition of the gas in the bubbles is uncertain, the actual and calculated values of the absorption cross section differ somewhat. Nevertheless, a knowledge of the frequency dependence of σ permits a study of the variation of the bubble-distribution function along the jet.

The intensity of an ultrasound wave propagating in a medium containing bubbles varies according to the law [3]

$$W(x) = W_0 e^{-n_R \sigma_R x}, \qquad (1)$$

where $W(x)$ is the wave intensity after penetrating a distance x into the layer with bubbles; W_0 is the wave intensity at the entrance to the layer; n_R is the number density of bubbles of radius R; and σ_R is the absorption cross section of a bubble of radius R.

It is well known [3] that the absorption of sound energy by a gas bubble is maximum at a frequency equal to the resonance frequency of the bubble [4]

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$$f = \frac{1}{2\pi R}\sqrt{\frac{3\gamma\left(p+\frac{2\sigma}{R}\right)}{\rho}},$$

where p is the hydrostatic pressure in the liquid; ρ is the density of the liquid; and γ is the adiabatic exponent.

Calculations presented in [2] are a good illustration of the resonance properties of bubbles and permit a determination of the bubble-size distribution function from measurements of the attenuation of sound energy at various frequencies.

We performed measurements in a hydroacoustic basin. A jet of water at the outlet from a four-jet cylindrical nozzle with cylinders 10 mm in diameter located symmetrically around a circle 20 mm in diameter had a velocity of ~25 m/sec. The nozzle was submerged to a depth of 50 cm; the jet was emitted in the horizontal direction. The distance between the ultrasonic receiver and radiator was fixed at 15 cm. The measuring tank was calibrated at several working frequencies between 300 and 2000 kHz in still water. A pseudoceramic plastic was used as a detector and the radiator was a sphere of TsTS-19. The use of a sphere almost completely eliminates the formation of standing waves in the acoustic tank. After calibration the jet was turned on and the amplitude of the wave which had passed through the jet was measured at the same frequencies at which the calibrations had been performed. The number density of bubbles was calculated from Eq. (1)

$$n(R) = \frac{2 \lg K}{\sigma_R x \lg e}, \quad (2)$$

where n(R) is the number density of bubbles in the range of radii R ± (1/2)ΔR, K is the ratio of the amplitude of the signal in the undisturbed jet to the amplitude of the signal at a distance x into the turbulent jet.

Taking account of the fact that the quality factor Q of a bubble as a resonance system depends on the frequency [5], the graph of the resonance frequency of a bubble as a function of its radius (values of the attenuation factor calculated in [5]) was used to find the range ΔR of bubble sizes corresponding to the extinction of the ultrasound wave of the given frequency.

The values of the number density of bubbles of a given size calculated by Eq. (2) were normalized to the range $\Delta R = 0.3 \cdot 10^{-4}$ cm, which was the smallest of the sizes found.

The dependence of the Q of a bubble on its size imposes an upper limit on the frequencies or a lower limit on the sizes of bubbles which can be measured by this method. Measurements at frequencies above 2 MHz, which corresponds to bubble radii smaller than $2 \cdot 10^{-4}$ cm, cannot be considered correct since the quenching of sound of a higher frequency is strongly affected by larger bubbles as well as by those of resonance dimensions. The lower frequency limit, or maximum size of measurable nuclei, is determined by the reverberation properties of the system. It is 300 kHz, which corresponds to bubble radii $\sim 1.3 \cdot 10^{-3}$ cm.

The bubble-size distribution function was taken at various positions from 0 to 137 cm from the nozzle outlet. The geometry of the jet was taken into account. The width of the jet was taken as the distance between the boundaries of a dense filler of visible air bubbles artificially introduced into the jet. The measurements confirmed that the effective boundaries of the jet are rectilinear [6]. Assuming that the bubbles were more or less uniformly distributed over the cross section of the jet, which is probably not a very crude approximation for a highly turbulent jet, the total number of bubbles in a cross section of the jet 0.51 mm thick was calculated. A layer of this thickness at the nozzle outlet has a volume of 1 cm^3.

Figure 1 shows the measured bubble-distribution function. The experimental points are denoted by small circles. In the calculations the value of K at each point was taken as the average of four or five measurements performed on different days. The deviation of K from the mean value did not exceed 20-30%. The number of bubbles in the layer with radii R ± (1/2)ΔR is plotted along the vertical. Curves 1-5 represent the bubble-distribution functions at distances of 5, 17, 37, 57, and 87 cm, respectively, from the nozzle outlet.

The total number of bubbles in a layer was estimated from the graphs, part of which are shown in Fig. 1, Analysis of the dependence of the total number of bubbles in a layer on the distance of this layer from the nozzle outlet shows that under our experimental conditions

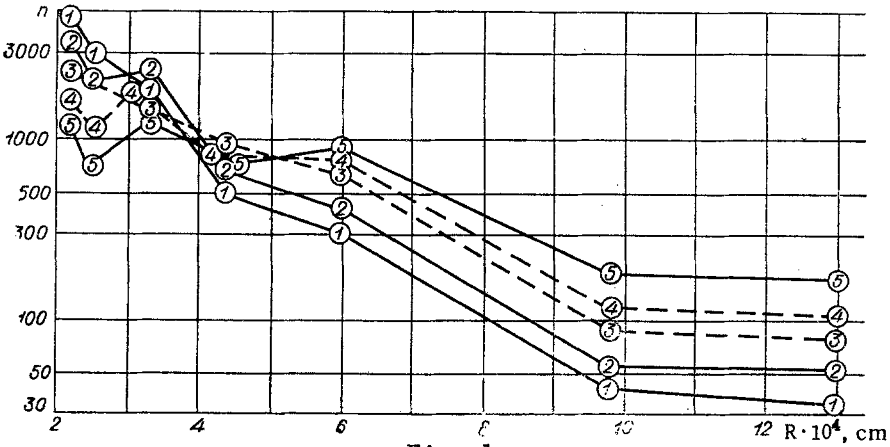

Fig. 1

the total number of bubbles with radii from $1.3 \cdot 10^{-3}$ to $2.15 \cdot 10^{-4}$ cm remains practically constant within the limits of error of the measurements and calculations up to distances ~120 cm.

From all appearances, most of the bubbles are produced inside the nozzle and only a small fraction in the immediate vicinity of the edge of the nozzle. Then the bubbles begin to grow as a result of diffusion and coagulation processes [7, 8]. Since the number of bubbles of the sizes monitored hardly changed, the diffusion process must be the most effective for our flow pattern. We present a further argument in favor of the diffusion process. In coagulation most of the free gas in bubbles of the sizes checked comes from bubbles of radii smaller than $2 \cdot 10^{-4}$ cm. To ensure the observed increase in the amount of free gas in bubbles of radius ~10^{-4} cm would require ~10^{6} bubbles in the layer. Such a number of bubbles would attenuate a 4-5 MHz signal much more strongly than is found experimentally.

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LITERATURE CITED

1. L. P. Gavrilov, "Free-gas content of a liquid and acoustical techniques for its measurement," Akust. Zh., 15, No. 3 (1969).
2. A. N. Sizov, "Dissipation of sound energy in small gas bubbles," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1975).
3. M. A. Isakovich, General Acoustics [in Russian], Nauka, Leningrad (1973).
4. A. D. Pernik, Problems of Cavitation [in Russian], Sudostroenie, Leningrad (1966).
5. C. Devin, "Survey of thermal, radiation, and viscous damping of pulsating air bubbles in water," J. Acoust. Soc. Am., 31, No. 12, 1654 (1959).
6. L. A. Bulis and V. P. Kashkarov, Theory of a Jet of Viscous Fluid [in Russian], Nauka, Moscow (1965).
7. É. M. Agrest and G. N. Kuznetsov, "Dynamics of the bubble-size distribution in sound fields," Akust. Zh., 20, No. 3 (1974).
8. Yu. N. Kalashnikov, "Effect of turbulent diffusion on the change in sizes of gas bubbles in a liquid," Akust. Zh., 16, No. 4 (1965).