OPTICAL METHOD FOR MEASURING THE DISTRIBUTION OF A SOLID ADMIXTURE IN TWO-PHASE FLOWS

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We discuss an optical method for measuring the density distribution of a solid admixture with a narrow particle-size distribution function by the intensity of the scattered light. A comparison of measurements made by the optical method and by a probe shows the suitability of the optical method for a number of types of two-phase flows.

Suction probes [1] are commonly used to obtain information on the distribution of a solid admixture in two-phase flows of the gas–solid particles type. By performing probe measurements under isokinetic conditions [2, 3] the distribution of the discharge mass concentration can be determined. The method has a number of merits but also has fundamental shortcomings which limit its range of applicability: the long time required for the measurements and the related large discharge of the solid admixture; the necessity of determining the magnitude and direction of the velocity of the continuous phase, which is a complex problem in spatial two-phase flows; the necessity of orienting the probe inlet along the velocity of the continuous phase; the high abrasive wear of the probe inlet, particularly for flow velocities of 100 m/sec and higher. The facts mentioned prompt a search for more efficient methods of measuring the distribution of the solid admixture.

A noncontact optical method based on the dependence of the intensity of scattered light on the properties of the scattering medium is very promising for a certain class of two-phase flows. In general, this dependence has a very complex character, but if the particle-size distribution function retains its form, on the basis of known ratios [4] for two rather small flow regions with coordinates x_i, y_i, and x_k, y_k we can write

$$\frac{\rho_{sd}(x_i, y_i)}{\rho_{sd}(x_k, y_k)} = \frac{I(\beta, x_i, y_i)\, I_0(x_k, y_k)}{I(\beta, x_k, y_k)\, I_0(x_i, y_i)}, \tag{1}$$

where $I_0(x, y)$ is the intensity of the incident beam in volume v with coordinates x, y; $I(\beta, x, y)$ is the intensity of the light scattered in volume v at angle β with the direction of the incident beam; ρ_{sd} is the dispersion density or the density of the discrete admixture distribution, i.e., the mass of particles in a unit volume.

Assuming that the Bouguer law holds for the medium under study and that according to [5] this law is valid in certain cases up to optical densities of the order $\tau = 12$, Eq. (1) can be rewritten to take account of the attenuation of the incident and scattered beams:

$$\frac{\rho_{sd}(x_i, y_i)}{\rho_{sd}(x_k, y_k)} = \frac{\tilde{I}(\beta, x_i, y_i)\exp\left[\int\limits_0^{l_i} K(x, y)\, dl + \int\limits_0^{l_i^1} K(x, y)\, dl\right]}{\tilde{I}(\beta, x_k, y_k)\exp\left[\int\limits_0^{l_k} K(x, y)\, dl + \int\limits_0^{l_k^1} K(x, y)\, dl\right]}, \tag{2}$$

where K is defined by the expression

$$K(x, y) = N_0(x, y)\int K(\rho, m)\, \pi r^2 f_N(r)\, dr. \tag{3}$$

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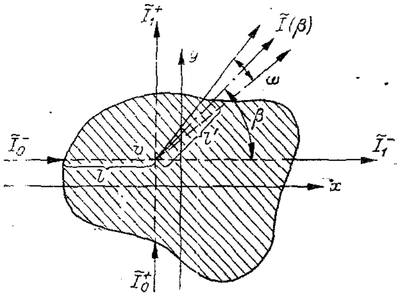

Fig. 1

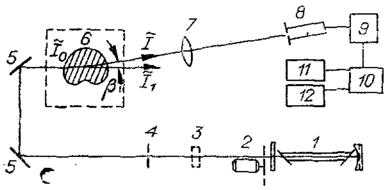

Fig. 2

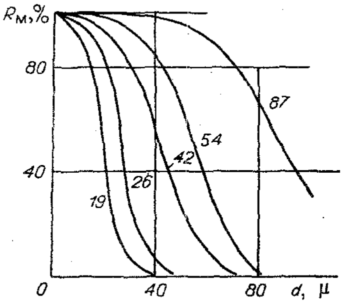

Fig. 3

Here $\rho = 2\pi r/\lambda$ is the diffraction parameter; $K(\rho, m)$ is the particle attenuation factor; $\tilde{I}$ is the intensity of the light outside the volume of the scattering medium. It should be noted that $K(\rho, m)$ may vary from 1 to 2 [6] depending on the recording conditions. We introduce the notation

$$\int K(x, y)\,dy = \tau_1(x) = \ln\frac{\tilde I_0^+}{\tilde I_1^+},$$

$$\int K(x, y)\,dx = \tau_2(y) = \ln\frac{\tilde I_0^-}{\tilde I_1^-},$$

where the integration is performed along the appropriate beam, and the meanings of the symbols $\tilde I_0^-$, $\tilde I_0^+$, and $\tilde I_1^-$, and $\tilde I_1^+$ can be seen from Fig. 1.

The values of the exponents characterizing the total attenuation can be determined very simply by selecting a suitable system of measurement for objects with central or axial symmetry. In the first case for scattering angles $\beta = 90°$ and scanning of the optical system in the xy plane along the y axis passing through the center of the scattering medium, it can be shown from (2) that

$$\frac{\rho_{sd}(0, y)}{\rho_{sd}(0, 0)} = \frac{\sqrt{\tilde I(\beta, 0, +y)\,\tilde I(\beta, 0, -y)}}{\tilde I(\beta, 0, 0)} \exp\left|\frac{\tau_2(y) - \tau_2(0)}{2}\right|.$$

For a similar measuring scheme but with a small angle of scattering with respect to the direction of the incident beam, Eq. (2) becomes

$$\frac{\rho_{sd}(x, y)}{\rho_{sd}(0, 0)} = \frac{\tilde I(\beta, x, y)}{\tilde I(\beta, 0, 0)} \exp\left[\tau_2(y) - \tau_2(0)\right].$$

The attenuation of the incident and scattered waves can be found from Eq. (3) by the method of successive approximations, taking as the initial approximation

$$K^{(0)}(x, y) = \frac{\tau_1}{\int \frac{\tilde I(\beta, x, y)}{\tilde I(\beta, 0, 0)}} \cdot \frac{\tilde I(\beta, x, y)}{\tilde I(\beta, 0, 0)}.$$

As noted above a sufficient condition for satisfying Eq. (1) is the preservation of the particle-size distribution function. Actually, in most two-phase aerodynamics processes there is a certain distortion of the particle-size distribution function, and therefore, the method considered can yield reliable information on the distribution of dispersion density only in flows with sufficiently narrow particle-size distribution functions. Even when this condition is satisfied its applicability must be tested for each class of flow by comparison with the results obtained by an independent method. It should be noted that such a comparison is not a verification of the present method, which is accurate, but a test of whether the assumptions on which the method is based are satisfied in actual two-phase flows. A comparison was made with the isokinetic probe method for flow in a circular tube of a two-phase submerged jet, and in a radial two-phase jet under subsonic flow conditions. The maximum error of the probe method, determined by a comparison of the flow rate computed from the profiles of the mass flow rate with the total flow rate of the admixture, is 10%. The instrument error is determined by the linearity of the scheme and is ~3%.

The arrangement shown in Fig. 2 was used to measure the distribution of the dispersion density in a radial two-phase jet. Its main elements are: an LG-75 laser operating in a multimode regime (1); a circular disk with 32 holes modulating a light beam with a frequency of 1600 Hz (2); a polarizing light filter for varying the intensity of the light beam (3); a circular diaphragm with a 1-mm-diameter opening (4); hinged mirrors (5); the volume of the dispersive medium under study (6); a long focal length lens F = 220 mm (7); a photomultiplier and plane diaphragm (8). The dashed line shows the plastic channel.

The equipment operates in the following way: The modulated light beam passes through the volume under study. Part of the light scattered in the volume being probed falls on lens (7) and is projected onto diaphragm (8). The signal from the photomultiplier passes through the cathode follower (9) and is fed into a V 6-4 narrow-band amplifier (10). The signal amplitude is recorded continuously by a KSP-4 potentiom-

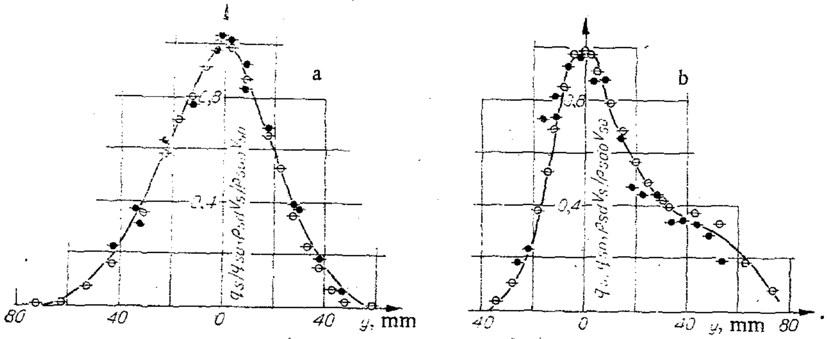

Fig. 4

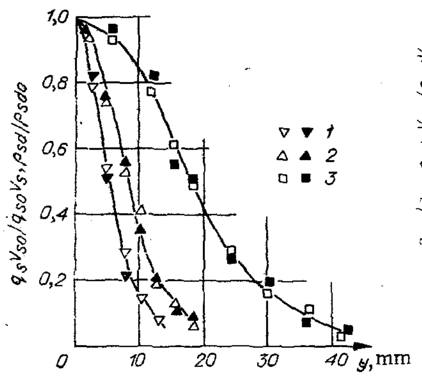

Fig. 5

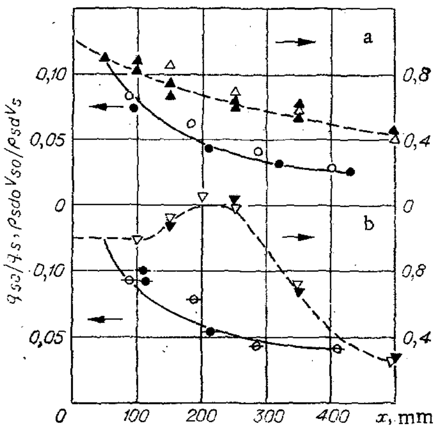

Fig. 6

eter. The absence of nonlinear distortions is controlled by an SI-5 oscillograph (12). The ratio $\tilde{I}_0/\tilde{I}_1$ is measured with the same arrangement. The volume v being probed extends 5 mm along the x axis.

A similar measuring scheme is used to investigate the two-phase submerged jet.

The velocity of the solid admixture V_s is measured by a modified laser Doppler velocimeter [7]. The error of the measurement, determined by comparing the velocity of smoke particles measured by the laser Doppler velocimeter and the velocity of the gas by a Prandtl tube, is 4%.

The discrete admixture used was powdered electrolytically produced corundum with weighted-mean sizes of 19, 26, 42, 54, and 87 μ shown by the histograms in Fig. 3.

Profiles of the relative mass flow rate of the admixture $q_s = \rho_{sd}V_s$ in the plane of symmetry of the radial two-phase jet obtained by probe (black points) and optical (light points) methods are shown in Fig. 4 for admixture sizes of 54 μ (a) and 19 μ (b) and discharge mass concentrations $\varkappa = 1.0$ and 0.6, respectively. The comparison was performed for a cross section close to the turn of the jet in which the maximum deformation of the initial particle size distribution function is observed.

Profiles of the relative dispersion density in a cross section of a two-phase jet 250 mm from the end of a tube 30 mm in diameter are shown in Fig. 5 for admixture particle sizes of 1) 26; 2) 42; 3) 87 μ.

From the point of view of the suitability of the optical method the most interesting details in our opinion are shown in Fig. 6, where curves of the attenuation of the relative mass flow rate are compared. The quantities refer to values averaged over the cross section at the mouth of the tube. The notation is the same as in Figs. 4 and 5.

Within the limits of experimental error the data of Figs. 4-6 show the suitability of the optical method of measuring the distribution of a solid admixture for powders with a narrow particle-size distribution function for the classes of two-phase flows considered.

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