METHOD FOR STUDY OF PARTICLE CONCENTRATION FIELDS IN DISPERSED FLOWS

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A technique for measuring local particle concentrations in dispersed flows is considered. Operation of the optoelectronic apparatus used is analyzed for "single particle" and "multiparticle" cases.

The simple method of dispersed particle concentration measurement proposed in [1] has been employed successfully in the study of two-phase flows of various types.

Below we will present a detailed description and analysis of this method with consideration of the following major assumptions: τ, the optical thickness of the dispersed medium studied, satisfies "single" scattering conditions; the particle diffraction parameter $\rho_S \gg 1$; the particle radius r_S satisfies the condition $r_S < r_f$ (here and below the index s indicates parameters of the dispersed particles).

One beam of a differential circuit laser [2] will be used with wave vector $\vec{k}_{02}$ and power P_0, focused on the portion of flow to be studied. The light scattered by the particles is collected by an optical receiving system located in the plane xy at an angle β to the direction $\vec{k}_{02}$ (Fig. 1a). The dimensions of the region to be considered depend on the radius of the laser beam r_f in the constriction region and the parameters of the receiver optical system, being defined by the following expressions:

$$\Delta x = 2\, r_f \cos^{-1}\beta;\ \ \Delta y = a \sin^{-1}\beta \left[\frac{d_1}{f_1} - 1\right];\ \ \Delta z = 2\, r_f. \tag{1}$$

The radius r_f at the level exp (−1) and the divergence angle θ, defining the degree of parallelism within the limits of the region Δy, are found from the expressions [3]:

$$r_f = \left\{\frac{1}{k_0}\left[\frac{R_e}{(1-d_0/f_0)^2 + (R_e/2f_0)^2}\right]\right\}^{1/2};$$
$$\theta = \left\{\frac{2\,\lambda_0}{\pi R_e}\left[\left(1-\frac{d_0}{f_0}\right)^2 + \left(\frac{R_e}{2\, f_0}\right)^2\right]\right\}^{1/2}. \tag{2}$$

The laser beam electric field complex amplitude distribution E(R, t) in the measurement region for the case of a Gaussian beam is given by

$$E(R,\ t) = \left(\frac{P_0}{\pi r_f^2}\sqrt{\frac{\mu}{\varepsilon}}\right)^{1/2} \exp\left[-\frac{x^2+z^2}{2\, r_f^2} + i\,(\vec{k}_0\vec{R} - \varphi)\right]. \tag{3}$$

The light intensity, or mean energy density in the beam section in the measurement volume, is found from

$$I(x,\ z) = \frac{1}{2}\sqrt{\frac{\varepsilon}{\mu}}\,[E(R,\ t)\,E^*(R,\ t)] = \frac{P_0}{\pi r_f^2}\exp\left(-\frac{x^2+z^2}{2\, r_f^2}\right). \tag{4}$$

Assuming that $r_S \ll r_f$ the light flux $P_S(\beta)$ scattered by a fixed particle with coordinates $x_K z_K$ into solid angle $\Delta\Omega$ in the direction $\vec{k}_S$ at an angle β to $\vec{k}_{02}$ is equal to

$$P_s(\beta) = I(x_K z_K)\int_{\Delta\Omega} d\sigma_K(\rho_s\beta) = I(x_K z_K)\, S_K(\rho_s,\ \beta,\ \Delta\Omega). \tag{5}$$

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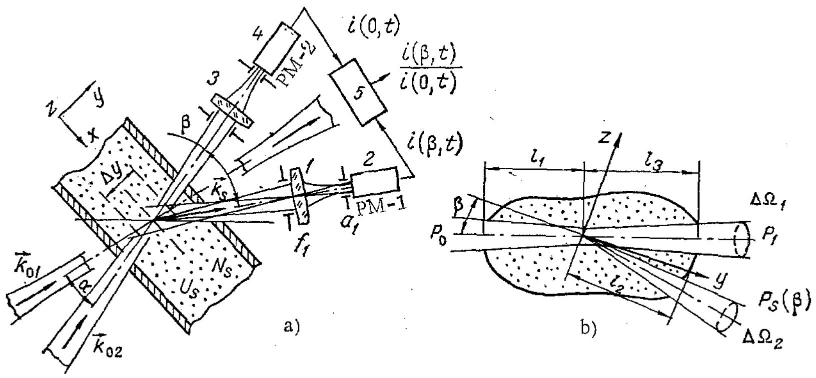

Fig. 1. Experimental geometry: a) overview; 1, 3, receiver objectives with aperture diaphragms for scattered (1) and direct (3) beams; 2, 4 point diaphragms ahead of type FÉU-68 photomultipliers for first (PM-1) and second (PM-2) channels; 5, electronic signal processing circuitry for both channels. b) Diagram of direct and scattered beams.

In writing Eq. (5) it was assumed that the change in light intensity over the particle can be neglected. From Eqs. (4) and (5) there follows an expression for the "optical signal" at the photodetector input

$$P_{s\text{к}}(\beta) = \tau_0 \frac{P_0}{\pi r_f^2} \exp\left(-\frac{x_\text{к}^2 + z_\text{к}^2}{r_f^2}\right) S_\text{к}(\rho_s, \beta, \Delta\Omega_2). \tag{6}$$

Light flux (6) defines the value of the constant electrical signal at the photodetector output. Introducing the quantity χ, which characterizes the sensitivity of the receiver system, we obtain from Eq. (6) an expression for the signal at the photomultiplier output from the fixed K-th scattering particle with coordinates $x_K y_K$ in the interval Δy:

$$j_\text{к}(\beta) = k_\Phi \frac{\eta e}{h\nu_0} \left\{\tau_0 \frac{P_0}{\pi r_f^2} \exp\left(-\chi^2 \frac{x^2 + z^2}{c^2}\right) S_\text{к}(\rho_s, \beta, \Delta\Omega_2)\right\}. \tag{7}$$

In analyzing dispersed flows as functions of particle concentration and size of the measurement region there exist two modes of measurement system operation: "multiparticle" and "single particle."

The "multiparticle" mode is realized under the condition $N_{SV} \gg 1$, where $N_{SV} = N_S \cdot V$ is the mean statistical number of particles in the volume V; N_S, mean particle concentration in the measurement region. In the given situation the mean (over time) value of the photocurrent at the photomultiplier output can be calculated from the expression

$$\overline{i_1(\beta, t)} = M\left\{\sum_{k=1}^{N_{sV}} j_\text{к}(\beta)\right\} = \overline{N_{sV}} \langle\langle j_\text{к}(\beta)\rangle\rangle. \tag{8}$$

In Eq. (8) M is the mathematical expectancy; a line above a quantity denotes averaging over time; the double brackets $\langle\langle\,\rangle\rangle$ denote averaging over coordinates and the set of particles. Now in Eq. (7) we take $x_K = U_S(t-t_K)$ and perform the averaging operations of Eq. (8) for $i_1(\beta, t)$, and we obtain

$$\overline{i_1(\beta, t)} = \overline{N_{sV}} \langle I_{0V}\rangle \left\{k_\Phi \frac{\eta e}{h\nu_0} \tau_0 \Phi^2(2\chi)\right\} S(\rho_s, \beta, \Delta\Omega_2). \tag{9}$$

The "single particle" operating mode occurs at $N_{SV} \leq 1$. Now the photocurrent $i_2(\beta, t)$ is a sequence of pulses with random amplitude and phase:

$$i_2(\beta, t) = \sum_{k=1}^{n_\text{т}} i_{0\text{к}} \psi(t - t_\text{к}), \tag{10}$$

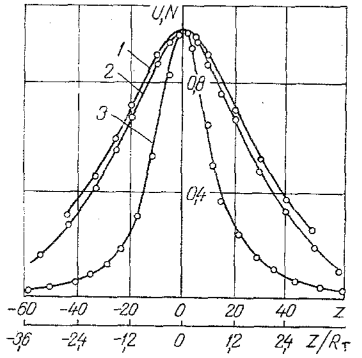

Fig. 2. Local mean velocity (1) and concentration (3) of particles and gas velocity (2) in two-phase turbulent blunt jet. z, mm.

where i_{0K} is the random amplitude of the signal from the K-th particle; ψ ($t-t_K$), a function characterizing the form of the signal; t_K, moment of arrival of the K-th particle at the center of the measurement volume. Assuming as a first approximation that the forms of the pulses from different particles are identical, the mean value of the photocurrent is found from [4]

$$\overline{i_2(\beta,\ t)} = \frac{n_T}{T} M(i_{0K}) \int_{-\infty}^{\infty} \psi(t - t_K)\, dt, \tag{11}$$

where $n_T = U_S \Delta z \Delta y N_S T$ is the number of particles which during the measurement time T pass through the section $\Delta z \Delta y$ of the measurement volume. From Eq. (11) for $\overline{i_2(\beta,\ t)}$ it follows that

$$\overline{i_2(\beta,\ t)} = \overline{N_{sV}} \langle I_{0V} \rangle \left\{k_\Phi \frac{\eta e}{h\nu_0} \tau_0 \Phi(2\chi)\right\} \langle S(\rho_s,\ \beta,\ \Delta\Omega_2) \rangle . \tag{12}$$

Within the framework of the assumptions made, Eqs. (9) and (12) reflect the direct relationship between i (β, t) and N_{SV} in both modes. In the general case Eqs. (9) and (12) must contain an auxiliary factor defining the degree of attenuation of the direct beam P_0 and the light flux $P_S(\beta)$ scattered into the reception angle. Omitting the averaging symbols, we rewrite Eqs. (9) and (12) with consideration of attenuation of the direct and scattered beams:

$$i(\beta,\ t) = \text{const}\, N_s P_0 \exp\left\{-\int_{l_1} \tau(l)\, dl - \int_{l_2} \tau(l)\, dl\right\} . \tag{13}$$

In Eq. (13) integration is performed over the entire length of the direct and scattered beams in the medium (Fig. 1b). Upon reception of the scattered beam at low angles $\beta \leq 20°$, given the condition $\Delta\Omega_1 \sim \Delta\Omega_2$, we can take $l_2 \simeq l_3$ and rewrite Eq. (13) in the following form:

$$i(\beta,\ t) = \text{const}\ N_s \left\{P_0 \exp\left[-\int_{l_1+l_3} \tau(l)\, dl\right]\right\} = \text{const}\ N_s i(0,\ t). \tag{14}$$

With consideration of Eq. (14), there follows from Eqs. (9), (12) and (13) a general expression for the ratio of the local mean numerical N_S (cm^{-3}) or mass ρ_{Sd} ($kg \cdot cm^{-3}$) particle concentrations in regions of the beams whose centers have the coordinates $x_i y_i z_i$ and x_j, y_j, z_j [1]:

$$\frac{N_{si}}{N_{sj}} = \frac{\rho_{sdi}}{\rho_{sdj}} = \left[\frac{i(\beta,\ t)}{i(0,\ t)}\right]_i \left[\frac{i(\beta,\ t)}{i(0,\ t)}\right]_j^{-1} . \tag{15}$$

A similar relationship can be obtained for a polydispersed medium, characterized by a particle distribution over size $f(r_S)$, defined by the relationship $dN(r_S) = N_S f(r_S) dr_S$. In this case Eq. (15) is written as

$$\frac{N_{si}}{N_{sj}} = \left[\frac{i(\beta,\ t)}{i(0,\ t) \int_{r_s} f(r_s)\, dr_s}\right]_i \left[\frac{i(\beta,\ t)}{i(0,\ t) \int_{r_s} f(r_s)\, dr_s}\right]_j^{-1} . \tag{16}$$

If the form of $f(r_S)$ is maintained within the flow volume, Eq. (16) takes on the form of Eq. (15); in the contrary case, in order to apply the method to polydispersed systems it is necessary to determine the function $f(r_S)$ in each region and introduce a corresponding correction.

Equations (15) and (16) are the operative formulas of the method. The task of the electronic apparatus is to express the ratio $i(\beta, t)/i(0, t)$ in the form of an electrical signal which is a function of flow coordinates. Further processing of graphs $i(\beta, t)/i(0, t) = f(x, y, z)$ and reduction to the form of Eqs. (15) and (16) is carried out by a computer with graph plotting equipment. In real experiments the dispersion of the values $i(0, t)$ is much less than the dispersion of $i(\beta, t)$, and the normalized rms error ξ of a single measurement in the case of frequency-limited "white noise" can be determined from [5]:

$$\xi = \left(\frac{1}{\sqrt{2\Delta\nu T}}\right)\left(\frac{1}{\sqrt{N_{sV}}}\right)\frac{\sqrt{\Phi(2\sqrt{2}\chi)}}{\Phi(2\chi)}. \tag{17}$$

It follows from Eq. (17) that ξ for given conditions depends on the values N_{SV} and T, while the time for a single measurement does not exceed 30-60 sec and is limited by expenditure of the solid phase, and the quantity N_{SV} is determined from the flow parameters and the resolution required. Under real conditions ξ lies in the interval $0.05 \le \xi < 0.20$. The expression for the signal to noise ratio W_s/W_n, obtained as ratio of desired signal energy W_s to "white noise" energy W_n in the receiver frequency band $\Delta\nu$ without consideration of attenuation has the form

$$\frac{W_s}{W_n} = N_{sV}\left(\frac{\eta}{2\,\Delta\nu h\nu_0}\right)\left[\frac{\tau_0 P_0}{2\,\pi r_f^2}\,\Phi(2\,\chi)\right]\langle S(\rho_s,\,\beta,\,\Delta\Omega)\rangle. \tag{18}$$

It follows from Eq. (18) that to increase (W_s/W_n) it is necessary to increase the laser power P_0 and narrow the receiver bandwidth $\Delta\nu$ with other parameters maintained constant. With simultaneous measurement of dispersed phase particle velocity profiles by laser Doppler anemometry the method also permits determination of absolute particle concentration values for a number of symmetrical flows. For example, in the case of escape of a dispersed mixture from a circular tube of radius R_T

$$(\rho_{sd})_i = G\left\{2\,\pi\int_0^{R_T}\frac{(N_s U_s)_i}{(N_s U_s)_{\max}}\,R_T dR_T\right\}, \tag{19}$$

where G is the known value of the solid phase flow rate, kg/sec. A typical distribution of gas phase velocity and velocity and concentration of Al_2O_3 particles with $\delta_s = 44\ \mu m$ in the section of a blunt jet x = 450 mm escaping from a circular tube with $D_T = 2R_T = 33.8$ mm, obtained by simultaneous use of the Doppler method and the technique described above, is shown in Fig. 2.

By simultaneous use of laser Doppler interferometry and the technique described above [6] various modifications of gas–solid particle type flows were studied [7, 8], providing information necessary to construct physical models of dispersed flows and to develop calculation methods.

NOTATION

ρ_s, particle diffraction parameter; r_s, particle radius; r_f, laser beam radius in constriction area; $\vec{k}_{0i}$, laser beam wave vector; P_0, laser power; I_0, light intensity at center of beam; x, y, z, Cartesian coordinates; β, angle at which scattered light is received; a, size of diaphragm ahead of photodetector; d_1, distance from measurement volume to receiver lens; f_1, focal length of receiver lens; f_0, focal length of transmitter lens; d_0, distance from laser to transmitter lens; θ, laser beam divergence angle; R_e, equivalent radius of confocal resonator; $\vec{R}$, radius vector joining origin of coordinate system to observation point; φ, wave phase; E(R, t), electric field intensity of laser beam; λ_0, wavelength of laser radiation; μ, magnetic permeability; ε, dielectric permittivity; $P_s(\beta)$, light power scattered into angle β; $\Delta\Omega$, solid angle; $\vec{k}_s$, scattering vector; I(x, y, z), light intensity at point x, y, z; $d\sigma$, differential scattering section; $S(\rho_s, \beta, \Delta\Omega)$, scattering section in receiver solid angle; τ_0, transmission of receiver optical system; χ, sensitivity coefficient, $c = \chi r_f$; $\Phi(\chi)$, probability integral; k_Φ, current amplification; η, quantum efficiency of photodetector; e, electronic charge; h, Planck's constant; ν_0, laser radiation frequency; V, measurement volume; N_s, mean concentration of particles in volume V; $\Delta\nu$, frequency passband of receiver; W_s, signal energy within receiver passband $\Delta\nu$; W_n, noise energy in receiver passband; U_{0m} gas velocity on jet axis in initial section; U_{sm}, particle velocity on jet axis in initial section.

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FORCED OSCILLATIONS IN A HOMOGENEOUSLY FLUIDIZED BED

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The characteristics of the steady-state oscillations in a bed of finite height are considered; the frequency dependence of the amplitude is oscillatory, which enables one to identify discrete spectra of resonant and antiresonant frequencies.

One of the promising ways of accelerating transfer processes in fluidized beds is to superimpose an oscillation by means of pulsations in the pressure or flow rate of the fluidizing medium, or oscillations in the distribution grid, etc. In some cases, this simplifies the fluidization of finely divided materials, in which clumping is characteristic, and it also enables one to expand the existence limits for homogeneous fluidization. We therefore have to consider the distribution of the amplitude of the oscillations in the porosity, phase velocities, and so on over the volume of the layer and the relationship of these to the physical and other parameters of the system and to the external perturbation.

The problem has been considered on several occasions for unbounded beds in relation to the stability of the homogeneous fluidized state (see [1-5] and reviews in [6, 7]). These studies imply instability in small perturbations, and the stabilizing effect of the internal stresses in the dispersed phase are insufficient to provide stability at values of the parameters usually employed in fluidization [4, 5]. As the perturbations propagate, the nonlinear interactions between the perturbations differing in wavelength become important, which results in a generation of waves of considerable amplitude [8, 9], with a subsequent possible formation of bubbles and other discontinuities and the establishment of inhomogeneous fluidization.

To a considerable extent, these conclusions were drawn because no allowance was made for the finite time spent by a perturbation in the bed or the stabilizing effect of the upper boundary. This time is finite in a bed of finite height and sometimes is insufficient for the perturbation amplitude to increase substantially (particularly in the fluidization of small particles by liquids), while the upper boundary in principle can give rise to a system of reflected waves, which interfere with the initial ones [10, 11].

Here we consider the propagation of forced weak perturbations in a bounded layer of small particles fluidized by a gas. We neglect inertia, gravity, and viscous stresses in the gas, while the hydraulic resistance of the bed is considered a linear function of the infiltration speed. These assumptions simplify the expressions considerably but do not affect the essentials of the problem.

Linearized Equations. We consider the fluidized bed in a continuum approximation and write the equations for conservation of mass and momentum of the phases in the form

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \mathbf{w}) = 0,\ \frac{\partial \rho}{\partial t} - \operatorname{div}(\varepsilon \mathbf{v}) = 0,\ d_1\rho\,\frac{d\mathbf{w}}{dt} = \mathbf{f} + d_1\rho\mathbf{g},\ -\nabla p - \mathbf{f} = 0,\ \varepsilon = 1 - \rho. \tag{1}$$

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