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METHOD OF MULTIEXPOSURE PHOTOGRAPHIC RECORDING OF PARTICLES IN HIGH-VELOCITY TWO-PHASE FLOWS

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UDC 532.57+621.375

There is a broad circle of experimental problems in the gasdynamics of multiphase systems when it is important to assure a high fast response of the measuring circuit in addition to the necessity to measure high velocities of $10\text{-}10^4$ m/sec. Here are problems that occur in studying two-phase pulsed flows, particle dynamics behind shocks in investigations of heterogeneous detonation or deposition of detonation coatings, etc., when the characteristic times of the processes are $\sim 10^{-1}\text{-}10^{-5}$ sec.

It should be noted that velocity measurement in the range $10\text{-}10^4$ m/sec assures utilization of laser-Doppler systems with direct spectrum analysis examined in detail in the survey paper [1]. However, the practical realization of laser doppler velocimeter (LDV) circuits with a resolution time of $\sim 10^{-5}\text{-}10^{-6}$ sec requires the development of special methods of recording the spectra, which constrains their extension to the area of problems related to the investigation of high-speed processes.

Here the development of a method of multiexposure photographic recording, based on the use of a stroboscopic light source yielding the frequency and duration of frame exposure, is of significant interest. By applying such a source in combination with different optical schemes (shadow, interferometer, holographic), extensive information can be obtained about the flow structure and particle parameters such as size, concentration, and velocity of their motion, can be determined.

Up to now, a number of papers [2-6] is known in which multiexposure photorecording was used to solve different problems, for instance, to investigate turbulent flows [2-3], measure drop velocity [4], convective fluid motion [5], particle free fall [6], etc.; however, all these papers refer to low velocity measurements $\lesssim 10$ m/sec.

The development of powerful pulse lasers as well as optical systems and photographic materials with high resolution permits significant expansion of the possibilities of this method by increasing its response, and spatial and time resolution. Utilization of a spatial-spectral method of analyzing multiexposure photographs [6] affords the possibility of substantially simplifying data processing and executing measurements in a broad range of concentrations. This paper is devoted to development of a multiexposure photorecording method to investigate rapidly progressing processes in heterogeneous flows.

1. In principle, the scheme for multiexposure recording of a particle image is the following. Several successive focussed images of a moving two-phase flow are recorded at equal time intervals Δt on the very

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 64-71, May-June, 1982. Original article submitted March 30, 1981.

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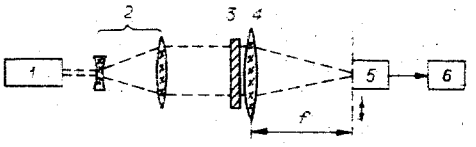

Fig. 1

same photographic material. This can be a hologram or the ordinary photograph made by a shadowgraph or a laser "knife" scheme [7]. In the simplest case, by measuring the distance h between two successive images and by knowing the time interval Δt between them, the velocity of particle motion $v = kh/\Delta t$ can be determined (k is a scale factor) as can their size. However, visual processing is sufficiently tedious, where automating this process by using an electronic computer is significantly difficult [3]. Hence, it is expedient to use it only to investigate the dynamics of individual particles in a gas flow. As an illustration, the problem related to the need for simultaneous observation of the nature of the motion of distinct (in shape, size, etc.) particles especially under conditions when their interaction plays a substantial part; i.e., particle collision, fractionation, coagulation processes, etc., can be mentioned.

In a number of experiments the main problem is measurement of the integrated two-phase flow parameters such as the mean velocity of particle motion, or their size and velocity distribution functions. In this case, most promising from the viewpoint of convenience and rapidity of information processing is the method of spatial spectral analysis (SSA) based on investigating the light intensity distribution in the Fraunhofer diffraction pattern obtained from a multiply recorded image of the particle flow.

Figure 1 clarifies the principle for realizing this method. If a transparency 3 with a multiple image of a two-phase flow is exposed to a parallel coherent light beam, then the pattern of a spatial spectrum carrying information about the particle parameters is formed in the focal plane of the lens 4 performing a Fourier transformation. Let us use the known relationship (see [8], for example) describing the Fourier transform for a plane subject with an arbitrary amplitude transmission factor located directly ahead of the lens. The intensity distribution in the diffraction pattern on a transparency with N successive images of one spherical particle of radius R has the form

$$I_f(\rho, \theta) = A\left|\int_0^R\int_0^{2\pi} \exp\left[-j\frac{2\pi\rho}{\lambda f} r\cos(\theta-\varphi)\right]\frac{1-\exp(-jN\omega v)}{1-\exp(-j\omega v)} r dr d\varphi\right|^2, \tag{1.1}$$

where $\omega = 2\pi\rho k\Delta t\cos(\alpha-\theta)/\lambda f$; ρ, θ, r, φ are polar coordinates in the transforming lens; f, its focal length; λ, wavelength of light; v, velocity of particle motion; α, angle giving the direction of particle motion; A, a phase factor; and k, a scale factor.

Let us examine the case when N = 2. When relationship (1.1) simplifies considerably:

$$I_f(\rho, \theta) = 2[1+\cos(\omega v)]B(R). \tag{1.2}$$

Here $B(R) = \left|\int_0^R\int_0^{2\pi} \exp\left[-j\frac{2\pi\rho}{\lambda f} r\cos(\theta-\varphi)\right] r dr d\varphi\right|^2$ is a function dependent only on the particle size.

For an ensemble of particles, distinctive by size and velocity of the motion, the expression for $I(\rho, \theta)$ has the form

$$I(\rho, \theta) = 2\left\{1+\int_0^\infty P_v(v)\cos(\omega v)\,dv\right\}\int_0^\infty P_R(R)B(R)\,dR, \tag{1.3}$$

where $P_V(v)$ and $P_R(R)$ are the particle velocity and size distribution densities. Let us note that the relationship (1.3) is written under the assumption of statistical independence of the velocity of particle motion from their size.

If the mean velocity of particle motion is introduced, defined as $v_{av} = \int_0^\infty vP_v(v)\,dv$, and the function $P_V(v)$ is centered relative to v_{av} by introducing $P_V(v') = P_V(v - v_{av})$ then (1.3) can be represented in the form

$$I(\rho, \theta) = 2\left\{1 + \cos(\omega v_{av}) \int_0^\infty P_v(v') \cos(\omega v')\, dv'\right\} \int_0^\infty P_R(R)\, B(R)\, dR. \quad (1.4)$$

It is seen from (1.4) that the diffraction pattern for an ensemble of particles is modulated, just as for the case of one particle [formula (1.2)], into parallel bands located normally to the velocity vector. The spacing H between the bands is here related to the mean velocity of particle motion v_{av}

$$v_{av} = \lambda f/(k\Delta t H), \quad (1.5)$$

and the nature of the change in interference fringe contrast is determined by the integral $\int_0^\infty P_v(v') \cos(\omega v')\, dv'$.

Therefore, by measuring H and knowing λ, f, Δt, and k, we can determine v_{av} from (1.5). It is also seen from (1.4) that the intensity distribution obtained during photometry of the spectrum in a direction perpendicular to the interference fringes ($\theta = \alpha$) carries information about the function $P_V(v)$. In particular, an analysis of the dependence $I(\rho, \theta)$ is presented in [6] for the case of a Gaussian velocity distribution. Data on the particle size distribution $P_R(R)$ can be obtained by investigating the intensity distribution along the band ($\theta = \alpha + \pi/2$).

2. A set of tests with model photographs was performed to check out the system to record the spatial spectra and to select the optimal conditions for realizing the method to investigate two-phase flows. To this end, the particles of a definite species were photographed multiply by using a microscope, with the subject table given a displacement before each exposure. The influence of the disperse particle composition, their concentration, the number of exposures, and also the parameter h/d (d = 2R) on the nature of the intensity distribution in the diffraction pattern was investigated.

The tests were performed on the apparatus displayed in Fig. 1. A helium–neon LG-38 laser 1 was used as light source. The intensity distribution was inscribed on the plotter 6 by using the photomultiplier 5 displaced in the focal plane of the transforming lens 4 with focal length 500 mm (2 is the telescopic system).

Photographs modeling a single-velocity, unidirectional stream of particles of identical size d with different concentrations are represented in Fig. 2a and b, while their corresponding diffraction patterns and intensity distributions are in Fig. 2c and d, and e and f. Figure 2a, c, e refers to the case when the mean spacing between particles is l > h, and Fig. 2b, d f corresponds to l < h. As is seen from Fig. 2b, it is quite complicated to identify several images of a definite particle; however, the diffraction pattern is recorded clearly here. The important advantage of the method of spectral analysis follows from this, which can be used for a high volume concentration of particles in the stream $\geqslant 1\%$, when visual processing becomes impossible. The tests performed also showed that from the viewpoint of convenience of the SSA processing method, the optimal value of the parameter h/d should be selected in the 3-10 range.

The spatial resolution of the spatial spectral analysis method, which permits recording the velocity field in a given stream domain, is determined by the aperture of the sounding beam d_b for restoration of the Fourier spectrum. It is known [9] that upon exposing a diffusely scattering object to coherent light the diffraction pattern in the focal plane of the transforming lens will have the form of a spotted structure (speckle-structure) that occurs because of interference between the diffraction patterns of the individual particles. The characteristic size of the spots is determined by the value of d_b (if d_b is less than the lens diameter) and is $\delta \sim \lambda f/d_b$. The presence of such a structure results in the appearance of signal fluctuations in the Fourier spectrum, which constrain the accuracy of determining the interference fringes. We shall consider that two fringes can be resolved if the spacing between them is $H \simeq \delta$. Taking account of (1.5), the limiting spatial resolution $d_{b\,min} \simeq h$ can be estimated from this condition. For $h/d \simeq 3$ and $d \simeq 100$ μm we have $d_{b\,min} \simeq 300$ μm. To diminish the error in recording the intensity distribution in the Fourier spectrum and, therefore, the particle motion velocity as well, the d_b must be enlarged; however, the spatial resolution of the method will here drop. Hence, the selection of d_b should be made taking account of the specific requirements of the experiment.

3. The main problem that occurs in the practical realization of the method of multiexposure photorecording of particles in high-velocity two-phase flows is associated with the creation of a light source to generate a series of short pulses with a given repetition rate. In order to obtain information about the particle shape and size, it is necessary that its displacement during exposure be much less than its diameter d. This imposes a constraint on the duration of an individual pulse $\tau \ll d/v$. The condition h = (3-10)d governs the optimal value of the interval between pulses. For the characteristic values $d \simeq 100$ μm and $v \simeq 10^2$ m/sec we obtain $\tau \ll 10^{-6}$ sec and $\Delta t = 3$ μsec.

Solid-state pulse lasers with periodic Q-modulation [10-12] are most promising for solving this problem, since they assure good sensitivity and fast response of the measuring scheme. A stroboscopic light source

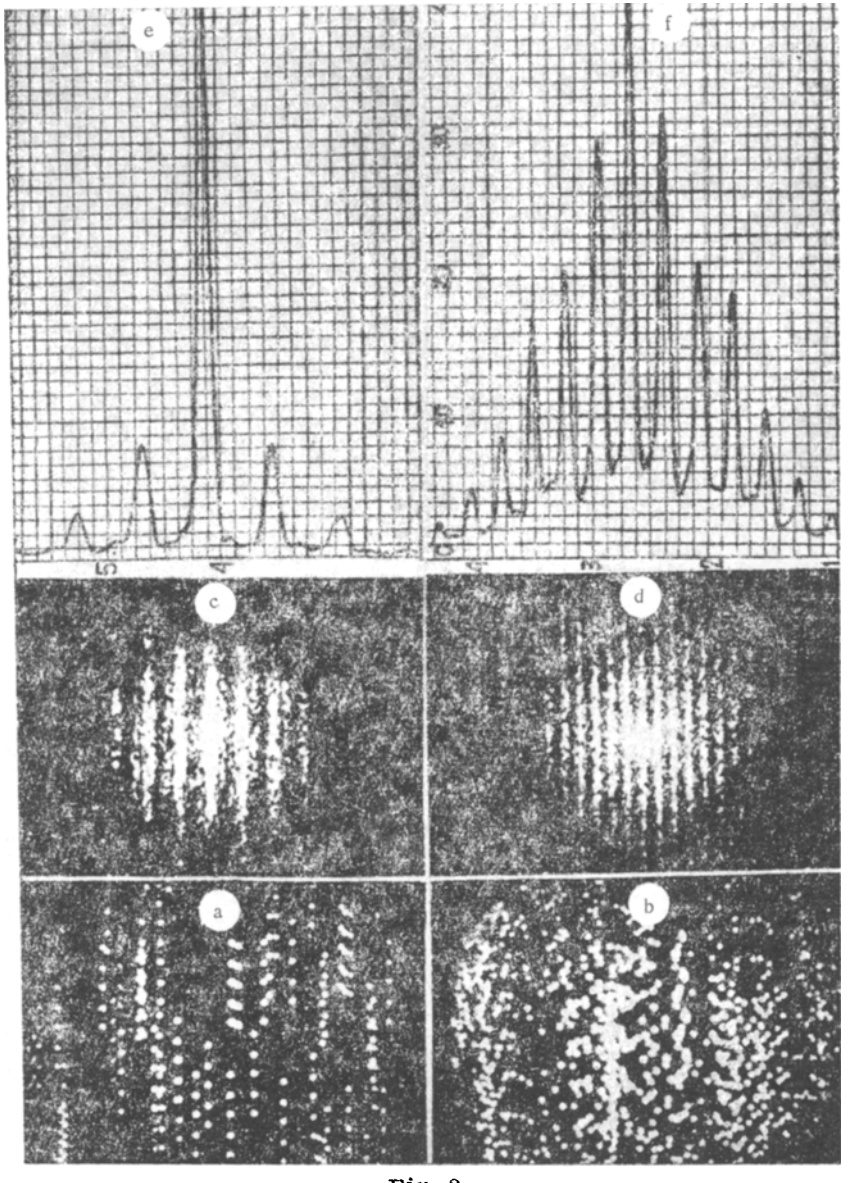

Fig. 2

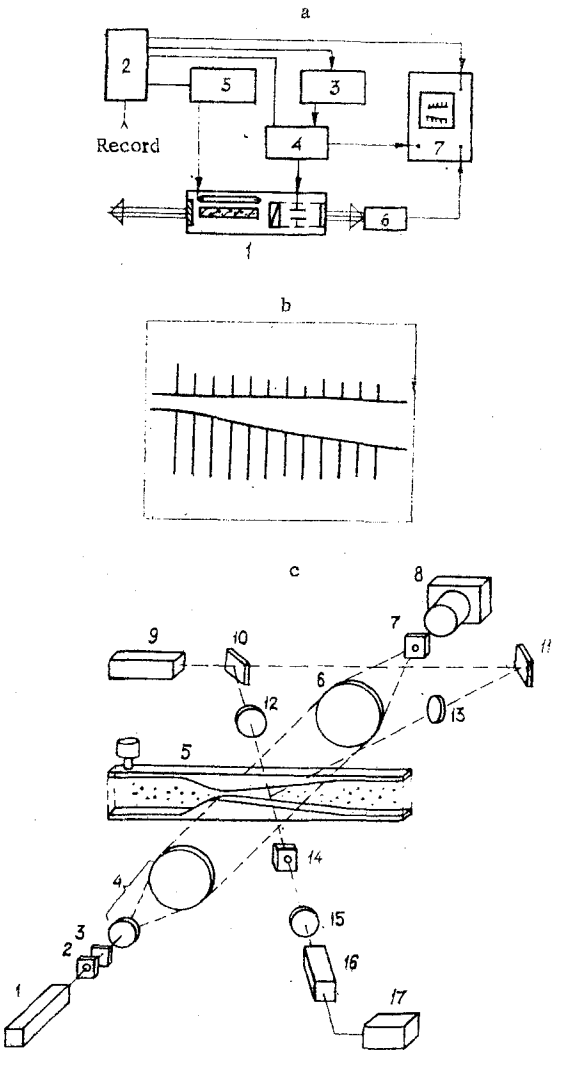

Fig. 3

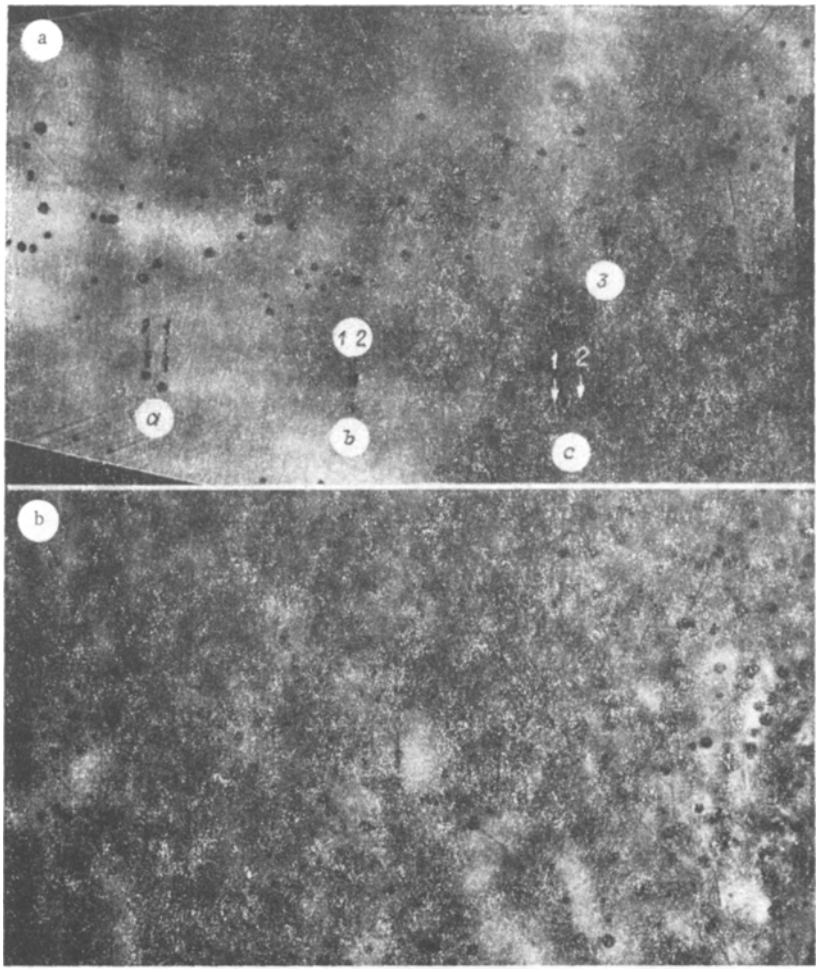

Fig. 4

(Fig. 3a) based on a ruby laser 1 was developed for the multiexposure particle recording in a gas flow in this research. A Kerr cell was the electro-optical modulator. Its parameters are: electrode length 50 mm, spacing between them 8 mm, control voltage 15 kV. The electronic control circuit of the cell was a synchronized pulse generator 2, a master oscillator 3 producing a series of electrical pulses with a given interval between them, and a shaper of high-voltage pulses 4 supplied to the Kerr cell (5, a capacitor bank to supply the pumping lamp; 6, photomultiplier; and 7, an oscilloscope). The laser assured generation of several (from 1 to 50) light pulses of duration $\tau \simeq 3 \cdot 10^{-8}$ sec. The intervals Δt between them were regulated within 3-500 μsec limits to 0.2 μsec accuracy. The characteristic shape of the electrical signal controlling the modulator (lower beam) is shown in Fig. 3b, and laser radiation pulses (upper beam) recorded by using the photomultiplier ($\Delta t = 20$ μsec) are also represented.

The necessary optical scheme for multiexposure particle recording can be realized when using the stroboscopic light source. Depending on the requirements of the experiment, flow visualization in the scattered (laser knife) or passing radiation can be used [7]. The diagram of a shadowgraph intended to investigate two-phase flows is presented in Fig. 3c. Its main elements are the ruby laser 1 that generates a series of controlled pulses, the diaphragm 2, the attenuating filter 3, the telescope system 4, the receiving objective 6, the visualizing diaphragm 7, the photorecorder 8. The resolution of the scheme was determined experimentally and was not less than 100 lines/mm for a total linear enlargement of 5.

A supersonic gas stream was produced by using the plane conical nozzle 5. The altitude of the critical section is 2.6 mm, the width is 20 mm, and the aperture angle is 11°. The pressure in the prechamber is $8.5 \cdot 10^5$ Pa, the temperature is 260°K, and the exit Mach number is 2.8. The particles being investigated were inserted into the gas flow at a distance of 240 mm ahead of the critical section. Organic glass particles ($d = 50$-300 μm, $\rho_1 = 1.2$ g/cm^3) and bronze ($d = 50$-230 μm, $\rho_1 = 8.6$ g/cm^3) were used in the experiments. A Doppler laser velocimeter scheme with direct spectrum analysis is also shown in Fig. 3c. It consists of the

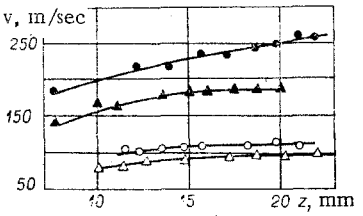

Fig. 5

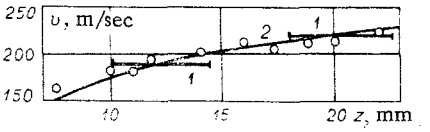

Fig. 6

LG-159 helium–neon laser 9, the splitter 10, rotating mirror 11, objectives 12, 13, 15, diaphragm 14, Fabry–Perot interferometer with photomultiplier 16, and oscilloscope 17. The diagram of the LDV apparatus and the method of measuring the velocity are described in greater detail in [13].

Certain results of experiments, obtained in investigating supersonic two-phase flows, are represented in Figs. 4-6. A typical three-exposure shadowgraph is displayed in Fig. 4a. Organic glass particles of d = 50-300 μm, $\rho_1 = 8.6$ g/cm^3 are inserted in the stream, and the interval between exposures is $\Delta t = 20$ μsec. Since the volume concentration of the disperse phase is not large ($l/d > 5$) the dynamics of individual particles can be tracked. Three successive images are easily found for the majority of them. For example, let us examine the two particles $d_1 = 200$ μm and $d_2 = 150$ μm noted by arrows in Fig. 4a. On the section ab corresponding to the time between the first and second exposures $v_1 = 185$ m/sec, $v_2 = 205$ m/sec, while on the section bc between the second and third exposures $v_1 = 200$ m/sec, $v_2 = 220$ m/sec. The difference in the motion velocity of particles of different diameter, resulting in a change in their relative position in the stream, is seen well. By processing such photographs, the nature of the change in the motion velocity of different particles (d, ρ_1) over the nozzle length $v = f(z)$ can be studied simultaneously. These results are represented in Fig. 5 and permit determination of the aerodynamic drag coefficients of fine particles during acceleration in a gas stream [13]: 1) organic glass particles $d_{av} = 80$ μm, $\rho_1 = 1.2$ g/cm^3; 2) organic glass particles $d_{av} = 210$ μm, $\rho_1 = 1.2$ g/cm^3; 3) bronze particles $d_{av} = 120$ μm, $\rho_1 = 8.6$ g/cm^3; 4) bronze particles $d_{av} = 200$ μm, $\rho_1 = 8.6$ g/cm^3. The relative measurement error is $\leq 3\%$.

Multiexposure photorecording in a shadow or interferometer scheme affords the possibility of investigating the nature of the change in density field microstructure with time. Local shocks being formed around the particle during their supersonic flow are seen well in Fig. 4a. Particle interaction with an obstacle (in the photograph it is a streamwise-mounted cylinder) results in a strong change in the wave structure near the body. It is not complicated to distinguish particles incident on 1, 2 and reflected from 3 the obstacle by the nature of the change in velocity. In particular, this permitted determining that the main role in the bow shock perturbation phenomenon during two-phase flow around bodies is played by particles reflected from the body and emerging into the supersonic flow zone [13].

To verify the processing methodology by the spatial spectrum analysis method, two-exposure photographs were made in which the Δt was diminished to 5 μsec. Paired images of particles (d = 50-200 μm) are seen well in Fig. 4b, some of which are marked by arrows. The value of the parameter is $h/d \geq 3$. The whole photograph was divided into squares with a side L = 4.5 mm along the nozzle axis. The intensity distribution in the diffraction pattern was recorded for each, and the mean velocity of particle motion v_{av} was determined from (1.5). These data are represented in Fig. 6 by sections of the horizontal line 1 whose length is L. Also superposed in Fig. 6 are values of v_{av} (points) obtained by visual processing, and results of measuring the velocity 2 by the Doppler laser method with direct spectrum analysis [13]. The satisfactory agreement of the data obtained by the two methods of multiexposure photography processing should be noted (the difference does not exceed 4%). The agreement between these results and the LDV data confirms the confidence in the information obtained and indicates the promise of using the method of multiexposure photorecording to investigate high-velocity two-phase flows.

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CONVECTIVE MASS TRANSFER BETWEEN A SOLID SPHERICAL PARTICLE AND A FLUID AT LARGE PÉCLET NUMBERS

M. S. Iskakov and V. E. Nakoryakov

UDC 532.529.6:541.12

Introduction

Mass exchange between a solid particle and a fluid is the main productive factor in many branches of chemical engineering and microbiology. This process is complicated and depends on many factors – radial diffusion, forced convection, free convection, the shape of the particle, the physical properties of the fluid and the particle, etc. Under actual conditions these factors act simultaneously, and many investigators have been confined, as a rule, to the study of mass exchange under the conditions of a uniform oncoming stream, where forced convection makes the largest contribution to mass transfer. This is explained by the relative simplicity of the investigation of processes of this kind, both theoretically and experimentally.

All the experimental methods used to investigate mass exchange in fluid–solid-body systems can be divided into two major groups, in which the following are used: the dissolving of solids in fluid streams; chemical transitions taking place at the surfaces of metallic electrodes under the action of an electric current. The advantages of the first group are the simplicity of the experimental procedure, the possibility of forming the desired hydrodynamic pattern with a high degree of accuracy, and the presence of a wide class of substances suitable for such an experiment, which enables one to vary the physical properties of the fluid and bodies within wide ranges. The main drawback is that a fixed phase interface is absent, as a consequence of which the hydrodynamics of flow over the particle constantly varies. Electrochemical methods are free from such a drawback, since the processes taking place at the electrodes proceed in opposite directions and the surface of the sensor is always clean, but there is the technical problem of fastening the sensor and reducing the influence of conducting contacts.

A number of reports are known which are devoted to the investigation of the intensity of mass exchange in uniform streams. The good agreement between results obtained by the electrochemical method and the data of other authors for Re = 400–12,500 was noted in [1]. The test data published in [2] cover a far wider range of Reynolds numbers, Re = 2–23,000. The approximation curve generalizing the data for $2 < Re < 20$,

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 3, pp. 71–77, May–June, 1982. Original article submitted April 13, 1981.

0021-8944/82/2303-0376$07.50