17. V. S. Erofeev, K. P. Kirdyashev, and E. V. Pelepelin, "High-frequency oscillations in an accelerator with an anode layer," in: Materials of the Second All-Union Conference on Plasma Accelerators [in Russian], Izd. Inst. Fiz. Akad. Nauk BelorusSSR, Minsk (1973).
18. V. S. Erofeev, A. V. Zharinov, and E. A. Lyapin, "Low-frequency instability of a radial ion beam formed in an EH-layer with a closed Hall current," in: Plasma Accelerators [in Russian], Mashinostroenie, Moscow (1972).
19. A. V. Zharinov, "The amplitude of potential oscillations of a quasineutral ion beam," Pis'ma Zh. Tekh. Fiz., 17, No. 9, 508 (1973).

DIAGNOSTICS OF SUPERSONIC TWO-PHASE STREAMS FROM SCATTERED LASER RADIATION

A. P. Alkhimov, V. M. Boiko,
A. N. Papyrin, and R. I. Soloukhin

UDC 532.57+532.137+536.51+532.14.08+531.787

Further development of the experimental research technique is required for the solution of a wide circle of problems arising in the investigation of high-velocity two-phase flows and connected with the study of the physical processes of the interaction between particles and a nonequilibrium gas stream [1], such as in the nozzle of a solid-fuel rocket engine [2] (investigation of the effects of the velocity lag and thermal lag of the particles, determination of their sizes and coefficient of aerodynamic resistance, etc.). Here the most promising are noncontact optical methods of diagnostics, the intensity of whose development in recent years has been promoted by the extensive application of lasers. The laser Doppler velocity meter (LDVM), the determination of the disperse composition and particle concentration from the attenuation and scattering of a laser beam, and holographic and other methods have now been successfully incorporated into gasdynamic experimental practice.

The present report is devoted to the development of the laser Doppler velocity meter and the method of pulsed laser visualization for the investigation of high-velocity two-phase streams.

The Laser Doppler Velocity Meter

It is known that LDVM systems can be divided into two main groups with respect to the means of measurement of the Doppler frequency shift of the scattered laser radiation. The first includes the most studied and widely distributed systems, in which the difference frequency is determined with the help of photodetectors (the photographic mixing method). A major cycle of research on the development of the theory and on the problems of the technical construction of such systems [the work of B. S. Rinkevichyus (Moscow Power Institute), V. S. Sobolev (Institute of Atomic Energy, Siberian Branch, Academy of Sciences of the USSR), G. L. Grodzovskii (Central Aerohydrodynamic Institute) and colleagues, and others] has contributed to the considerable progress in this field and has led to the creation of experimental models of instruments which have been used successfully in gasdynamic research. It should be noted, however, that from the point of view of practical realization these LDVM are simple enough in the measurement of relatively low velocities $v \le 10^2$ m/sec and are used most extensively and successfully in the study of subsonic streams, whereas the measurement of velocities $v \ge 10^3$ m/sec by such a method presents considerable technical difficulties.

Of major interest on these grounds are the laser Doppler systems of the second class [3-9], which accomplish the direct measurement of the Doppler frequency shift with the help of high-resolution spectral instruments (such as the Fabry-Perot interferometer); at present they are still inadequately studied and are used considerably less often in gasdynamic research. These LDVM systems permit the practically unlimited expansion of the measurement range into the region of higher velocities and evidently are more promising for the investigation of supersonic and especially of hypersonic streams, since for the spectral recording method the reliability and accuracy of the measurements only increase with an increase in velocity.

In this connection it seemed desirable to conduct further research directed toward the development of laser Doppler systems of this type and, in particular, toward the creation of a scanning spectrometer having

Novosibirsk, Minsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 36-46, March-April, 1978. Original article submitted February 17, 1977.

a high resolution and transmission. The main demands imposed on the spectrometer in an LDVM system are formulated below, and a description is given of the LDVM system which is the result of the continuation of work [3-5] on the development of the method of velocity measurement based on the spectral means of recording and which is designed for conducting experiments on the investigation of the effect of the velocity lag of particles in supersonic gas streams.

As noted in [3], to conduct experiments of this kind one must measure the velocities of the gas and the particles at the same time. Because of the complexity of the use of the traditional methods of measuring gas velocity (with a Pitot tube, for example) in a two-phase stream, however, one can use the LDVM method for this purpose, but in doing so one must also introduce aerosols into the stream along with the particles being studied; the aerosols follow the stream with high accuracy ($\Delta v/v \leq 0.01$) and therefore they carry information on the gas velocity. Particles with a size $d \leq 0.1$-$1\ \mu m$ fully satisfy this demand on the data of a number of investigations. However, the necessity of the simultaneous recording of the laser radiation scattered on particles of different types requires the creation of an LDVM system possessing high sensitivity and providing for the recording of Doppler frequency shifts in a wide spectral range, since in this case it is necessary, on the one hand, to measure the "absolute" velocities in the range of $v = 10^2$-10^3 m/sec and higher and, on the other hand, to measure the relative velocities Δv of particles of two (or more) sorts introduced simultaneously into the stream, for which one must decrease the lower limit $v_{min} \leq 10$ m/sec of the measured velocity and increase the measurement accuracy. In this case one can formulate the main demands imposed on the laser in the LDVM system – minimum spectral width of the emission line, high frequency stability, and sufficiently high emission power – and on the spectrometer – high spectral resolution and sufficient speed and sensitivity.

Let us consider some questions connected with the choice of the parameters of the scanning spectrometer, which determines the main characteristics of the LDVM system (when a laser source with given parameters is used): the measurement range and accuracy, its sensitivity, and the spectrum recording time τ_p.

As shown by tests conducted earlier [3], with the use of Fabry-Perot interferometers with plane mirrors [3, 6, 7], which are usually used in the photoelectric recording of the spectrum, the LDVM sensitivity did not provide reliable recording of the scattered signal, since it was necessary to isolate a narrow section of the spectrum (using a small diaphragm), which led to large light losses. A considerable gain in transmission can be obtained by a change to a confocal (spherical) resonator in the LDVM system [8, 9], permitting the use of a receiver having a considerably larger angular aperture for recording a certain wavelength without a loss of spectral resolution [10].

To characterize the efficiency of the spectrometer in an LDVM system it is convenient to use the parameter $P = UR$, where U and R are the transmission and resolution of the interferometer. Comparing the expressions $P = UR$ for a spherical interferometer (P_s) and a Fabry-Perot etalon with plane mirrors (P_{pl}), we obtain [10]

$$K = P_s / P_{pl} = 8(nL)^2/D^2,$$

where nL is the optical length of the interferometer; D is the plate diameter (the coefficients of transmission of the two interferometers are assumed to be the same). Taking the diameters D of the etalon plates as 3 cm, we find that for $nL = 10$ and 1 cm the ratio P_s/P_{pl} equals 90 and 0.9, respectively. In order to assure the measurement of a velocity $v_{min} \lesssim 10$ m/sec one must use interferometers with a high resolution at $nL \simeq 5$-10 cm. In this case the efficiency of the use of a confocal spectrometer, as seen from the example considered above, is much higher than that for a plane Fabry-Perot etalon, with the parameter $K = P_s/P_{pl}$ growing as $\sim L^2$ with an increase in L. We note also that a confocal spectrometer is more convenient in operation, since the demands on the accuracy of adjustment of the confocal mirrors are considerably lower, which is important from the point of view of the adjustment and operation of the interferometer at the high level of vibrations and acoustic noise under the conditions of a gasdynamic installation.

The high speed of an LDVM system, which determines the recording time τ_p of the spectrum of the scattered signal, also acquires importance in the investigation of two-phase flows with different concentrations of foreign particles, as well as in the measurement of the velocity in nonsteady streams.

It is known that the formation of the signal of a Doppler particle-velocity meter is influenced by a whole series of factors, determined both by the properties of the particles scattering the radiation and by the parameters of the measurement system. In particular, such factors include the amplitude U and duration t_1 of the pulses from individual particles, which depend on the disperse composition of the aerosols and their velocities, and the ratio between the repetition frequency $\nu_2 = 1/t_2 = v/l$ of these pulses (l is the mean distance between particles in the stream and v is their velocity) and the recording time τ_p of the spectrum of the scattered signal, determined by the spectrum scanning rate, other experimental conditions being equal (particle size spectrum, instrumental width, etc.). The time of luminescence of an individual particle while crossing the detection volume (transverse size $d \approx 100\,\mu m$) in a supersonic stream is $t_1 \ll \tau_p$ ($t_1 \lesssim 10^{-6}$ sec for v = 500 m/sec and $d = 100\,\mu m$), so that to record the profile of the scattered signal one must assure the passage of a large enough number of particles through the experimental volume during the measurement time, i.e., satisfy the condition $\tau_p \gg t_2$. For measurements in a stream with a low dust content this leads to an increase in the required value of τ_p. For example, tests conducted in an investigation of the effect of the velocity lag of "single" particles in a supersonic nozzle [12] (p_0 = 8 atm, T_0 = 260°K, M = 2.8), i.e., under conditions when the distance between particles in the stream exceeded their mean size by two or more orders of magnitude ($l \geq 10^2 d_r$), showed that τ_p must be in the range of 0.1-1 sec.

On the other hand, in the investigation of pulsed processes and in the measurement of velocity under the conditions of stream pulsations one must decrease the measurement time so that $\tau_p \ll \tau$ (the characteristic time of the process). For example, to record the "instantaneous" velocity in the presence of stream pulsations with a frequency of $\sim 10^3$ Hz the value of τ_p must be $\lesssim 10^{-4}$ sec. Thus, the solution of the various problems of aerophysical experimentation requires the creation of an LDVM scanning system providing for variation of τ_p in the range of $\tau_p = 10\text{-}10^{-4}$ sec or less.

Tests on the investigation of various systems of photoelectric recording (through variation in the pressure, using piezoceramics, and using a dual image converter) showed that the most acceptable (from the point of view of sensitivity and time resolution, as well as simplicity and convenience in operation) is an LDVM system based on a confocal interferometer in which the spectral scanning is accomplished with the help of piezoceramics. In this case the section of the spectrum corresponding to the region $\Delta\lambda_0 = \lambda^2/4L$ of free dispersion of the etalon can be recorded in a time $t \leq 10^{-3}$ sec, which corresponds to the time of recording the instrumental profile $\tau'_p \leq 10^{-4}$ sec, where τ'_p can be varied in the range from 10^{-4} to 10 sec or more.

The main drawback of the method of photoelectric recording of the spectrum through variation of the pressure in the interferometer chamber, which is the most common in high-resolution spectroscopy, is the low speed. For example, when this scanning method is used in an LDVM system it is hard to obtain a value of $\tau'_p \leq 0.1$ sec [6]. A high time resolution ($\tau'_p \approx 10^{-7}$ sec) can be obtained using a scanning device based on a combination of a stationary multibeam interferometer and a dual image converter (DIC), first suggested for recording the spectrum of scattered laser radiation in an LDVM system in [3]. As shown by the tests conducted, however, for the successful application of a DIC in a gasdynamic experiment one must use more powerful lasers (W ≈ 0.1-1 W), since the sensitivity of such an installation (a Fabry-Perot interferometer in conjunction with a DIC), which employs only part of the light flux (isolated in some order of interference), is considerably less than the sensitivity of a system in which a scanning confocal interferometer is used with subsequent recording of the spectrum with a photomultiplier.

A diagram of the LDVM is presented in Fig. 1. An LG-159 helium-neon laser 1 with a wavelength λ = 6328 Å, an emission power W = 5 mW, and a frequency stability of 10^8 operating in the one-frequency mode was used as the radiation source. The laser radiation, passing through the diaphragm 2 and the plane-parallel plate 3, intended for obtaining two beams, one of which plays the role of the reference beam, was focused by the lens 4 through the entrance window into the experimental region of the stream 8 (5 is a filter). The radiation scattered by the particles was recorded at an angle α = 31°44'. In this case the Doppler shift $\Delta\nu$, defined in the general case as

$$\Delta\nu = (1/2\pi)\mathbf{v}(\mathbf{K}_s - \mathbf{K}_0)$$

(where $\mathbf{K}_0$ and $\mathbf{K}_S$ are the wave vectors of the incident and scattered radiation, respectively, and **v** is the velocity vector of the moving particles), for α = 31°44' and a laser wavelength λ = 6328 Å, was

$$\Delta\nu\,(\text{sec}^{-1}) = 8.7\cdot 10^5 v\,(\text{m/sec}). \tag{1}$$

The Doppler frequency shift was recorded with the help of the scanning interferometer on the piezoceramic 6. When the variable scanning voltage (block 9) is applied to the piezoceramic element of the etalon its length varies within the limits of several wavelengths. The resonance frequency of the interferometer varies in the process, and it successively records the frequency spectrum of the incident radiation. A type FÉU-79 photomultiplier 7 (10 is the power-supply unit), a U2-4 amplifier 11, and an oscillograph 12, the sweep of which is synchronized by the scanning voltage, are used to record this spectrum. In this case the time axis on the oscillograph screen corresponds to the frequency axis of the spectrum being studied.

The scanning interferometer consists of a confocal resonator with a length L = 10 cm formed by mirrors with radii of curvature R = 10 cm onto which multilayered dielectric coatings with a coefficient of reflection

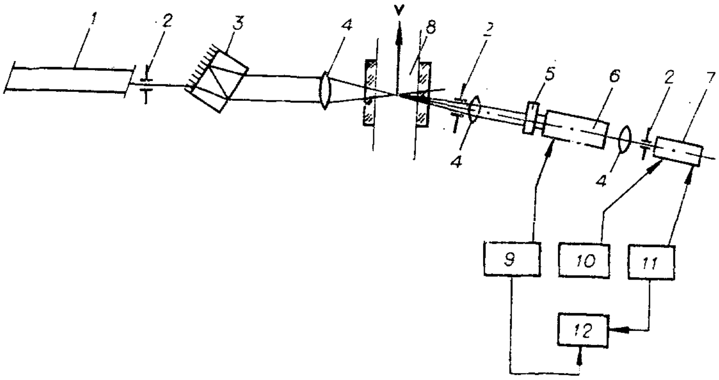

Fig. 1

r = 95% for the wavelength $\lambda = 6328$ Å are deposited. The main characteristics of this spectrometer are as follows: region of free dispersion $\Delta\nu_0 = 750$ MHz, instrumental width $\delta\nu \simeq 10$ MHz; from (1) this gives a value of $v_{min} \approx 10$ m/sec for the minimum measurable velocity. The spectrum scanning rate, and hence the value of $\tau'_p = 10\text{-}10^{-4}$ sec, can be varied within wide limits with the help of the sweep generator 9.

As an illustration of the operation of the given LDVM on a gasdynamic installation (Fig. 2) we present typical oscillograms obtained with light scattering on different particles (bronze particles with $d_{av} = 80$ μm and $\rho_r = 8.6$ g/cm^3 and particles of club moss with $d_{av} = 25$ μm and $\rho_r = 0.5$ g/cm^3) accelerated in a supersonic nozzle ($p_0 = 8$ atm, $T_0 = 260$°K, Mach number at cut M = 2.8). The two signals corresponding to the different velocities of these two components introduced simultaneously into the stream ($v_1 = 130$, $v_2 = 350$ m/sec) are well seen; with an increase in concentration their interaction begins, leading to a change in the spectrum of the finer particles.

In noting the advantages of the given meter, one must mention first of all its high resolution, assuring a wide range of measurements of velocities at $v \geq 10$ m/sec, the possibility of conducting measurements at different concentrations of dust particles, and the high reliability in operation. The rather high speed (the time of recording a line profile is $\tau'_{p\,min} \approx 10^{-4}$ sec) makes it possible to use it to study transient process, in contrast to LDVM systems in which a pressure-scanned Fabry-Perot interferometer is used to scan the spectrum [6].

Thus, the given system, created on the basis of a one-frequency laser and a high-resolution confocal spectrometer with photoelectric recording of the spectrum, is evidently optimal from the point of view of spectral and time resolution and can be used successfully to study diverse processes in supersonic multiphase streams. The further improvement of the system, as shown by the experiments conducted, should be carried out in the direction of an increase in the LDVM sensitivity, since for weakly scattering particles at a low concentration it was difficult to obtain reliable results for analysis, since the signal-to-noise ratio was $\lesssim 1$ under these conditions. It is clear that in this case one can follow both the path of the use of more powerful lasers and that of an increase in the sensitivity of the recording system.

On the basis of the previous LDVM system we developed and tested a more sensitive installation LDVM-2 (Fig. 3a), in which the method of synchronous detection [11] was used to increase the signal-to-noise ratio. In this case the laser beam was modulated in amplitude with an ML-4 optical modulator or a mechanical modulator 2 (modulation frequency 18 kHz) and part of it was directed to a photomultiplier 10, the signal from which was used as the reference signal for the V9-2 synchronous detector 15, whose minimum time constant of 0.5 sec was reduced to 10^{-2} sec. The main signal, modulated in amplitude with the same frequency, was sent to the detector from the output of the U2-6 selective amplifier 11 and was recorded on an S1-19B oscillograph or a type KSP recorder 16: 1) LG-159 laser; 3) splitting plate; 4) focusing lens; 5) plane conical nozzle; 6, 9, 14) collecting lenses with diaphragms; 7) adjusting lens; 8) scanning interferometer; 12) sweep unit; 13) deflecting mirror; 15) synchronous detector. The parameters of the Fabry-Perot interferometer are as follows: region of free dispersion $\Delta\nu_0 = 750$ MHz; instrumental width $\delta\nu = 10$ MHz.

Tests conducted on an aerodynamic installation showed that this system can record the signal from scattered radiation when its signal-to-noise ratio is $\gtrsim 0.1$ and it can be used to obtain a signal sufficient for analysis when the particle concentration is close to the conditions of natural air dustiness. As an illustration, in Fig. 3 we present signals of radiation scattered on aluminum particles ($d_r = 1\text{-}25$ μ) obtained with and without the use of the method of synchronous detection (Fig. 3b and c, respectively). The use of the given system appears to

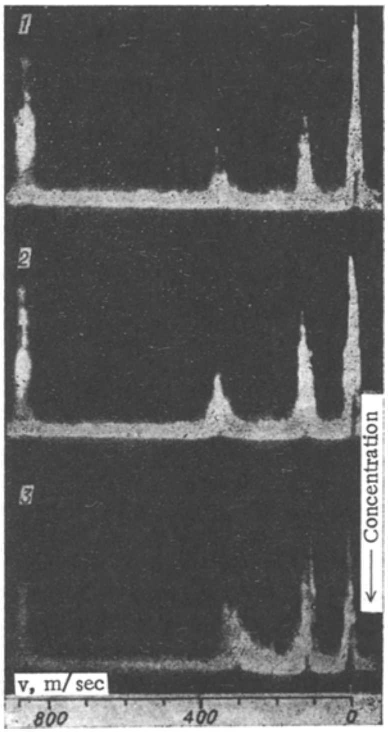

Fig. 2

be especially effective in experiments with a high level of background illumination, such as in the motion of particles in a stream of radiating gas, in measuring the velocities of hot particles, etc.

On the Method of High-Speed Photographic Recording of Particles in a Gas Stream

The use of the method of high-speed visualization, which under certain conditions permits the determination of the size as well as the concentration distribution of particles in a gas stream, together with the LDVM seems very promising in the investigation of two-phase streams. The basic scheme for the visualization of gas streams containing light-scattering particles is well known and consists in the following. A plane-parallel light beam (a light "knife"), which is introduced into the experimental region of the stream, is formed with the help of a special optical system. By recording the radiation scattered by the particles (at a 90° angle to the plane of the beam, for example) one can obtain information on the flow structure in any given plane. By using powerful pulsed lasers and optical systems and photographic materials with high resolution one can considerably expand the potentialities of the visualization method, increasing its sensitivity and its spatial and time resolution.

Let us briefly discuss some properties connected with the use of this method for the photographic recording of particles in a supersonic gas stream. The mode of operation of the installation which allows one to

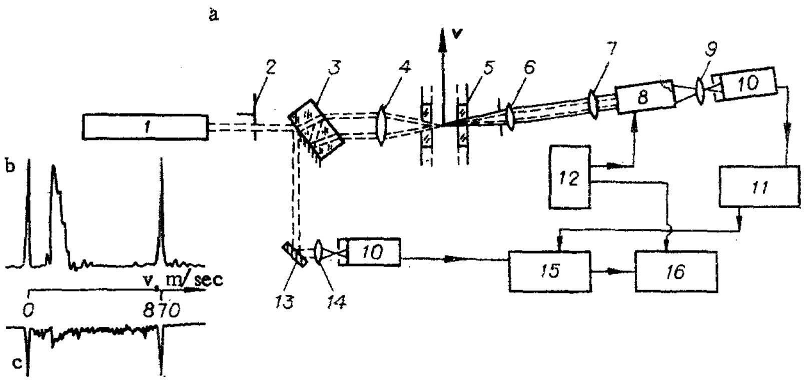

Fig. 3

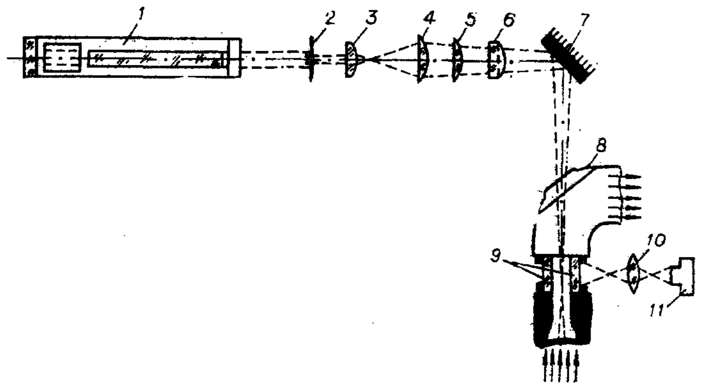

Fig. 4

record the laser radiation scattered from individual particles is of the greatest interest from the point of view of obtaining information on the particle sizes and their concentration distribution in a given region of the stream. In this case the main parameters of the optical system must be chosen with allowance for the following simple considerations.

The minimum particle size d recorded in an experiment determines the required resolution of the optics transmitting the image and of the photographic material: $R_0 \geq 1/d_{min}$. In this case the pulse duration τ_{pu} of the laser radiation must be $\leq r_r/v$ (r_r is the radius of a particle and v is its velocity), so that the movement of a particle during the exposure does not exceed $\sim r_r$. The condition of the resolution of individual particles moving in a stream and having a certain concentration n_0 ($1/cm^3$) also leads to a limit on the transverse size t (thickness) of the light beam. Since the total number N of particles lying in the illumination plane and recorded with the condition of the absence of superposition of the images from individual particles must be $N < S/S_0$ (S is the surface area of the light "knife" lying in the field of view of the objective and $S_0 \simeq \pi r_r^2$ is the mean cross-sectional area of one particle), at a certain concentration n_0 this leads to the condition $N = n_0 tS \leq S/\pi r_r^2$ and, consequently,

$$t \leqslant 1/\pi r_r^2 n_0.$$

It is also obvious that to obtain a sharp image of the particles falling into the region of the light "knife" it is necessary that its transverse size t be less than the depth Γ of sharpness of the objective: $t < \Gamma \simeq 2l\delta/D_0M_0$, where δ is the attainable value of the circle of confusion; M_0 and D_0 are the magnification and the diameter of the aperture diaphragm of the objective, respectively; l is the distance from the entrance pupil of the objective to the aiming plane. With allowance for the factors discussed above, one must, in accordance with the concrete requirements of the experiment (the size and concentration of the particles, their velocity, etc.), select the appropriate values of the resolution and magnification, the depth of sharpness and aperture ratio of the optical recording system, and the transverse size t of the laser beam.

An optical diagram of an installation designed for the visualization of a supersonic two-phase stream in a nozzle is presented in Fig. 4: 1) ruby laser; 2) diaphragm; 3-6) elements of focusing optics; 7) deflecting mirror; 8) entrance window; 9) window for exit of scattered radiation; 10) objective; 11) photographic apparatus. The main elements of this installation are as follows: a ruby laser with a power of $\sim 10^8$ W per pulse, an adjustable quarter-wave Kerr cell of nitrobenzene ($\tau_{pu} \simeq 30$ nsec), a telescope system (lenses of $f_3 = 30$ mm and $f_4 = 180$ mm) designed to increase the cross section of the laser beam to the required size and to decrease the angle of divergence $\alpha \simeq 5 \cdot 10^{-4}$, and a system for forming the plane-parallel beam (a spherical lens $f_5 = 1600$ mm and a negative cylindrical lens $f_6 = 400$ mm).

Figures 5 and 6 illustrate some possibilities of the method of high-speed photographic recording in experiments on the investigation of a supersonic two-phase stream produced with a plane profiled nozzle. The dimensions of critical cross section are as follows: height H = 14.5 mm; width $l = 30$ mm. The plane of the laser beam, whose transverse size was $\simeq 1.5$ mm, passed through the nozzle axis parallel to the glass side walls through which the observation was carried out. A characteristic photograph obtained in the mode of the observation of individual particles (polydisperse bronze particles of $d_r = 20$-200 μm) is presented in Fig. 5. The duration of the radiation pulse of the ruby laser was $\tau_{pu} = 30 \cdot 10^{-9}$ sec and the resolution of the receiving optics ($R_0 \simeq 50$ lines / mm) assured the recording of particles of $d_{min} \simeq 20$ μm. By analyzing such photographs one can obtain the particle sizes and concentration, as well as the concentration distribution in the detection region. With the choice of the approximate magnification and the use of high-resolution optics and photographic

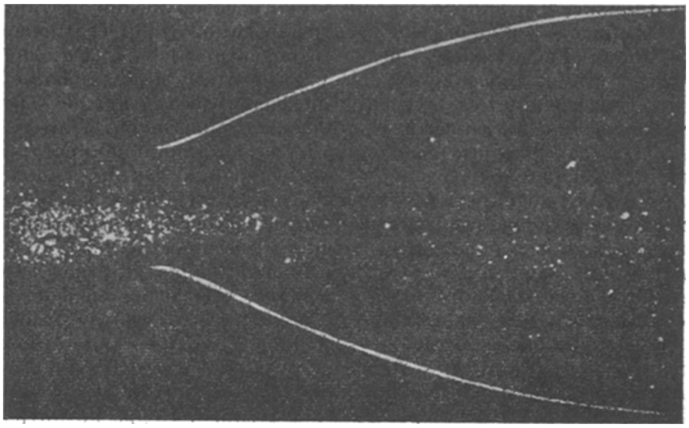

Fig. 5

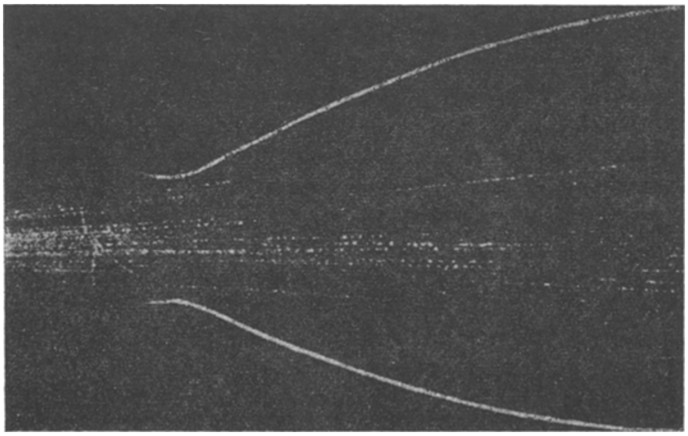

Fig. 6

materials, the measurement of particle sizes d = 1-2 μ in a gas stream is quite realistic.

Using a series of laser pulses following with a certain frequency, or, in the simplest case, with the laser operating in the mode of "spike" generation, one can measure the velocity of the particles and study their trajectories (see Fig. 6, spherical bronze particles of $d_{av} \simeq 80$ μm), which is of considerable interest, particularly for the observation of the limiting streamlines during the motion of particles in a nozzle.

Thus, the tests conducted show that the method of high-speed laser photographic recording, permitting the determination of a number of parameters such as the particle size and concentration, can be used successfully in conjunction with a laser Doppler velocity meter to solve a wide range of problems connected with the investigation of the dynamics of particles in high-velocity two-phase streams. The results of the experiments on the gasdynamic installation and, in particular, the data pertaining to the study of the effect of the velocity lag of fine particles in a supersonic gas stream by the LDVM method are presented in [12].

The authors thank E. G. Zaulichnyi for useful discussions and A. L. Predein for help in conducting the studies.

LITERATURE CITED

1. S. L. Soo, Fluid Dynamics of Multiphase Systems, Blaisdell Publ. Co., Waltham, Massachusetts (1967).
2. R. F. Hoglund, "Recent advances in gas-particle nozzle flows," ARS J., 32, No. 5, 662 (1962).
3. A. P. Alkhimov, V. A. Arbuzov, A. N. Papyrin, R. I. Soloukhin, and M. E. Shtein, "A laser Doppler velocity meter for the investigation of fast gasdynamic streams," Fiz. Goreniya Vzryva, 9, No. 4 (1973).
4. A. P. Alkhimov, A. N. Papyrin, and A. L. Predein, "The use of lasers to measure the velocity of particles in high-velocity gas streams," in: Reports to the Scientific–Technical Conference "The Use of Lasers in Modern Technology" [in Russian], Leningrad (1975).

5. A. P. Alkhimov, A. N. Papyrin, and A. L. Predein, "The use of a high-speed confocal spectrometer in an LDVM system," in: Problems of Gasdynamics [in Russian], Izd. Inst. Teor. Prikl. Mekh. Sibirsk. Otd. Akad. Nauk SSSR, Novosibirsk (1975).
6. B. S. Rinkevichyus and A. V. Tolkachev, "An optical Doppler velocity meter for gas streams," Kvant. Elektron. (Moscow), 1, No. 9 (1974).
7. Yu. G. Vasilenko, V. V. Dontsova, and Yu. N. Dubnitsev, "A laser Doppler velocity meter using a Fabry-Perot interferometer," Avtometriya, No. 3 (1971).
8. D. M. Paul and D. A. Jackson, "Measurement of supersonic velocity and turbulence by laser anemometry," J. Phys. E, 4, 173 (1971).
9. H. Morse, B. Tillis, H. Seifert, and W. Babcock, "Development of laser-Doppler particle sensor for the measurement of velocities in rocket exhausts," J. Spacecr. Rockets, 6, No. 3, 1168 (1969).
10. H. G. Heard, Laser Parameter Measurement Handbook, Wiley, New York (1968).
11. B. S. Rinkevichyus, "The Doppler method of measuring local velocities using lasers," Usp. Fiz. Nauk, 111, No. 2, 305 (1973).
12. A. P. Alkhimov, A. N. Papyrin, A. L. Predein, and R. I. Soloukhin, "An experimental study of the effect of the velocity lag of fine particles in a supersonic gas stream," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1977).

ROLE OF VIBRATIONAL RELAXATION IN THE NONEQUILIBRIUM FLOW OF AIR IN NOZZLES

V. N. Komarov

UDC 533.6.011.8

As is known, the nonequilibrium excitation of vibrational degrees of freedom occurs along with chemical reactions in a high-enthalpy air stream in a nozzle. The role of vibrational nonequilibrium has been studied insufficiently, and in calculations it is assumed, as a rule, that the vibrational degrees of freedom are excited in equilibrium [1-4].

The nonequilibrium air flow in a nozzle of hyperbolic profile is analyzed in the present report for the ranges of temperatures and stagnation pressures of $3000 \le T_0' \le 5000$°K and $1 \le p_0' \le 100$ atm characteristic of the existing hypersonic experimental installations. The dependence of the frozen-in internal energy on the mode of flow is analyzed on the basis of the calculations conducted. Conclusions are drawn about the influence of vibrational relaxation on the gasdynamic parameters of a stream.

Gas-Kinetic Model

The following system of chemical reactions [4] is taken as basic for air in the range of temperatures and pressures under consideration:

$$O_2 + M \rightleftarrows 2O + M,\ N_2 + M \rightleftarrows 2N + M,$$
$$NO + M \rightleftarrows N + O + M,\ O + N_2 \rightleftarrows NO + N,$$
$$NO + O_2 \rightleftarrows N + O_2,\ N_2 + O_2 \rightleftarrows 2NO,$$

where M is any of the molecules O_2, N_2, O, NO, or N.

It is assumed that the vibrational temperature of nitric oxide is in equilibrium with the translational temperature. The kinetic equations of [3] describing the vibrational relaxation in a mixture of polyatomic gases were used to calculate the vibrational energy of the N_2 and O_2 molecules.* The system of one-dimensional gasdynamic equations is described in detail in [1-5]. The expressions for the vibrational relaxation times and the reaction rate constants are taken from [6-8].

*As calculations show, in this case the influence of dissociation on the excitation of the vibrational degrees of freedom of the molecules is slight.

Zhukovskii. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 46-49, March-April, 1978. Original article submitted March 10, 1977.

