AN EXPERIMENTAL STUDY INTO THE NONSTEADY RADIATION OF A JET CONSISTING OF AN IMPACT-HEATING GAS CONTAINING CO_2

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UDC 533.906

A large number of studies [1-5] has been devoted to questions dealing with the formation of a steady-state supersonic flow where an axisymmetric or plane nozzle has suddenly been opened. We know that when the pressure of the ambient space (P_∞ > 1-0.1 Pa) is not exceedingly low, that when the flow is well described by the equations for a continuous medium, a jet of rather complex nonsteady structure is generated in the starting area. In addition to the actual front of the escaping gas, this structure includes the primary shock wave (SW), propagating through the background gas, and a secondary SW which brings the pressure in the gas being discharged into line with the pressure of the surrounding space. As the secondary SW moves upstream at velocities lower than the velocity of the flow, it is gradually carried away by the flow from the section at which it is formed, near the outlet of the nozzle, to its steady-state position $x_{st} \approx 1.5(P_0/P_\infty)h_*$ [6] (h_* represents the half-width of the critical nozzle cross section and P_0 is the deceleration pressure).

Thus, in experimental observation of flow parameters at the fixed point x ($0 < c < x_{st}$) we should initially observe elevated values for pressures and temperatures corresponding to the parameters behind the primary and secondary SW, and we should then encounter values gradually approaching their steady values. The density and radiation intensity values for the visible and IR regions, elevated in comparison to their steady-state values, were observed in the initial signal zone during measurement in impact-heated flows in supersonic nozzles and jets [7, 8].

It is the purpose of the present study to experimentally investigate the nonsteady gasdynamic and physicochemical processes which lead to the appearance of bursts of IR radiation in the stage of formation for a supersonic jet.

The experiments were conducted on an installation which is a combination of a shock tube with a diameter of 50 mm and a flat vacuum chamber in which the two-dimensional jet was contained by walls separated to a distance of ℓ = 45 mm. The discharge of the gas heated by the reflected SW passed through a slit with a half width of h_* = 1 mm. The low-pressure chamber of the shock tube and the vacuum chamber were filled with the gas being studied, which in this case was a mixture of CO_2 with N_2 and H_2O vapors, to pressures of $P_\infty = (1.3\text{-}26)\cdot 10^3$ Pa. The pressure of the propulsion gas He amounted to $(2\text{-}5)\cdot 10^6$ Pa. The velocity of the incident SW was measured along two bases with an accuracy of 1-2%. The equilibrium parameters of the gas behind the reflected SW, i.e., the deceleration parameters for the discharge jet varied within limits of T_0 = 1500-2500 K and $P_0 = (1\text{-}6)\cdot 10^6$ Pa. The jet pulse was diagnosed by the methods of multichannel emission and absorption spectroscopy in the IR region of the spectrum. A black body source whose temperature varied within limits of 1500-2500 K served as the standard radiation source and the temperature was determined immediately prior to the experiment by means of a TRU 1300-2350 constant filament lamp in which the accuracy was no lower than 2%. All of the optical elements of the circuit were fabricated out of CaF_2, and FSG-223A photoresistances were used as the radiation receivers, with a time resolution of ~1 μsec, the space resolution of each channel being 1-2 mm.

Interference light filters produced by the firm "Spectrum System" served as the spectral elements of the apparatus, and these had a certified wing shape. The measurements in the 4.3-μm band (transitions of the antisymmetric mode ν_3) were carried out in the direction from the absorption maximum of cold CO_2 in the wavelength range 4.45 ± 0.2 μm, and in the 2.7-μm band (transitions of the mixed modes $\nu_1\nu_3$ and $\nu_2\nu_3$) with use of a broadband 2.7 ± 0.4 μm filter to provide for the capture of the entire oscillation-rotation band for the complete range of oscillatory and translation-rotational temperatures in the gas being studied. Figure 1 shows examples of typical oscillograms obtained at various distances from the nozzle

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 31-38, July-August, 1990. Original article submitted March 7, 1989.

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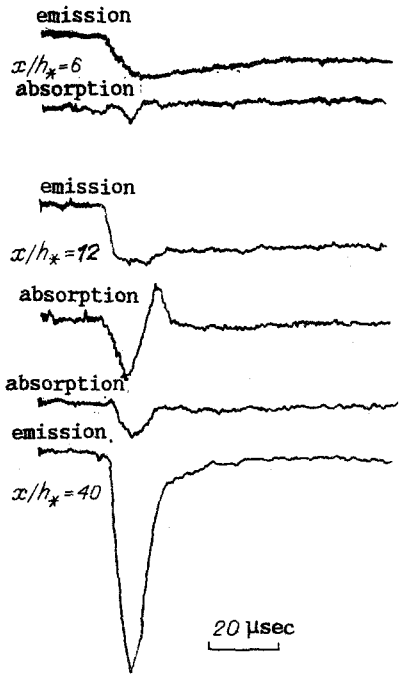

Fig. 1

outlet for the case in which $\lambda = 2.7$ μm, from which it is clearly seen that with increasing distance from the nozzle an intensive maximum of both the emittance and absorptance of the gas is formed in the starting zone of the flow. The duration of the maximum, reflecting the nonsteady stage of the flow, increases from 20-30 μsec (x = 12.5 mm) to 50-60 μsec (x = 40.5 mm). The peak amplitudes of the emission signals depend rather strongly on the flow regimes and in the "hottest" regimes at maximum distances from the nozzle outlet they reach approximately a tenfold multiple of the subsequent steady-state values.

The absorption signals, in view of the fact that the temperature of the radiation source is close to that in the gas being studied, in a number of cases exhibit a rather complex form (see Fig. 1). Qualitatively the deviation of the signals upward from the initial level corresponds to a temperature for the population of the recorded spectral transitions in this particular gas that is lower than the temperature of the black-body radiation source, while the downward signal deviations point to a higher temperature. In this case it is essential that we bear in mind the initial level of source radiation absorption in the background gas, which in view of the rarefaction of the flow within the jet may be comparable to the level of the useful signal.

By processing the derived signals it became possible to determine the population temperatures of the optically active transitions, i.e., to draw conclusions with regard to the distribution of energy in the molecules of the escaping gas, and in certain cases it became possible to establish the concentration of absorbing molecules (essentially, the density of the flow at the point being recorded).

With a three-temperature distribution of energy in the carbon dioxide (the existence of a Boltzmann distribution of energy in the antisymmetric mode with temperature T_3, a solitary Boltzmann distribution of energy in the symmetric and deformed mode with temperature T_2, and a translational-rotational temperature T_t) the relationship between the population of the upper N_j and lower N_i states of the $i \to j$ transition has the form

$$\frac{N_j g_i}{N_i g_j} = \exp - \left[\frac{hc}{k} \left(\frac{\omega_{\text{rot}}^{ij}}{T_t} + \frac{\omega_{1,2}^{ij}}{T_2} + \frac{\omega_3^{ij}}{T_3} \right) \right]. \quad (1)$$

Here g_i and g_j are the statistical weights of the corresponding states; $\omega_{\text{rot}}{}^{ij}$, $\omega_{1,2}{}^{ij}$, and $\omega_3{}^{ij}$ are the wave numbers defining the contribution of the rotational and oscillatory degrees of freedom in the total wave number of the $i \to j$ transition: $\omega^{ij} = \omega_{\text{rot}}{}^{ij} + \omega_{1,2}{}^{ij} + \omega_3{}^{ij}$. For all of the lines included in the 4.3 μm CO_2 band, $\omega_{1,2} \ll \omega_3$; however, the contribution of the term $\omega_{\text{rot}}{}^{ij}/T_t$ relative to $\omega_3{}^{ij}/T_3$ when $T_t \ll T_3$ may be noticeable. Consideration of this term in relationship (1) requires advance information as to the magnitude of

T_t. Under more unfavorable conditions ($T_t \approx 500$ K, $T_3 \approx 2000$ K) the error introduced by neglecting ω_{rot}^{ij}/T_t, in the case of the filter being used does not exceed 10%, and the intensity of the emission signal in the spectral range $\Delta\omega_f$ of the filter is subsequently approximately written as

$$I_e = \int_{\Delta\omega_f} D_\omega R_\omega A_\omega \, d\omega \approx \overline{D}\,\overline{R}\,\overline{A}\,\Delta\omega_f, \tag{2}$$

where $\overline{D} = \frac{1}{\Delta\omega_f}\int_{\Delta\omega_f} D_\omega \, d\omega$ is the aperture coefficient of system transmittion; $\overline{A} = \frac{1}{\Delta\omega_f}\int_{\Delta\omega_f} A_\omega \, d\omega$ is the averaged absorptance of the gas; $\overline{R} = \frac{2hc\omega_f^2}{\exp(hc\omega_f/kT_3 - 1)}$ (ω_f is the mean wave number of the filter transmission band). The quantity $\bar{A}$ is determined from absorption measurements in which the following signal is recorded:

$$I_a = I_s + I_e,$$

where

$$I_s = (1 - \overline{A})I_0; \tag{3}$$

$$I_0 = \overline{D}\,\frac{2hc\omega_f^2}{\exp(hc\omega_f/kT_r) - 1}\,\Delta\omega_f \tag{4}$$

is the intensity of radiation from a source with temperature T_r and an effective average wave number ω_f, impinging on the receiver. Having introduced the approximate values of $\bar{R}$ into relationship (2) with the effective wave number ω_f, for the measurements in the 4.3-μm band in conjunction with (4) we obtain

$$\frac{I_0 - I_s}{I_e} \approx \frac{\exp(hc\omega_f/kT_3) - 1}{\exp(hc\omega_f/kT_r) - 1},$$

i.e., the experimental measurements of the emission I_e and absorption I_a signals in this gas at a known source temperature T_r make it possible to determine the oscillational temperature T_3 of the antisymmetric mode.

The measurements in the 2.7-μm band were conducted, as noted earlier, with the use of a broadband filter ($\Delta\omega_f \approx 1100$ cm^{-1}), which enabled us to find the integral absorptance of the band in the spectral range of the filter:

$$\overline{A} = \frac{1}{\Delta\omega_f}\int_{\text{band}} (1 - e^{-\sigma_\omega n l}) \, d\omega$$

(n is the total CO_2 contentration), which in the case of the optically thin layers ($\sigma_\omega n\ell \ll 1$) is represented in the form

$$\overline{A} = S_0 n l, \tag{5}$$

where

$$S_0 = \frac{1}{\Delta\omega_f}\int \sigma_\omega \, d\omega = \frac{\pi e^2}{mc^2\Delta\omega_f}\,\frac{1}{z}\sum f_i g_i \exp\left(-\frac{hc\omega_{rot}^i}{kT_t} - \frac{hc\omega_{1,2}^i}{kT_2} - \frac{hc\omega_3^i}{kT_3}\right) \tag{6}$$

is the effective cross section of the optical transmission; z is the static sum of the CO_2 molecule; f_i is the oscillator force of an individual line. The summation in (6) is carried out over all oscillation-rotational lines of the band. With $\max(T_t, T_2, T_3) \leq 2000$ K, S_0 can be replaced with an accuracy of ~10% by the constant quantity

$$S_0 = \frac{\pi e^2}{mc^2}\,\frac{1}{\Delta\omega_f}\,f_\Sigma = (3.5 \pm 0.5)\cdot 10^{-21} \ \ (\text{cm}^2). \tag{7}$$

The experimental measurement of $\bar{A} = (I_0 + I_e - I_a)/I_0$ here, in accordance with (3) and (5), yield direct information regarding the complete concentration n of the carbon dioxide. The

temperature values derived from the emission and absorption measurement in the 2.7-μm band under the assumptions of (5) essentially correspond to the population transition temperature (00^00-10^01) and (00^00-02^01) CO_2, $T_{2,3}$, which in the three-temperature approximation (see above) are presented as follows:

$$\frac{hc\omega^{ij}}{kT_{2,3}} = \frac{hc\omega_{1,2}}{kT_2} + \frac{hc\omega_3}{kT_3} + \frac{hc\omega_{\text{rot}}}{kT_t} \approx \frac{hc\omega_{1,2}}{kT_2} + \frac{hc\omega_3}{kT_3}.$$

The magnitude of the CO_2 absorptance in the 2.7 ± 0.4 μm spectral range was studied experimentally. Experimental calibration demonstrated that in the cold background gas the linear relationship of the Lambert–Bouguer law is satisfied:

$$\ln (I/I_0) = -S_0 nl \tag{8}$$

(S_0 is determined by relationship (7), which is in good agreement with the literature data [9, 10]). Earlier we analyzed the assumptions under which relationship (8) is suitable to find the fields of carbon dioxide concentration in the medium being studied.

Thus, if we know the temperature of the black-body radiation source and the total amplitude of the signal I_0 from that source, further establishing in accordance with (8) the level of absorption in the background gas, from the instantaneous values of the amplitudes of I_e and I_a, within the framework of the assumptions made, it is possible to determine the instantaneous values of the total CO_2 concentration and the population temperatures of the isolated spectral transitions in the 4.3- and 2.7-μm bands.

A number of additional difficulties arose in analyzing the measurements in the 2.7-μm band in the diagnostics of mixtures containing considerable amounts of H_2O vapors which exhibited an intense absorption band in the 2.7-μm region. In analysis of these experiments it was approximately assumed that the oscillatory temperatures of all H_2O modes are in equilibrium with the translational degrees of freedom, while the integral coefficient of H_2O absorption at temperatures of 1000 K is greater approximately by a factor of 3 than in CO_2 [10]. Such assumptions made it possible approximately to account for the contribution of the H_2O vapors both in the absorption and emission signals in the 2.7-μm band.

Figure 2 shows an example of a processing of the emission-absorption signals obtained at wavelengths of 2.7 ± 0.4 (1) and 4.45 ± 0.2 (2) μm in a carbon-dioxide jet ($x/h_* = 40$, $T_0 = 2700$ K, $P_0 = 3 \cdot 10^6$ Pa). We see that the starting zone for the flow is characterized by higher density values for ρ and for the oscillatory temperatures T_2 and T_3, as opposed to the subsequent steady flow. The difference in the temperature curves for various oscillational CO_2 modes under these conditions is quite insignificant, whereas in jets of a $1CO_2$ + $10N_2$ mixture we observed noticeable excess over the level of excitation of antisymmetric oscillations of CO_2 (T_3) over the paired (T_2). The absolute magnitudes of each of these oscillation temperatures in such a mixture increase monotonically throughout the entire nonsteady stage, all the way to the establishment of steady values.

When to the mixture $1CO_2$ + $10N_2$ approximately 6% H_2O is added, the picture changes fundamentally. There is a noticeable reduction in the level of oscillation excitation in the CO_2 in the steady stage of the flow, whereas the relative (in terms of the steady stage) level of oscillation excitation in the jet starting stage becomes even higher than in a jet of undiluted CO_2.

Fundamental to an analysis of the experimental data is the distribution of density and the oscillatory temperature along the axis of the jet in the steady stage of the flow. Figure 3, in generalized coordinates $(\rho_{st}/\rho_0)N$ and $x/(h_*N)$ ($N = P_0/P_\infty$), shows a reduction of the experimental results derived at various distances from the outlet of the nozzle and in various flow regimes. With an accuracy of ±20% the data are generalized by the following relationship:

$$\rho_{st}/\rho_0 = 0.14 h_*/x. \tag{9}$$

The cited empirical distributions of density are in satisfactory agreement with the earlier experiments and calculations for flows in plane jets [6, 8, 12].

The experimental data on the distribution of density along the axis of the steady jet were subsequently used for approximate estimates of the values for the translational temperatures of the flow under the assumption of total thermodynamic equilibrium. In Fig. 4 these

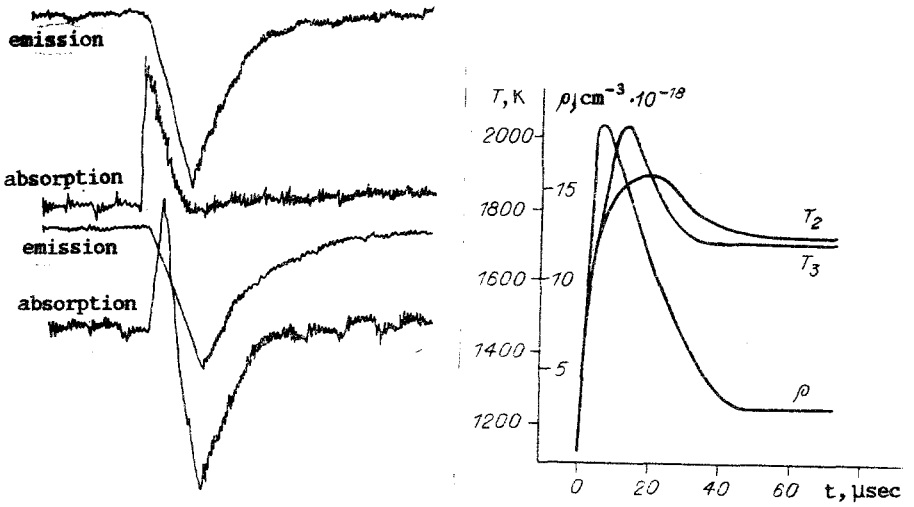

Fig. 2

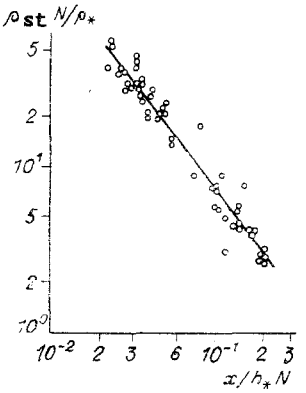

Fig. 3

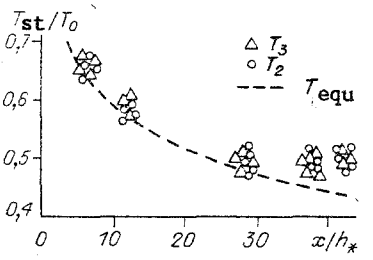

Fig. 4

estimated values of the equilibrium temperatures for CO_2 (T_{equ}), found from the isentropic relationships with specific heat-capacity ratios of $\gamma = 1.2$ (equal to the equilibrium for CO_2 when T = 1000-1500 K), are comparable to the experimental measurements of the oscillatory temperatures for the antisymmetric and paired CO_2 modes. We see that at small distances from the outlet of the nozzle the flow is nearly equilibrium, and the noticeable "freezing in" of the oscillatory temperatures is observed only at distances of $x > (20\text{-}30)h_*$. Qualitatively this result is confirmed by comparison of the times of oscillational relaxation for the CO_2 [11] with the characteristic gasdynamic flow times.

In a $1CO_2 + 10N_2$ mixture we observe some stratification in the oscillatory CO_2 temperatures; thus, at a distance of $x = 18h_*$ the temperature T_3 of the axisymmetric mode amounts to 0.7-0.8 of the deceleration temperature T_0, whereas the temperature of the paired modes lies somewhat lower: $T_2 \approx (0.5\text{-}0.6)T_0$. The value of the equilibrium flow temperature at this point, calculated from the isentropic relationships (for $\gamma \approx 1.3$) and from the density data, $T_t \approx 0.3T_0$. The addition to this mixture of 6% of H_2O vapors leads to an acceleration of the oscillational relaxation, and at a distance of $x = 18h_*$ the oscillational temperatures for CO_2, $T_3 \lesssim 0.5T_0$ and $T_2 \lesssim 0.4T_0$.

The cited experimental results defined the fundamental quantitative relationships of the realized steady-state supersonic oscillational-nonequilibrium expansion out of the slit into a space bounded by walls. In an analysis of the nonsteady stage of the flow it is natural to refer the measured values for density and the temperatures to their steady values at the same points in the flow.

In processing all of the oscillograms we noted that the origination and development of a thickened zone stood out clearly at the front of the flow.

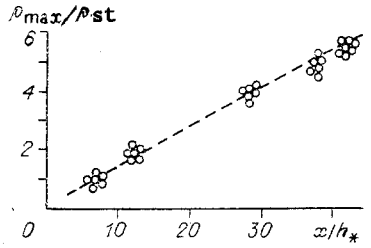

Fig. 5

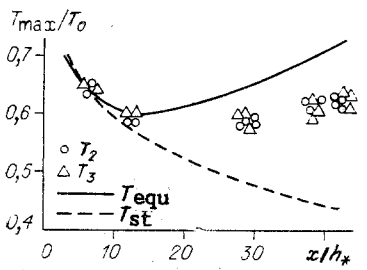

Fig. 6

In view of the finiteness of the space–time resolution of the measurements (~2 mm and 1 μsec) the detailed structure of the nonsteady segment of the flow was not analyzed, but only the maximum values of the parameters were established (density and the oscillatory temperatures) these having been recorded in this zone.

Figure 5 shows the increase in the density maximum in the condensed zone, with increasing distance from the outlet to the nozzle. We can see that the ratio ρ_{max}/ρ_{st} is independent of the flow regime and may be approximated by a linear function of the following type:

$$\rho_{max}/\rho_{st} = 0.15x/h_* \tag{10}$$

(the straight line in Fig. 5). When we compare relationship (10) with the change in density along the axis of the steady jet (9), it is easy to see that $\rho_{max}/\rho_\infty \approx 0.02n$, where $n = \rho_0/\rho_\infty$ represents the initial difference in density and $\rho_{max} = 0.02\rho_0$. Such quantitative relationships for the change in the density maximum in the condensed zone of the nonsteady jet, depending on the flow regime and the distance from the nozzle outlet, were ascertained for the first time. In the experiments in [13] and in the calculations of [3], involving a study of the operation of a plane supersonic nozzle, we can observe an approximate constancy of density in this zone at various distances from the critical cross section of the nozzle. In [3] the quantity ρ_{max}/ρ_∞ = const was determined from the density difference across the primary SW, propelled by the front of the expelled gas. The density in the flow of the discharge gas, compressed by the secondary SW, proved to be in the studies considerably lower than ρ_{max} and diminished further, with increasing distance from the nozzle outlet. The ratios ρ_{max}/ρ_∞ and ρ_{max}/ρ_{st}, as functions of the flow regime and distance from the nozzle outlet, as derived above, allow us to determine the corresponding Mach numbers M_1 and M_2 of the shock waves propagating through the background gas and in the steady flow. The Mach number of the primary SW

$$M_1 = \left[\frac{\rho_\infty}{\rho_{max}}\left(\frac{\gamma+1}{2}\right) - \left(\frac{\gamma-1}{2}\right)\right]^{-1/2} \tag{11}$$

on substitution of the experimental values of ρ_∞/ρ_{max} and on the assumption that $\gamma \approx 1.2$ changes as a function of the flow regime from 2 to 4. The equilibrium temperature of the background CO_2, attained behind such a SW, does not exceed 1000 K, which is substantially lower than the experimentally measured values of T_2 and $T_{2,3}$ in the condensed zone. Therefore, in the following we will relate the experimental values of density and oscillatory temperatures in the condensed zone with the passage of the secondary SW, propagating upward along the stream of the discharge gas which has parameters close to those of the steady flow. The Mach number M_2 of the secondary SW, determined from a relationship similar to (11), as the experimental values of ρ_{st}/ρ_{max} are substituted into the latter and on the assumption that $\gamma \approx 1.2$ (close to the equilibrium values of γ for 1000-1500 K) change with increasing distance from the nozzle outlet from 1 to 3.5 and can be approximated by the empirical relationship

$$M_2 = (0.76 \pm 0.05) + (0.06 \pm 0{,}01)\, x/h_*. \tag{12}$$

Figure 6 shows a comparison of the change in the maximum relative values of the oscillatory temperatures T_3/T_0 and T_2/T_0 as functions of the distance from the nozzle outlet and the equilibrium temperature of the CO_2 behind the secondary SW with M_2, determined from (12). We see that the increase in the oscillatory temperatures T_2 and T_3 lags noticeably behind the equilibrium temperature. This is natural when we take into consideration the realistic V–T relaxation time for the CO_2 under these conditions, which in accordance with the data from [11] amounts to 3-10 μsec, which is comparable to the time that the particles

in the flow spend behind the front of the secondary SW, as can easily be estimated from the velocity and geometry of the flow.

In the $1CO_2 + 10N_2$ mixture the oscillatory temperatures for all of the CO_2 modes cannot "track" the changes in the flow parameters in the condensed zone of the jet and in the frontal layers exhibit even lower values than in the steady flow. This effect apparently reflects the specific nature of the conducted experiments in which the discharge of the jet begins simultaneously with the reflection of the SW from the end of the tube, in view of which, in the frontal layers of the mixture containing 91% of slowly relaxing nitrogen, the oscillatory temperatures failed to reach the equilibrium values of the deceleration temperature.

In a mixture of 8% CO_2 + 86% N_2 + 6% H_2O the processes of oscillatory-translational exchange of all modes is considerably accelerated, and it is not only the steady flow but also the nonsteady flow that is nearly in a state of equilibrium. Thus, at distances of $x = 18h_*$ from the nozzle outlet we have $\rho_{max}/\rho_{st} \approx 3$, $M_2 \approx 2.2$ (for $\gamma \approx 1.3$). The equilibrium temperature T_{equ} of the flow behind such a SW must increase to $T_{equ}/T_0 = T_{equ}/T_{st}T_{st}/T_0 \approx 0.62$. The experimentally observed maximum oscillatory temperatures of the CO_2 in the starting zone for the flow are $T_3/T_0 \approx 0.6$ and $T_2/T_0 \approx 0.56$.

Thus, in all of the flow regimes investigated here the appearance and development of a condensed zone was observed in the jet starting stage, and the oscillational-translational and oscillational-oscillational exchange proceeds without equilibrium and differs significantly from the steady-state, with the fundamental significance of this difference represented by the composition of the outflowing gas and the jet flow regime.

Among the most characteristic quantiative relationships which appear in the experiments we should make particular note of the increase in the relative rise in the oscillatory temperatures in the condensed zone (relative to the steady-state value) with acceleration of the relaxation processes in the gas being discharged, i.e., an increase in the relative intensity of the IR radiation "bursts" at the instant of jet actuation.

In conclusion, the authors extend their gratitude to I. M. Naboko for his management of this study and to É. I. Vitkin for the useful discussion of the derived results.

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DYNAMICS OF THE CONDENSATION FRONT DURING LASER REDUCTION OF METALS IN HIGH-PRESSURE GASES

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UDC 536.422.4

Adiabatic expansion of the vapors from a target in a vacuum under the action of laser emission of moderate intensity against solid targets is accompanied by condensation of that vapor into droplets, and here a condensation discontinuity is formed near the surface [1]. As a result of this laser vaporization of the materials in a gaseous medium of elevated pressure (0.1-10 MPa) a condensed phase is also formed [2]. With laser irradiation of the oxides in a reduction gaseous medium we can find conditions under which the condensed phase will consist primarily of metal particles.

The efficiency of the physicochemical processes of laser reduction of oxides in gaseous reduction media of elevated pressure is determined to a considerable extent by the nature of the gasdynamic flows of multiphase vapor-gas mixtures. A study of the dynamics of the multiphase medium near a surface under the action of laser emission (LE) against materials in gases of elevated pressure by a high-speed photographic recording method demonstrated that the nature of the flows depends to a considerable extent on the pressure and kind of gas, the density of the LE flux, etc. [3, 4]. However, the method of high-speed photographic recording does not allow us to study in detail the process involved in the formation of the dispersion phase within the condensation region. We cannot establish the relationship between the space–time characteristics of the condensation region and the pressure of the gas, the energy parameters of the LE, etc. Moreover, it remains unclear as to when condensation begins, i.e., during the time that the LE is directed at the material, or at the conclusion of this stage.

It is demonstrated in this study that a condensation front analogous to this condensation shock arises in the vapor-gas cloud. Double-exposure holographic interferometry was employed to investigate the dynamics of this condensation front while a laser beam was directed against a target in a gas of elevated pressure.

The diagram of the experimental setup is shown in Fig. 1. The radiation from the diagnostic ruby laser 1, on passing through diaphragm 2, is expanded by negative lens 4, is divided into subject and reference rays by means of semitransparent mirror 5, and it is

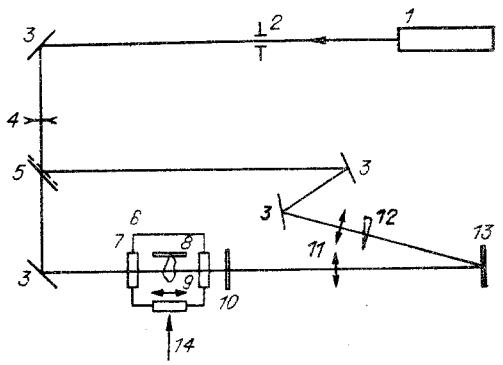

Fig. 1

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 38-41, July-August, 1990. Original article submitted February 17, 1989.

0021-8944/90/3104-0540$12.50