

INFLUENCE OF HOMOGENEOUS CONDENSATION ON THE GASDYNAMICS
AND RADIATION OF A FREE CARBON DIOXIDE JET

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The influence of homogeneous condensation on the gasdynamics and radiation of carbon dioxide gas during jet expansion into a vacuum is investigated experimentally and theoretically.

Free gas expansion in a vacuum possesses a number of features making it acceptable for investigation of the kinetics of energy exchange processes under nonequilibrium conditions. One of the main features of a low-density free jet is the possibility of producing any degree of nonequilibrium and its stationary maintenance. Giving the geometric (diameters of the critical d_* and output d_a nozzle sections, the aperture angle α) and the thermodynamic (pressure P_0 and temperature T_0 in the forechamber) parameters for the gas under investigation substantially determines the level and nature of the relaxation processes. For instance, conditions for the occurrence and progression of homogeneous condensation, and vibrational and rotational relaxation are realized quite simply during jet expansion of carbon dioxide gas into a vacuum. The domain of the modal parameters (P_0 , T_0 , d_*) in which the simultaneous progress of condensation and vibrational relaxation is observed [1, 2] is most interesting and difficult.

It should also be noted that nonequilibrium processes governed by thermal gasdynamic expansion conditions can, in a number of cases, exert a noticeable energetic effect on the expanding gas flow [2]. In these cases, questions of the gasdynamics and kinetics should be considered jointly. The influence of condensation and vibrational relaxation on the gasdynamics and radiation of a carbon dioxide jet issuing from a sonic nozzle into a low-density medium is investigated experimentally and theoretically in this paper.

EXPERIMENTAL SET-UP AND MEASUREMENT METHOD

Experiments were performed at the low-density vacuum gasdynamic installation of the Institute of Thermophysics of the Siberian Branch of the Academy of Sciences of the USSR [3]

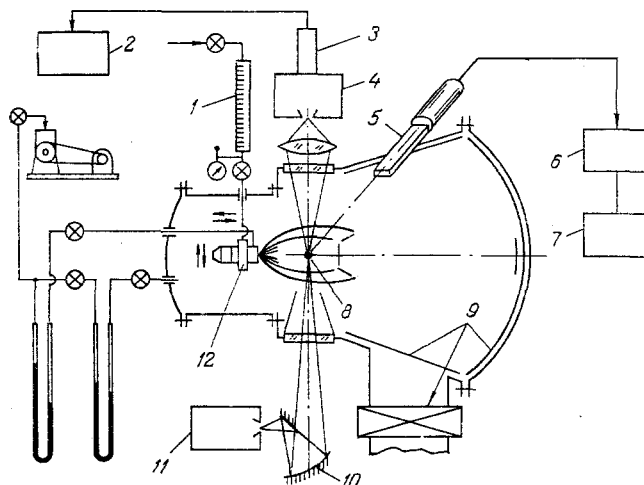


Fig. 1. Diagram of the experimental installation.

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whose diagram is represented in Fig. 1. The installation vacuum chamber ($V \approx 3 \text{ m}^3$) is equipped with an evacuation system based on oil-diffusion and nitrogen cryogenic pumps 9 assuring a 0.1-Pa background gas pressure level for a stationary gas flow rate to 1.5 g/sec. Within the chamber is a three-component coordinate mechanism on which the gasdynamic source 12 is mounted. It was an ohmic heater with a sonic nozzle whose critical diameter section d_* was 0.5 mm in these experiments. The working gas was supplied to the source 12 through the rotameter 1. The parameters in the fore-chamber of the heater varied within the ranges $T_0 = 300\text{-}800^\circ\text{K}$ and $P_0 = 0.75\text{-}3 \text{ MPa}$. A gas of both technical purity and precleansed by a cryogenic vacuum method was used as working gas. For diagnostic purposes the vacuum chamber is equipped with electron-beam equipment with the following electron beam parameters 8: accelerating voltage 20 kV, beam current 1 mA. The electron beam 8 passing through the gas causes radiation in a broad spectrum range, from x rays to the visible range. Under definite conditions the intensity of this radiation is proportional to the gas density and the electron beam current.

Recording of the UV and visible range radiation was realized by a system consisting of the monochromator 4 (SPM-2 type), the photomultiplier 3 (FÉU-39A type), and recorder 2 (ÉPPV-60MZ type).

The system to measure the x-ray brehmsstrahlung consists of the x-ray detector 5, including a Soller collimator, the scintillation counter BDS-9, and the recording apparatus consisting of the intensimeter 6 (PI-5 type) and recorder 7 (KSP-4 type).

The natural radiation of the heated gas jet (near IR spectrum range) was focused by a high-speed lens 10 onto the entrance slit of the spectrometer 11 (SDL-1 type). The spectrum width of the slit was constant and equal to 0.02 μm in all the measurements. A calibrated tungsten lamp was used for energetic calibration of the spectrometer.

The local density in the intensity of the x-ray brehmsstrahlung excited by the electron beam in the gas and the infrared radiation of the heated CO_2 jet were measured to study the features of nonequilibrium CO_2 expansion.

A methodological feature of the experiments was execution of the density and intrinsic IR radiation measurements for the CO_2 jet at fixed distances x from the nozzle exit for given pressures in the source fore-chamber P_0 , constant pressure in the vacuum chamber, and changes in the fore-chamber temperature T_0 from the initial value (ordinarily room temperature) up to the maximal value for a given heating tempo. This permitted variation of the fraction of condensed molecules and the mean size of the clusters in the selected jet section.

THEORETICAL ANALYSIS OF GAS EXPANSION INTO A VACUUM

Analyses of the flow in a jet issuing from an axisymmetric sonic nozzle into a vacuum were performed in addition to the experimental investigations. A numerical method based on utilizing a coordinate system formed by the streamlines and the normals to them [4] was applied to compute the stationary two-dimensional flow in the jet outside the sonic nozzle. The initial system of gasdynamic equations has the following form in natural coordinates

$$\rho U A = \text{const}, \quad (1)$$

$$\rho U \frac{\partial U}{\partial s} + \frac{\partial P}{\partial s} = 0, \quad (2)$$

$$\rho U^2 \frac{\partial \varphi}{\partial s} + \frac{\partial P}{\partial n} = 0, \quad (3)$$

$$h + \frac{U^2}{2} = \text{const}. \quad (4)$$

The method of computing the flow in the CO_2 jet assured taking account of the influence of the nonequilibrium condensation and vibrational relaxation processes proceeding simultaneously. The vibrational relaxation was described within the framework of a relaxation equation for the CO_2 specific vibrational energy [5], while the nonequilibrium homogeneous condensation was described on the basis of the classical theory of seed-formation. Details for the schemes to compute such flows are elucidated in [1, 5].

The method to compute the flow in a jet with the simultaneous progress of condensation and vibrational relaxation taken into account is to combine the algorithms to compute the

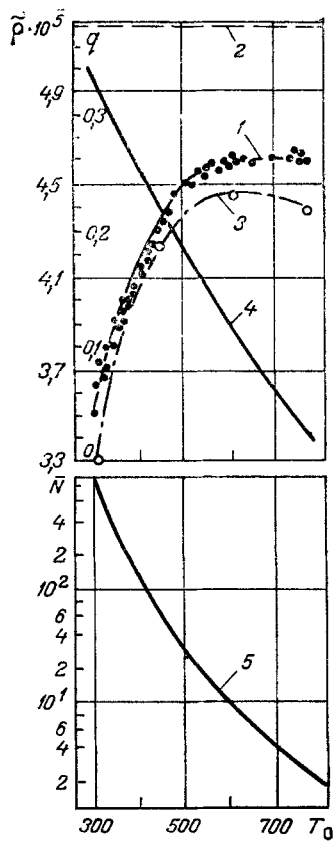


Fig. 2

Fig. 2. Dependence of the relative density $\tilde{\rho}$, the condensate mass fraction q , the cluster mean size \tilde{N} (moles/kl) on the temperature in the forechamber T_0 , °K for $x/d_* = 40.4$, $P_0 = 1.5$ MPa: 1) experiment; 2-5) computation (2) $\tilde{\rho}$ for $\kappa = 1.4$; 3) $\tilde{\rho}$ with simultaneously taking account of vibrational relaxation and condensation; 4) q ; 5) \tilde{N}).

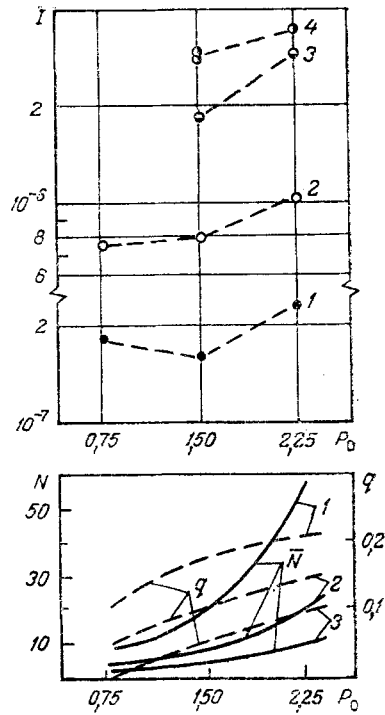


Fig. 3

Fig. 3. Dependences of the integral band intensity I (in relative units), the mass fraction of condensate q , the mean cluster size \tilde{N} (mole/kl) on the pressure in the fore-chamber P_0 (MPa) in the jet section $x/d_* = 40.4$ for fixed temperatures $T_0 = 525$; 2) 648; 3) 693; 4) 720; I experiment; q , \tilde{N} computation.

flow with condensation [1] and the flow with vibrational relaxation [1, 5]. In this case the expression for the enthalpy of the gas-condensate mixture, the equation of state, and the relaxation equation have the form

$$h = \frac{\kappa}{\kappa - 1} RT + e_v(T_v) - Lq, \quad (5)$$

$$P = \rho RT (1 - q), \quad (6)$$

$$U \frac{de_v}{ds} = \frac{e_v(T) - e_v(T_v)}{\tau}. \quad (7)$$

In the case under consideration the initial system consists of (1)-(7) as well as relationships describing the increment in the mass fraction of condensate [1]. (Here ρ in (1)-(3), (6) should be understood as the density of the gas-condensate mixture.)

The problem was solved in the simplest formulation, i.e., it was assumed that the vibrationally excited molecules are condensed exactly as are the unexcited molecules, while the presence of the condensate does not alter the vibrational relaxation time.

Computations showed that taking account of the vibrational energy relaxation results in a downstream shift of the point at which the saturation state and the condensation front are reached, whereupon the intensity of the condensation process is reduced.

RESULTS AND DISCUSSION

For a given nozzle and species of gas the condensation and vibrational relaxation processes are determined by the magnitudes of the parameters P_0 and T_0 . In a free CO_2 jet the homogeneous condensation, exactly as the vibrational relaxation, changes the nature of the expansion resulting in a reduction of the relative density on the jet axis [1, 2]. In its turn, this diminution in the number of emitters should result in a diminution in the intensity of the intrinsic CO_2 jet radiation. The necessity for the joint examination of the data obtained on the jet radiation and the relative density $\bar{\rho} = \rho/\rho_0$ on the jet axis becomes clear. Analysis of the density change on the jet axis, the condensate fraction q , and the mean cluster size \bar{N} can be performed by means of the results of computations and measurements represented in Fig. 2. As is seen from the figure, a change in the relative density $\bar{\rho}$ is not monotonic in nature, which can be explained by the appearance of condensation and vibrational relaxation effects. As the temperature T_0 rises in the CO_2 jet, excitation of the vibrational degrees of freedom resulting initially in retardation of the growth of $\bar{\rho}$ in the domain of primary influence of condensation becomes noticeable, and later, the reduction of the relative density after passage through the maximum. The domain of the shallow maximum $\bar{\rho}(T_0)$ is characteristic of the simultaneous progress of the condensation and vibrational relaxation processes. Comparing the computed dependence $\bar{\rho}(T_0)$ with that obtained in experiment, we note that the computational model that simultaneously takes account of condensation and vibrational relaxation describes the behavior of the $\bar{\rho}(T_0)$ observed in experiments well, which indicates the validity of taking account of heat liberation during condensation in the stream formation, i.e., the correctness of the condensation model utilized. The analogous nature of the experimental and computational dependences $\bar{\rho}(T_0)$ is also observed for other values $P_0 = 0.75$ and 3 MPa. It follows from the dependences obtained for $\bar{\rho}$, q , \bar{N} that the temperature domain where the jet IR radiation measurements were performed ($T_0 = 525\text{--}720^\circ\text{K}$) is characterized by the simultaneous progress of the condensation and vibrational relaxation processes, by the small average size of the clusters ($\bar{N} < 60$ according to the computations) by the mass fraction of condensate less than 0.15. Results of measuring the dependence of the integral intensity I of the $4.3\text{-}\mu\text{m}$ band on the pressure P_0 for several fixed temperatures T_0 and the computed values of the condensate fraction and the mean cluster size corresponding to these regimes are represented in Fig. 3. Let us note that the authors of [6] obtained a different character of the dependence of the integral band intensity on the stagnation pressure $I \sim P_0^{-0.5}$ for similar values of q and \bar{N} (in the developed condensation domain). In our opinion, the singularities in the vibrational degrees of freedom excitation in the glow discharge [6] in a strong gradient flow with clusters are a possible reason.

The experimental data were processed as follows to analyze the IR measurement results: the number of carbon dioxide gas molecules in the jet volume V exposed to the optical system $n_{\text{CO}_2} = V\rho n_0(1 - q)$ is compared to the computed fraction of condensate q for each value of I . The relationships I/n_{CO_2} obtained as a function of the temperature T_0 are presented in Fig. 4 for each P_0 . Curve 1 in this figure is the computed value of the integrated band intensity (in relative units) obtained under the assumption that the vibrational temperature T_v equals the gas temperature T^* in the nozzle critical section. Curves 2, 3, 4 are an analogous computation for the integrated band intensity I executed by using lower values for T_v , obtained from a computation of the flow in the jet with relaxation taken into account for $P_0 = 0.75, 1.5, 3$ MPa, respectively. Taking into account that the quantities q and \bar{N} are small for $P_0 = 0.75$ MPa and $T_0 = 618^\circ\text{K}$, it is assumed for superposition of the experimental results that the experimentally measured quantity I/n_{CO_2} is related just to the relaxation process in the gas phase, i.e., is determined by the temperature T_v obtained from computation for these conditions. Reference of the experimental value of I/n_{CO_2} (for $P_0 = 0.75$ MPa and $T_0 = 618^\circ\text{K}$) to the computed curve 2 permitted normalization of the remaining experimental points by a constant factor determined by this method. Analysis of these data on the influence of T_0 and P_0 on the integrated IR radiation intensity in the presence of a condensed phase in the jet shows that there is a tendency to magnification of the vibrational relaxation as the temperature T_0 is reduced (i.e., as the condensation process is amplified). This can be associated with the presence of relaxation in the clusters in the flow. However, un-

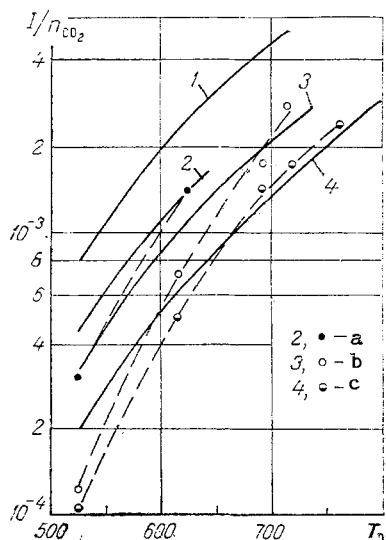


Fig. 4. Dependences of the reduced integral band intensity I/n_{CO_2} (in relative units) on the temperature T_0 ($^{\circ}K$) in the fore-chamber for the jet section $x/d_* = 40.4$ for fixed pressures P_0 (MPa) in the fore-chamber: a) $P_0 = 0.75$; b) 1.5; c) 3.0. Solid curves are computations, and dashes are experiment.

der the conditions for the conducted experiments the influence of this process is slight, the difference between the experimental and theoretical curves is within 10–15% of the change in the vibrational temperature in the flow.

NOTATION

d , nozzle diameter; α , nozzle aperture angle; x , distance from the nozzle exit; ρ , density; U , velocity; P , pressure; T , temperature; A , current tube area; h , specific enthalpy; φ , angle between the tangent to the streamline and the axis of symmetry; s , n , coordinates along the streamline and along the normal to it; κ , ratio of the specific heats; R , gas constant; e_v , specific vibrational energy; T_v , temperature of the vibrational degrees of freedom; L , specific heat of vapor formation; q , mass fraction of condensate; τ , vibrational relaxation time; $\tilde{\rho} = \rho/\rho_0$, relative density; N , mean cluster size; I , integrated band intensity; V , volume. The subscripts are: $*$ is at the nozzle critical section; 0 is at the nozzle fore-chamber; a is at the nozzle output section.

LITERATURE CITED

- N. G. Zharkova, V. V. Prokkoiev, A. K. Rebrov, P. A. Skovorodko, and V. N. Yarygin, "The effects of nonequilibrium condensation and vibrational relaxation in supersonic expansion of carbon dioxide," *Rarefied Gas Dynamics*, 2, 1141–1151, CEA, Paris (1979).
- N. G. Gorchakova, P. A. Skovorodko, and V. N. Yarygin, "Free jet expansion with a strong condensation effect," 13th Int. Sympos. Rarefied Gas Dynamics Abstracts, Vol. 2, 357–359, Inst. Thermophysics, Novosibirsk (1982).
- A. A. Bochkarev, E. G. Velikanov, A. K. Rebrov, R. G. Sharafutdinov, and V. N. Yarygin, "Gasdynamic low-density installations," *Experimental Methods in Rarefied Gas Dynamics* [in Russian], Inst. Thermophys. Sib. Branch USSR Acad. Sci, 6–28, Novosibirsk (1974).
- F. P. Boynton and A. Thomson, "Numerical computation of steady, supersonic, two-dimensional gas flow in natural coordinates," *J. Comput. Phys.*, 3, No. 3, 379–398 (1963).
- P. A. Skovorodko, "Vibrational relaxation in a free carbon dioxide gas jet," *Certain Problems of Hydrodynamics and Heat Transfer* [in Russian], Inst. Thermophys. Sib. Branch, Academy of Sciences of the USSR, Novosibirsk (1976), pp. 63–74.
- A. A. Vostrikov, S. G. Mironov, A. K. Rebrov, and B. E. Semyachkin, "Investigation of the vibrational relaxation of CO_2 molecules in a heterogeneous gas-cluster system," *Kvantovaya Elektronika*, 8, No. 6, 1356–1358 (1981).