TEMPERATURE STUDIES OF A SUBSONIC JET IN MOLECULAR GASES AT LOW PRESSURES

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The results of measurements of the temperature in an air and nitrogen plasma jet at low pressures on the VGU-2 setup are presented.

In addition to the studies carried out in [1] the measurements of the temperature in a subsonic plasma jet in two media — nitrogen and air — on the VGU-2 gasdynamic setup are interesting.

Improvement of the induction plasmatron [2] made it possible to carry out studies under pressures significantly below atmospheric pressure in a wide range of power injected into the discharge. The following conditions were realized: working gas — air, nitrogen; pressure — $5 \cdot 10^3$–10^5 Pa; flow velocity — 150-30 m/sec; and, diameter of the jet — 25-40 mm. The power was measured in the anodic circuit of a lamp generator. Air flowed under a pressure drop out of the laboratory enclosure and was purified by passing it through filters. Nitrogen was injected into the discharge channel from tanks.

Radiation from the plasma was recorded by two methods: photoelectrically on a McPherson monochromator with a dispersion of 0.8 nm/mm (absolute measurements) and photographically on a DFS-13 spectrograph with a dispersion of 0.2 nm/mm (identification of the spectrum; measurement of the radiation intensity). The plasma jet was projected on the slit of a spectrograph, and in addition in one case the discharge axis was oriented parallel to the slit of the apparatus and in the other case it was oriented perpendicular to the slit.

In the first case the distribution of the parameters along the axis of the discharge was determined, and in the second case the radial dependences of the measured quantities were studied. The dissociated-air plasma was studied under pressures of $5 \cdot 10^3$–10^5 Pa (the power equaled 31.6, 37.4, and 40.2 kW), and the nitrogen plasma was studied for two values of the pressure 10^4 and $3 \cdot 10^4$ Pa (the power equaled 37.4 kW).

Measurements along the axis of the discharge were performed in the following sections: in the zone of energy liberation ($z \sim 125$ mm from the upstream cutoff of the channel) and at the channel cutoff and further downstream to the section $z \sim 60$ mm from the cutoff of the plasmatron channel.

The flame of the air and nitrogen plasma jet has a characteristic structure: a high-temperature core and a peripheral part — a mixing layer with a lower temperature. The core of the nitrogen plasma jet is wider than that of the air plasma jet for the same values of the pressures and powers.

The air and nitrogen plasma contained nitrogen atoms, N_2 molecules (which emit the first and second positive systems), and N_2^+ molecules (the first negative system). In addition, the air plasma jet contains oxygen, nitrogen oxide, and cyanogen. The mixing layer of the air plasma has a violet color, and in the nitrogen jet the sheath is yellow. The radiation intensity of the nitrogen plasma is higher than that of the air plasma because of the large thickness of the high-temperature layer.

In the zone of energy liberation the discharge has a virtually uniform structure.

Measurements of the "rotational temperature" in air and nitrogen were performed based on the distribution of the relative intensity in the rotational structure of the bands (0 — 0) λ = 391.4 nm, (0 — 1) λ = 427.8 nm, (1 — 2) λ = 423.6 nm of the first negative system (1^-) N_2^+ and (0 — 0) λ = 337.1 nm of the second positive system (2^+) N_2. The excitation temperature of the atomic levels was determined from the absolute intensity of a number of nitrogen lines in the range 820-875 nm and the oxygen lines λ = 615.8 nm and 844.6 nm. The rotational

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structure of the N_2 and N_2^+ bands was calculated on a computer followed by identification of the spectra obtained experimentally. The accuracy of the measurements of the "rotational temperature" does not exceed 15%, while the accuracy of the measurement of the excitation temperature of the atoms does not exceed 5%.

The distribution of the intensity in the rotational structure of N_2^+ was studied in the entire pressure range for different sections of the jet. A series of curves $\log I_S = f(K)$ was obtained for the (0 — 1) λ = 427.8-nm band in an air plasma for pressures of $5 \cdot 10^3$–10^5 Pa. The curves have two sections: a rectilinear section with quantum numbers $10 \leq K \leq 50$ and a second section with $K > 50$, characterized by a large spread in the experimental points. The same picture is observed for the (0–0) λ = 391.4-nm band. In the (1–2) λ = 423.6-nm band the curves are rectilinear up to rotational numbers $K \leq 50$; lines with $K > 50$ are superposed on one another. Such an intensity distribution is characteristic for all downstream sections of the jet, beginning with the cutoff of the plasmatron channel. In the zone of energy liberation the distribution of N_2^+ over the rotational levels had a Boltzmann character in the entire range of rotational quantum numbers.

Based on the analysis of the distributions obtained it may be conjectured that the air plasma contains two groups of N_2^+ molecules in the entire pressure range. The first group is characterized by temperatures of 5000-5800°K, and their distribution over the rotational levels is close to a Boltzmann distribution. The second group of molecules populates levels with $K > 50$, and does not obey the Boltzmann law; these levels are overpopulated. The anomalous population of the high rotational levels of N_2^+ molecules was discussed in [3, 4] and elsewhere. The authors explain the overpopulation obtained by several mechanisms depending on the specific conditions: inelastic collisions with heavy particles, with slow electrons, with secondary electrons, etc. In this experiment the most suitable of the enumerated mechanisms is the interaction with heavy particles, as a result of which the N_2^+ molecules acquire excess rotational energy.

If the frequency of collisions between the excited molecules and normal molecules is much higher than the probability of radiative decay of the excited level and the rates of other processes, the distribution of molecules over the rotational levels is close to a Boltzmann distribution with a temperature equal to the temperature of the gas [5]. Under the conditions of the experiment for pressures of $5 \cdot 10^3$–10^5 Pa the collision times $\tau_{col} \sim 2 \cdot 10^{-8}$–$9 \cdot 10^{-9}$ sec, and lifetime of the zeroth vibrational level of the $B^2\Sigma$ state of the N_2^+ ion is $\tau \sim (5\text{-}7) \cdot 10^{-8}$ sec, i.e., over the lifetime of an excited state the molecule undergoes several collisions, required for establishing the equilibrium distribution. Thus in spite of the fact that the N_2^+ distribution over all rotational levels is not the equilibrium distribution, in a certain energy interval there exists a group of molecules which can be employed to determine the gas temperature in the plasma jet.

In the nitrogen plasma under pressures of 10^4 and $3 \cdot 10^4$ Pa the "rotational temperature" could not be determined for the (0–1) λ = 427.8-nm band, since the N_2^+ distribution is not a Boltzmann distribution. This could be attributable to the experimental technique, since the spectra in this case were measured on an instrument with the lowest dispersion of 0.8 nm/mm. In the (0–0) band of the system (2^+) of N_2 at a pressure of 10^4 Pa Boltzmann distributions of molecules with a temperature of 5800°K are observed at the cutoff of the channel and with a temperature of 5100°K at a distance $z \sim 30$ mm downstream from the cutoff. For a pressure of $3 \cdot 10^4$ Pa too high values of the rotational temperature are obtained (~8000-10,000°K).

Aside from anomalies in the population of the rotational levels both in nitrogen and air plasma, the low-temperature mixing layer surrounding the core of the jet, which distorted the radiation of molecules passing through it all the more strongly the thicker the layer, also has an effect. As interferometric measurements showed, the thickness of the layer increases as the pressure increases and as the distance downstream away from the cutoff of the channel increases.

In a free nitrogen and air plasma jet at $P = 10^4$ Pa the distribution of the intensity of the main radiators of molecular nitrogen N_2 and N_2^+, nitrogen atoms, and oxygen atoms along the axis of the jet was determined. The radiation of N_2^+ and atomic nitrogen is maximum at the channel cutoff, while the radiation of N_2 molecules increases monotonically from a minimum value on the axis to a stationary value at a distance $z \sim 8$ mm from the cutoff. The deviation of the points toward decreasing intensity of the radiation on curves for N_2 and N_2^+ at a distance of $z \sim 16$ mm from the cutoff is associated with the effect of the low-temperature mixing

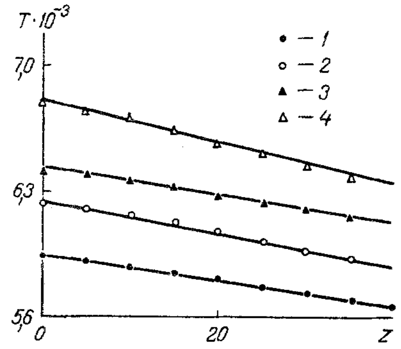

Fig. 1

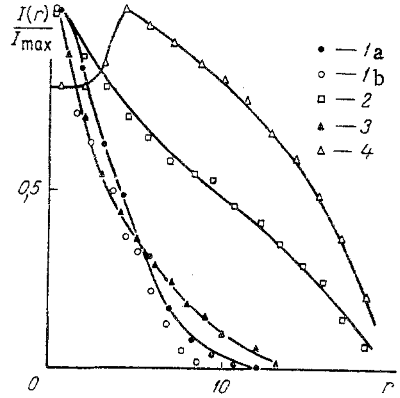

Fig. 2

Fig. 1. Distribution of the temperature T (K) along the axis of the jet z (mm): 1, 2) $P = 10^4$ Pa, N = 31.6 and 37.4 kW, respectively; 3, 4) $P = 3 \cdot 10^4$ Pa, N = 31.6 and 37.4 kW, respectively.

Fig. 2. Radial distributions of the relative intensity of the radiation $I(r)/I_{max}$ of N_2^+ (1, 2) and atomic oxygen (3, 4) in different sections of the jet: radiation of N_2^+: 1a, 3) cutoff; 1b) z = 60 mm; 2, 4) zone of energy liberation $P = 10^4$ Pa.

layer. For atomic nitrogen such an effect is not observed, since it radiates from the core of the jet. The density distributions of the nitrogen atoms and molecules along the jet, calculated from the measured absolute intensities, are similar in character to the dependences of the intensity along the jet.

In an air plasma the excitation temperature of the nitrogen and oxygen atoms was determined in the wavelength range 600-872 nm for pressures of $1 \cdot 10^4$ and $3 \cdot 10^4$ Pa and two values of the power (31.6 and 37.4 kW) at the cutoff of the channel and along the axis of the free jet at a distance of z ~ 40 mm from the cutoff. The temperatures determined from the different spectral lines of nitrogen and oxygen agree within the limits of error of the measurements. The excitation temperature in the free air jet exhibits an insignificant longitudinal gradient $\Delta T/\Delta z$ ~ 5-10 K/mm (Fig. 1). As the pressure increases and the power injected into the discharge increases, the rectilinear character of the dependences remains, and only the value of the temperature increases from 6000°K at $P = 1 \cdot 10^4$ Pa up to 6800°K at $P = 3 \cdot 10^4$ Pa. Analogous dependences on the coordinate z with approximately the same temperatures were obtained for the nitrogen plasma. For a free nitrogen and air plasma jet the distribution of the gas temperature along the z axis was determined for a pressure of 10^4 Pa. Within the limits of accuracy of the measurements the gas temperature equals the excitation temperature, though T for the gas is observed to drop off more rapidly along the axis, which can be explained by the effect of the mixing layer, since the molecules occupy a wider region than the atoms, and the thickness of the mixing layer increases as the distance from the cutoff of the channel increases. Thus the small temperature drop along the axis of the free jet indicates that the jet is not isothermal.

All above-described measurements of the temperature in the nitrogen and air jets were performed in a direction perpendicular to the axis of the jet. To clarify the effect of the nonuniformity of the emitting layer of the plasma along the line of observation on the measured temperature the radial distributions of the radiation intensity of a number of oxygen and nitrogen lines and the excitation temperatures in different sections of the jet were studied.

The discharge is axially symmetric, so that the transition from radiation intensities, integrated over the depth of the source, to the corresponding local values of the radiation intensity was carried out with the help of Abel's integral equation. The equation was solved with the help of Pierce's method on a computer after a preliminary numerical experiment, in which the optimal number of partitions and the method for processing the experimental data were determined.

The intensity of the radiation as a function of the radius of the air plasma jet is shown in Fig. 2 for different sections. The curve 1a is drawn through the points corresponding to the channel cutoff and the section at a distance z ~ 30 mm, while the curve 1b corresponds to a distance of 60 mm from the cutoff. As one can see from the figure, the dimensions of the emitting high-temperature core are independent of the coordinate along the axis of the jet right up to z ~ 60 mm. In the zone of energy liberation (curve 2) the region of radiation of the N_2^+ molecule becomes substantially smeared. But oxygen atoms emit from an even more extended region in the zone of energy liberation (curve 4). At the cutoff oxygen emits from a slightly smaller region than N_2^+ (curve 3). This graph gives an idea of the radial dependence of the density of the emitting components N_2^+ and oxygen in different sections of the air plasma jet: at the cutoff there is a distinct emitting core.

The character of the radiation from particles of different type in the nitrogen plasma is indicated in Fig. 3. The dependences are analogous for N_2^+. The dimensions of the region of emission of molecules depend quite strongly on the pressure in the nitrogen and air plasma. As the pressure increases from $1 \cdot 10^4$ to $3 \cdot 10^4$ Pa the dimensions of the region increase by a factor of 2-3, and at the same time the region of emission (the region of the discharge) of the air plasma is smaller than that of the nitrogen plasma. For the same pressure atoms emit primarily from the part of the jet near the axis (curve 3), while molecules also emit from the peripheral regions (curve 1).

The radial temperature distributions for the air and nitrogen plasma were determined from the absolute intensity of the atomic nitrogen and oxygen lines and the rotational line in the (0—0) band of the (2^+) system of the N_2 molecule. Data on the composition from [6] and the results of calculations carried out by S. N. Kubarev were employed.

In the free air plasma jet the character of the temperature curves changes insignificantly as the pressure increases (Fig. 4, curves 1-3). Decreasing the power to 31.6 kW lowers the level of the curves on the average by 600°K and sharpens them somewhat.

Thus the increase in the pressure and power liberated in the discharge with a constant flow rate of the gas gives rise to an expansion of the region of the discharge (the radiation brightness and the size of the core of the jet increase). This is explained by the fact that the number of interparticle collisions and therefore the efficiency of excitation of molecules and atoms increase.

The same values of the temperature were obtained for the nitrogen plasma, with the difference that the region of emission of the atoms is wider than in the air plasma, and this difference increases as the pressure increases. For a nitrogen plasma the radial distributions of the excitation temperature of the rotational line in the molecular band were also determined, they agreed with the excitation temperature of the atoms.

Comparison of the radial dependences of the radiation intensity with the analogous temperature distributions at the channel cutoff shows that the lines of atomic nitrogen and oxygen are radiated from a region of the jet with a higher temperature. The local values of the excitation temperature on the axis of the discharge for different pressures are 150-200 K higher than the temperatures averaged over the line of sight, which falls within the limits of accuracy of the measurements. Thus, nonuniformities of the emitting layer do not affect the measurement of the excitation (electron temperature) in the jet. This indicates that the nitrogen and oxygen atoms are concentrated in the region of the jet near the axis and measurement of the temperature from the radiation of the lines of these atoms gives the temperature of the core of the jet.

For the gas temperature measured in the bands of N_2^+ and N_2, the difference between the temperature on the axis and the temperature averaged over the line of sight is larger, since their concentration extends to the peripheral regions.

The radial dependence of the electron temperature in the zone of energy liberation at a distance of z ~ 125 mm upstream from the channel cutoff is different (curve 4 in Fig. 4).

The curve 5 in Fig. 4 was obtained in an air plasma at the channel cutoff and refers to the temperature determined from the absolute intensity of the rotational line R(34) in the band of N_2^+. The number of points on curve 5 is limited because there are no data on the composition of N_2^+ at temperatures below 6000°K. As one can see, the temperatures on the axis agree. In the zone of energy liberation for the same power of 31.6 kW and pressure of 10^5 Pa the excitation temperature of the atomic levels of oxygen is 1300°K higher than the gas temperature determined from the N_2^+ bands, while at the channel cutoff this difference decreases to 500°K, which falls within the measurement error.

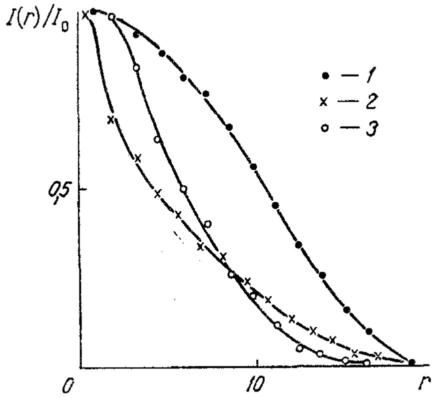

Fig. 3

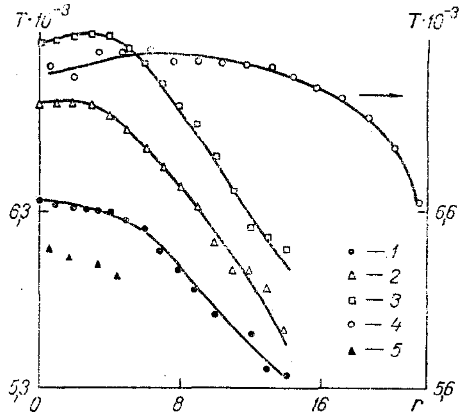

Fig. 4

Fig. 3. Relative intensity of the radiation $I(r)/I_0$ of N_2 and N versus the radius of the jet r at the channel cutoff: 1, 2) radiation of N_2 for $P = 3 \cdot 10^4$ and $1 \cdot 10^4$ Pa, respectively; 3) radiation of N for $P = 3 \cdot 10^4$ Pa.

Fig. 4. Distribution of the temperature T along the radius r in an air plasma jet: channel cutoff, N = 37.4 kW: 1, 2, 3) $P = 10^4$, $3 \cdot 10^4$, $9 \cdot 10^4$ Pa, respectively; 4) zone of energy liberation, $P = 10^4$ Pa, N = 40.2 kW; 5) excitation temperature of the rotational line in the band of N_2^+.

Thus the zone of energy liberation in an air plasma is in a nonequilibrium state, associated with the fact that the oxygen atoms are excited primarily by hot electrons, which acquire energy from the field and are concentrated in the peripheral regions of the jet while on the axis their density drops. For this reason, oxygen and nitrogen atoms emit from zones at distances exceeding 4 mm from the axis of the discharge. The nitrogen molecules, on the contrary, are concentrated in the region near the axis with a lower temperature, and moreover the energy of the electrons is transferred more efficiently to the vibrational degrees of freedom than to rotational and translational degrees of freedom [7].

The small dip at the axis (curve 4) is a manifestation of the skin effect, which insignificantly affects the temperature profile; the heating of the electrons is mainly quite uniform over the profile of the discharge. The profiles of the gas temperature in the zone of energy liberation could not be determined, since the intensity of the radiation of N_2^+ is only slightly greater than the equilibrium intensity, but, judging from the radial dependences of the emission intensity, the N_2^+ molecules (curve 2 in Fig. 2) occupy a narrower region at the axis than do the atoms.

The skin effect is absent at the channel cutoff, and owing to diffusion the electron density on the axis increases, while the difference between the gas temperature and the electron temperature practically vanishes.

Thus the gradual drop in the temperature curves in the free jet and especially in the zone of energy liberation indicates that there are no large temperature gradients in the high-temperature region of the plasma.

Thus the conditions in the channel cutoff in the air and nitrogen plasma for a pressure of 10^4 Pa are close to equilibrium. This proposition is confirmed by the results obtained from measurements of the heat content of a nitrogen plasma jet with enthalpy sensors. The temperature determined from these measurements equaled the gas temperature determined by spectral methods. The gas temperature in the plasma jet can be measured by using a Boltzmann population distribution for the group of N_2 and N_2^+ molecules in a definite interval of values of the rotational quantum numbers, and in addition the N_2 molecule is preferable, since it is subjected less to chemical transformations. No significant difference was observed in the radiative properties of air and nitrogen plasmas.

NOTATION

N, anodic circuit power; P, pressure; z, coordinate along the axis of the jet; λ, wavelength; I, radiation intensity; I_0, intensity on the axis; I_{max}, maximum intensity; S, line strength; K, rotational quantum number; T, temperature; τ_{col}, time between two collisions; τ, lifetime of the excited state; and r, coordinate along the radius of the jet.

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THERMICALLY NONEQUILIBRIUM IONIZATION IN A CO_2:N_2:He MIXTURE

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The results of measuring the electron density in a supersonic stream of a laser-active mixture are given.

The development of laser technology and of nonequilibrium plasma chemistry is stimulating interest in the problem of obtaining a volumetric discharge in a dense molecular gas. As is well known, the uniform ignition of a discharge proves possible only with the application of special procedures, the most important of which is an increase in the initial level of electron density in the discharge gap through preliminary ionization of the gas. One of the interesting and, evidently, promising methods of uniform preionization of large volumes of dense gases in rapid-flow laser systems is thermally nonequilibrinm ionization [1, 2]. Such a method can be realized by heating and adiabatic cooling of the gas in a time less than the relaxation time of vibrational states of diatomic molecules (CO, N_2).

The electron densities recorded in experiments with a stream stagnation temperature $T_0 \approx 2000°K$, $P_0 \approx 15$ atm, and a nozzle Mach number M = 4 were $n_e \approx 10^{10}$-10^{11} cm^{-3}, which exceeds the value of n_e calculated by Saha's method for equilibrium conditions by several orders of magnitude [3]. The degrees of ionization attained made it possible to ignite an externally maintained discharge in a supersonic stream of nitrogen [4], through which one can effectively increase the energy stored in vibrational degrees of freedom of the molecules of laser-active media.

The mechanisms of nonequilibrium ionization proposed up to now, although they allow one to conclude that vibrationally excited molecules have a decisive influence on ionization processes, cannot explain the entire collection of experimental data available [5, 6]. The theoretical description of processes of nonequilibrium ionization in the case of a CO_2:N_2:He laser-active medium, of practical importance, is a still more difficult and, to a certain extent, indeterminate problem. Experiments acquire special importance here.

In the paper we give the results of research on the influence of carbon dioxide on the electron density in a supersonic stream of vibrationally excited nitrogen. We give the results

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