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TEMPERATURE MEASUREMENTS ON AN AIR PLASMA JET IN AN INDUCTION PLASMATRON AT REDUCED PRESSURES

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Temperature measurements are reported for a subsonic free air-plasma jet derived from a VGU-2 plasmatron in the pressure range $5 \cdot 10^3 \leqslant P \leqslant 10^5$ Pa.

There are a few papers in which temperatures in air induction plasmas have been measured by spectral methods; they relate to discharges with air blown through them [1-5] or without throughflow [6] and relate in the main to the energy deposition zone. Although there were substantial differences between the equipments and various spectral methods were employed, it has been found that the state of an air plasma at atmospheric pressure is close to an equilibrium one. This conclusion cannot be transferred to the case where the induction plasma is produced in an air flow at pressures below atmospheric until additional studies have been made. This can then form the basis for temperature measurements in subsonic air jets at pressures of $5 \cdot 10^3$-10^5 Pa.

We consider the first negative system of N_2^+ ($B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$ vibronic transition), which is observed in a spectral range convenient for measurement (3600-5200 Å), and which is reasonably strong and whose bands are present throughout the pressure range. We examined the relative intensity distribution of the lines in the rotational structure of N_2^+ in order to determine the gas temperature. We then derived the dependence of the jet temperature on pressure and the temperature distribution along the axis.

We examined the subsonic plasma jet obtained in a high-temperature gasdynamic apparatus type VGU-2. Jet parameters: power N = 31.6 kW, working gas air, pressure range P = $5 \cdot 10^3$-10^5 Pa, flow speed V = 30-150 m/sec, and jet diameter D = 25-40 mm. The power was checked on the plate circuit of the vacuum-tube generator and was kept constant at 31.6 kW at all pressures.

Two complimentary methods were used: photographic (recording, spectrum identification, and absolute intensity measurement) and photoelectric (absolute intensity measurement).

In the photographic recording, the plasma column was imaged on the entrance slit of a DFS-13 grating spectrograph by means of an Industar-37 achromatic objective (the focal length 300 mm), the spectrograph having a dispersion of 2 Å/mm and a slitwidth of 50 μm. The image scale was 1:1. The photoelectric recording was made with a grating monochromator and spectrograph by the firm of McPherson (aperture 1:8.3, dispersion 8 Å/mm, slitwidth varied from 15 to 80 μm). The image in the entrance slit plane was formed with a scale of 1:2 or 1:1. The detector was an EMI photomultiplier behind the exit slit. The photomultiplier signal passed via an amplifier to a Rikadenki two-pen recorder.

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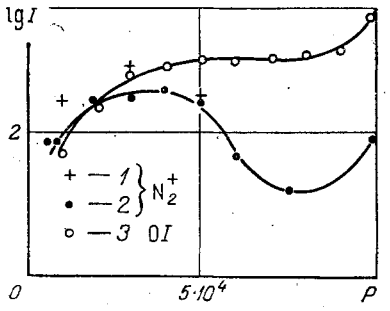

Fig. 1. Dependence of the emission intensities from N_2^+ and O I (log I) on pressure P (Pa): 1 and 2) N_2^+ emission, sections I and III correspondingly; 3) oxygen emission at end of nozzle.

The emission spectra were examined in the following parts of the subsonic jet: zero section (0) in the energy-deposition zone between the turns of the two-turn coil, the first one (I) at the end of the nozzle, and the others further up the flow at distances of 30 mm (II) and 60 mm (III) from the end of the nozzle.

The photographic recording was applied to the end of the nozzle (section I), and these spectra were used to identify the rotational structure; all the measurements at the axis of the discharge in the various sections were made photoelectrically.

In the DFS-13 spectrograph, the spectra were recorded with plates of types UV-1 and WU-1 made by Orwo (GDR), which are sensitive in the visible and ultraviolet regions. The exposure times were t $\sim$ 5 min for P = $5 \cdot 10^3$-$5 \cdot 10^4$ Pa and t $\sim$ 40 sec for P = 10^5 Pa.

All the spectra showed emission from the CN radical, whose intensity (and therefore the concentration) relative to N_2^+ increased away from the end of the nozzle. The intensity was least in section 0 (in the energy deposition region).

The N_2^+ (1^-) spectrum was compared with the emission spectrum of CN in order to correct for the effects of the CN emission, which indicate the rotational lines of N_2^+ (1^-) that coincided with the lines of this radical. These lines were discarded in the processing. We also excluded lines in the N_2^+ heads and also lines from the P and R branches having identical K.

Figure 1 shows how the logarithm of the intensity for the head of the 1:2 band at λ = 4236.5 Å varies with pressure, which reflects the behavior of the emission from the N_2^+ system as a whole. The N_2^+ intensity falls away from the end of the nozzle. The form of the curves for the two sections is the same: as the pressure increases, so does the intensity up to P = $5 \cdot 10^4$ Pa, but then there is a reduction followed by a further rise to atmospheric pressure. The intensity increase in the range 1-$3 \cdot 10^4$ Pa is associated with increase in the concentration of N_2^+. The fall in intensity in the range P = $5 \cdot 10^4$-10^5 Pa is associated with absorption of the N_2^+ emission by nitric oxide, which accumulates in the test chamber. A check was made on the absorption from the head of the 0-1 band. At P = $7.5 \cdot 10^4$ Pa, there was selective absorption, while at P = 10^5 Pa there was partial disruption of the rotational structure for N_2^+. It is true that this occurred only in section III (60 mm from the end of the nozzle), while the rotational structure of the 0-1 band in section I (end of the nozzle) remained normal at P = 10^5 Pa. The ratio of the components in the doublet also varied with pressure: at atmospheric pressure they are equal in intensity (P 44 etc.), but the intensity of one of the components begins to increase as the pressure is reduced. One of the doublet components was used in the measurements.

Curve 3 in Fig. 1 applies to the emission in one of the lines of the oxygen triplet λ = 6158.18 Å. As the pressure increased, there was a monotone increase in the intensity in the oxygen-atom line.

The intensity distributions were determined on the rotational structures of the following bands: 0-0, λ = 3914.4 Å, 0-1, λ = 4278.1 Å, and 1-2, λ = 4236.5 Å, in the first negative system of N_2^+.

All the measurements were processed by computer. The program converted the blackening densities in the rotational line into intensities and determined the function log I = f(K) giving the best description (least-squares fitting). The error in temperature measurement was ∿15%.

The log I = f(K) curves for the 0-0 and 0-1 bands show characteristic kinks throughout the pressure range for sections I-III. One therefore splits up the curve into two parts: a rectilinear part (K = 10-50), which fits to a Boltzmann distribution with a temperature of T ≃ 4500-5500 K dependent on the pressure, and a second part for K > 50, which is characterized by a large spread in the experimental points, and in some cases by deviations from the straight line drawn by least squares exceeding the experimental error, with the line intensities larger than those corresponding to a Boltzmann distribution. If it was possible to draw a straight line, the temperatures were clearly overestimated at ∿7000-13,000°K. The degree of deviation δ from a Boltzmann distribution was 7-20% ($\delta = \Delta \log I / \log I_B$). In the 1-2 band, λ = 4236.5 Å, the relationship was rectilinear and without kinks T ∿ 5000-5500°K.

The distribution over the rotational levels of N_2^+ in section 0 (energy-deposition region) at atmosphere pressure was of Boltzmann type for all quantum numbers from 12 to 60.

The deviations in the observed intensity distributions from straight lines were approximately the same at all the pressures used. Deviations were observed in the points for the lines with rotational numbers K = 6, 8, 10 and K > 50. The number of points not fitting on the straight line decreased as the pressure increased, an exception being represented by the distribution for P = 10^5 Pa (at 60 mm from the end of the nozzle), where the deviations are related to deviations in the rotational structure.

The deviations of points with quantum numbers K = 6, 8, and 10 in the R branch are due to overlap from points corresponding to lines in the P branch with K = 30, 32, and 34 on account of the inadequate resolution (McPherson monochromator).

The above leads one to suggest that there are two groups of molecules: the first is characterized by temperatures of T ∿ 4500-5700°K, and they have a nearly Boltzmann distribution over the rotational levels. The second group populates levels having K > 50 and does not fit a Boltzmann distribution. Under our conditions, at pressures of $5 \cdot 10^3 \leqslant P \leqslant 10^5$ Pa, the times between two successive collisions for the ions are $\tau_c \sim 2 \cdot 10^{-8}$-$9 \cdot 10^{-9}$ sec, and the lifetime of the zero vibrational level of the $B^2\Sigma_u^+$ state in N_2^+ is $\tau \sim 5$-$7 \cdot 10^{-8}$ sec [7]. Therefore, the condition $\tau_c < \tau$ is obeyed [8], so the intensity distribution in the rotational structure should be of Boltzmann type, at least beginning with P = $1 \cdot 10^4$ Pa, i.e., the temperature of the distribution calculated for lines with small rotational numbers should be equal to the gas temperature.

The second group of molecules (with K > 50) may involve an excitation mechanism in which the N_2^+ ions acquire excess rotational energy. One assumes that the population of high rotational levels is related to interactions with heavy particles (atoms and molecules) and involves energy release, since the temperature characterizing this population exceeds the translational value.

It has been suggested [8] that the effective cross section for the transfer of rotational motion to N_2^+ during collision with particles increases with the rotational quantum number, which can lead to deviations from a Boltzmann distribution in the rotational structure for lines with large rotational numbers.

A similar pattern was found in [9-11], although under conditions somewhat different from ours. Gas temperature measurements by other methods indicated that the rotational temperature determined from the slope of the straight line through the points for lines with small quantum numbers coincides with the gas temperature, while the higher levels are overpopulated.

It is possible that the Boltzmann distribution for N_2^+ is distorted under our conditions by the effects of the mixing layer when radiation passes through it. This is indicated by measurements on the N_2^+ distribution from the rotational levels made in various sections of the jet beginning with the energy-deposition zone (section 0) and ending with section III, which is 60 mm from the end of the nozzle. The thickness of the mixing layer is small in the energy-deposition region, and the distribution of N_2^+ over all the rotational levels is of Boltzmann type, while the deviation from a Boltzmann distribution increases away from this region (at large values of K) and becomes substantial in the parts from the end of the nozzle out to distances of 60 mm. Interference measurements on the outer part of the free

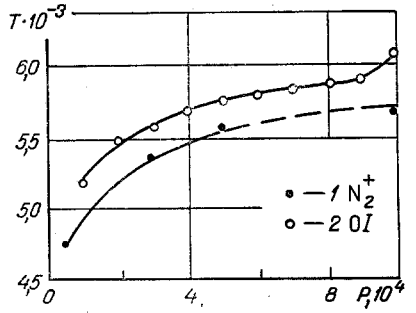

Fig. 2

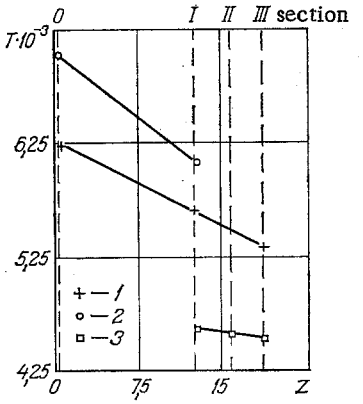

Fig. 3

Fig. 2. Dependence of the gas temperature T (K) on pressure P (Pa): 1) temperature measured in the P and R branches of the 0-0, 0-1, and 1-2 transitions in the (1^-) N_2^+ system; 2) excitation temperature of O I.

Fig. 3. Distribution of gas temperature T (K) along the axis of the jet z (cm): 1 and 2) measurements made at P = 10^5 Pa for N_2^+ and O I correspondingly; 3) P = 10^4 Pa for N_2^+.

jet confirmed the presence of the mixing layer. The thickness of that layer increases along the flow direction. There is an increase in the intensity of the chaotic motion of the eddies in the mixing layer as the pressure and air flow rate increase.

There is a group of molecules whose populations fit a Boltzmann distribution in a certain energy range, and this can be used to measure the gas temperature, although this naturally involves estimating the collisional process times.

The excitation temperature for the oxygen atoms was determined at the end of the nozzle by measuring the absolute intensity of the λ = 6158.18 Å line from the oxygen triplet by a standard method. The O I oxygen line at λ = 6158.18 Å was completely resolved. The temperature was determined throughout the pressure range with step of 10^4 Pa. The error in the temperature measurements from the O I line did not exceed 5%.

Figure 2 shows the pressure dependence of the temperature in section I. Curve 1 in Fig. 2 has been drawn through the points derived from the 0-0, 0-1, and 1-2 bands, with particular emphasis on the measurements in the 0-1 band, which were obtained by averaging the photoelectric and photographic data (measurements on the P and R branches with even and odd K). We also showed points relating to the vibrational temperature found from the ratio (0-0)/(2-4) of the intensities in the heads. Curve 2 in Fig. 2 relates to the excitation temperature of O I. The temperatures measured by the various methods agree satisfactorily within the accuracy limits.

The part of curve 1 in Fig. 2 for the pressure range $6 \cdot 10^4$-10^5 Pa has been shown by a dashed line, because it was not possible to measure the rotational temperature in this region on account of the strong absorption of the N_2^+ radiation, which disrupted the rotational structure. The pressure dependence of T in section III is the same, while there is only a slight shift in the temperature difference $\Delta T \sim 800°$ as the pressure increases, which shows that the temperature is only slightly dependent on the pressure.

The vibrational temperature (from CN) at 60 mm from the end of the nozzle coincides with the gas temperature, whereas the value is much less than the gas temperature at the end of the nozzle ($T \sim 4000°K$). It is possible that the CN radiation at the end of the nozzle comes not from the core of the jet but from the periphery and the mixing layer; it would seem that the radical is formed here and does not have time to diffuse into the core of the jet. The picture is different at 60 mm.

Figure 3 shows the temperature distribution along the plasma column. The origin coincides with the zero section, which is in the middle of the coil. The z axis is directed along the flow. The dependence of the temperature at the axis on the coordinate is rectilinear.

At both pressures, there is a slow temperature fall from the end of the nozzle to z = 60 mm. The temperature difference over this part is ∿100-250°K, i.e., the jet is fairly homogeneous in temperature. At atmospheric pressure, there is a difference between the gas temperature (1) and the oxygen-atom excitation temperature (2) in the zone of the coil. As these measurements apply to the energy-deposition zone, it is possible that the oxygen atoms are excited by hotter electrons, and their excitation temperature is close to the electron temperature rather than the gas one. An interesting point is that the temperature-dependence curves come together in section I.

Therefore, it seems that one can use a method of measuring the gas temperature at the core of the jet based on the intensity distribution in the rotational structure of the first negative system of N_2^+. This is confirmed by measurements on the excitation temperatures for oxygen atomic levels in the core of the jet.

NOTATION

N, anode circuit power; P, pressure; V, flow velocity; D, jet diameter; t, exposure time; K, rotational quantum number; λ, wavelength; I, radiation intensity; T, temperature; I_B, radiation intensity corresponding to Boltzmann distribution; τ_c, time between two collisions; τ, level lifetime; δ, degree of deviation from Boltzmann distribution; z, axis along the jet.

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