DISTRIBUTION OF THE GAS TEMPERATURE IN STREAMER DISCHARGE IN AIR

O.V. Bolotov, V.I. Golota, S.D. Gurtovoi

NSC "Kharkov Institute of Physics and Technology" Kharkov, Ukraine

E-mail: bolotov@kipt.kharkov.ua

The temperature of nitrogen molecules in streamer discharge in point-to-plane electrode system was determined by using optical emission spectroscopy. The emission spectra of streamer discharge in air, in a wavelengths range 300…400 nm, were studied. The electronic-vibrational-rotational structure of (0-0) – band emission spectrum of N^{2+} nitrogen system ($C^3\Pi_u$-$B^3\Pi_g$ transitions) was analyzed for different points along streamer propagation in discharge gap. The gas temperature was calculated on the basis of measurements of relative intensities in the rotational structure of the spectra. It was shown that gas temperature in the discharge gap varies in the range of 380…730 K. It was noted that for different discharge conditions the gas temperature in vicinity of the anode and cathode area is higher than in the central part of the discharge gap.

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INTRODUCTION

Investigations of plasma-chemical [1,2] and the physical processes [3] which occur in the gas discharge plasma require information about gas temperature distribution in the discharge gap. In particular it is important to prevent the spark breakdown which mainly depends from the value of the gas temperature [4].

There are many methods for measuring the temperature of particles in gas discharge. Optical emission spectrometry methods are widely used as they are non-contact, have no perturbation effects on the object of study and provide high precision measurements.

In current paper the spectrometric method based on measurements of relative intensities in the rotational structure of emission spectrum was used to measure the distribution of gas temperature in the streamer discharge in ambient air. The electronic-vibrational-rotational structure of (0-0)-band emission spectrum of N^{2+} nitrogen system ($C^3\Pi_u$–$B^3\Pi_g$ transitions) was analyzed for different points along streamer propagation in discharge gap to determine the temperature.

1. EXPERIMENTAL SETUP

Experiments were carried out using the experimental setup schematically shown on Fig. 1.

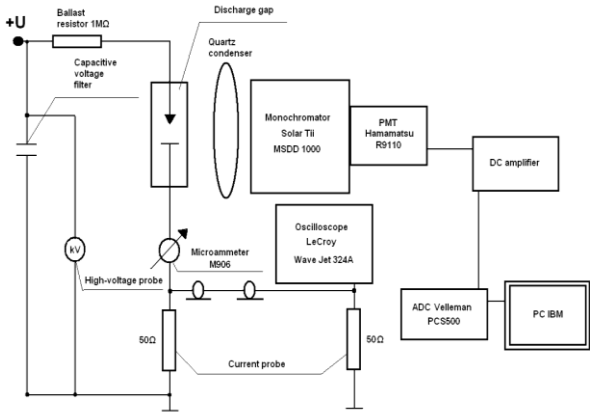

Fig. 1. Schematic diagram for the experimental setup

The optical bench consists of optical discharge cell, quartz condenser, double dispersion monochromator-spectrograph "Solar-Tii" MSDD-1000 equipped with high-speed photomultiplier tube Hamamatsu R9110. To provide high spectral resolution in a wavelength range 200…500 nm a double diffraction grating with 2400 grooves per 1mm was used. The reciprocal linear dispersion of the diffraction grating is 0.41 nm/mm. The Hamamatsu R9110 high-speed photomultiplier tube has a spectral bandwidth of 185…900 nm and signal pulse rise time of $\tau_\Gamma = 2.2$ ns. The software PC-Lab2000 allows to acquire the emission spectrum on computer and visualize the spectrum in real time mode.

2. RESULTS

2.1. INVESTIGATION OF SPECTRAL CHARACTERISTICS OF THE STREAMER DISCHARGE

The emission spectra of the streamer discharge radiation were registered. All the streamers occur in regime in which they cross the discharge gap. Measurements were carried out at air pressure of P=1 atm. The discharge gap was 8 mm. The emission spectra were registered from the cathode and anode regions and from central part of the discharge gap along streamer propagation with the step of 1 mm.

The emission spectrum of the streamer discharge radiation within the wavelength range of 300…400 nm is shown on Fig. 2. The obtained spectrum corresponds to N^{2+} nitrogen system [5].

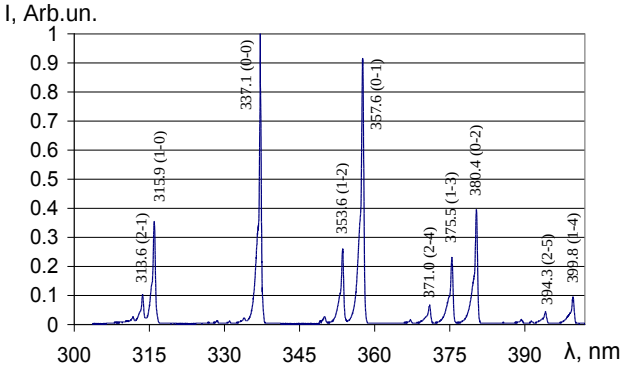

Fig. 2. The emission spectrum of the streamer discharge in wavelength range 300…400 nm. The wavelengths of spectral lines edges and the corresponding vibrational levels are marked on the spectrum

Spectral line λ = 337.1 nm ($C^3\Pi_u$, υ' → $B^3\Pi_g$, υ"; υ'=υ"=0 transition) was used to study the rotational structure of spectra and to determine the rotational temperature of N_2. Selection of this line was caused by its highest intensity within the investigated wavelength range.

2.2. MEASURING THE N_2 ROTATIONAL TEMPERATURE

Measurements of relative intensities of rotational lines at (0-0)-band of N^{2+} nitrogen system were carried out in the wavelength range 334…336 nm (Fig. 3) with high spectral resolution in wavelength (Δλ~0,0125 nm).

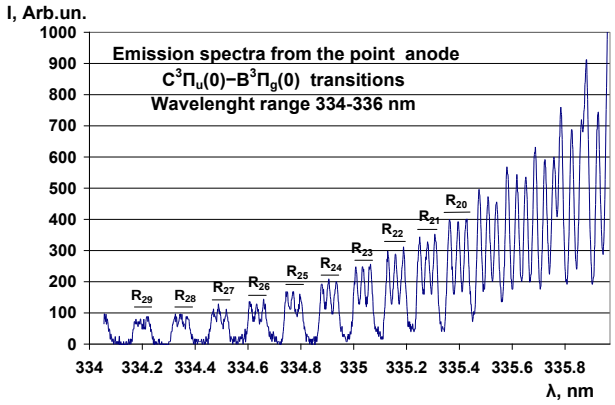

Fig. 3. Rotational structure of $C^3\Pi_u(0)$-$B^3\Pi_g(0)$ band. Spectrum obtained from vicinity of point anode. Parameters of the streamer discharge: applied voltage U = 8.9 kV, the average discharge current I= 37 μA

The P, Q and R branches of electronic-vibrational-rotational (0-0)-band of N_2^{2+} were identified from obtained spectrum (see Fig. 3). The rotational single lines of R-branch are clearly visible at Fig. 3. The (R_J) numbers at Fig. 3 indicate on the rotational quantum numbers for given rotational transitions. It is important to note that due to high spectral resolution in wavelength**,** the groups of triplets were identified [6]. Each of triplets (R_J) caused by different spin projections on the axis of the nitrogen molecule.

To determine the rotational temperature of N_2, it is necessary to use only a spectral range in which there is no considerable superposition of the spectral lines and the intensity of R-branch dominates on intensities P and Q branches. Analysis of the spectrum (see Fig. 3) shows that only single lines of R-branch with rotational quantum numbers J = 20…29 can be used for calculation the N_2 rotational temperature.

The intensity of rotational line is given by the following equation [7]:

$$I(\lambda) \sim \lambda^{-4} \cdot \frac{B_e^{'}}{kT_r^*} \cdot S_{J'J''} \cdot \exp\left(-\frac{B_e^{'} J^{'}(J^{'}+1)}{kT_r^*}\right), \qquad (1)$$

where $S_{J'J''}$ – the Henley London intensity factor [8]; λ – transition wavelength; $F(J^{'}) = B_e^{'} J^{'}(J^{'}+1)$ – the energy of rotational levels of the molecule; T^*_r – rotational temperature; $B_e^{'}$ – rotational constant; J' – rotational quantum number of the upper energy level; k – Boltzmann constant.

Equation (1) was obtained with assumption of Boltzmann distribution of the rotational levels population. The relationship between the experimentally measured line intensity and the rotational temperature T^*_r of the excited state of the molecule can be used to determine the rotational temperature value. The relation (1) can be used for determining the rotational temperature only in case when the linear dependence $\ln \frac{I(\lambda)}{\lambda^{-4} \cdot S_{j'j''}}$ on *F(J')* exists in the experiment. It is very important to observe that linear dependence during the experiment. If the linear dependence violates we can not use the equation (1) for determining the rotational temperature.

Analysis of the emission spectra that were registered from different points along streamer propagation allowed to determine the distribution of the rotational temperature in discharge gap. The typical distribution of the N_2 rotational temperature in discharge gap is presented at Fig. 4.

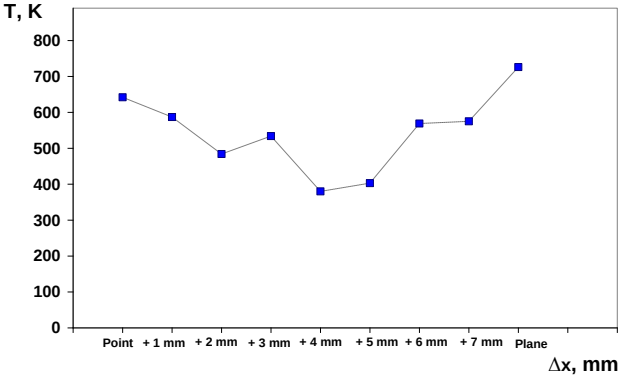

Fig. 4. The distribution of the N_2 rotational temperature in discharge gap. Streamer discharge. Air pressure P = 1 atm. Discharge gap 8 mm, applied voltage U = 7.6 kV, the average discharge current I = 45 μA, current pulse repetition rate T = 56 μs

Fig. 4 shows that the rotational temperature in discharge gap varies from 380 to 730 K. The gas temperature in the discharge gap has maxima in vicinity of the anode and cathode area. In the central part of the discharge gap, the gas temperature doesn't exceed 400 K and then gradually increases to the cathode direction. It is necessary to note that such trend preserves at entire range of applied voltages in burning regime when streamers cross the discharge gap.

Generally the relationship between the measured rotational temperature T^*_r and the gas temperature T_g depends on the time of establishment of local temperature equilibrium. In the case when the frequency of collisions ν_c of excited molecules with gas molecules is much higher in comparison with the frequency of spontaneous emission ν_s, the relation $T^*_r = T_g$ can be used [9]. Estimations, for typical conditions of our experiments, show that the time between collisions of molecular nitrogen in the ground state $N_2(X^1\Sigma_g)$ equals to $\tau_c = 1/\nu_c = \lambda/V_t = 0.19 \cdot 10^{-9}$. λ-mean free path, V_t – thermal velocity of molecules. Collision cross-section was taken as $\sigma = 4.31 \cdot 10^{-15}$ cm^2 [10], the radiative

lifetime of $N_2(C^3\Pi_u)$ according to [11] equals to $\tau_r = 1/\nu_s = 37 \cdot 10^{-9}$. As the result for streamer discharge at atmospheric pressure the relation $\tau_r >> \tau_c$ is realized and the relation $T^*_r = T_g$ takes place regardless of the mechanism of excitation and deactivation of $C^3\Pi_u$ state. Therefore the distribution of rotational temperature that is shown at Fig. 4 corresponds to the distribution of the gas temperature along the track of streamer propagation in discharge gap.

CONCLUSIONS

The emission spectra of the N^{2+} nitrogen system for streamer discharge in air in the wavelength range 300-400 nm were studied. Distribution of emission intensity in electronic-vibrational-rotational bands, that correspond to $C^3\Pi_u - B^3\Pi_g$ transitions of molecular nitrogen, was analyzed.

The N_2 rotational temperature for different regions of discharge gap was obtained by measurements of relative intensities in the rotational structure of (0-0)-band of N^{2+} emission spectrum. It was shown that the gas temperature on the needle anode (642 K) and flat cathode (726 K) is higher than the gas temperature in other regions of the discharge gap. In the middle of the gap the temperature reaches a minimum (380 K). Theoretical calculations and estimations were made and the correlation between the N_2 rotational temperature and the gas temperature was demonstrated. It was shown that at the typical conditions of experiments the N_2 rotational temperature equals to the gas temperature.

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РАСПРЕДЕЛЕНИЕ ТЕМПЕРАТУРЫ ГАЗА В СТРИМЕРНОМ РАЗРЯДЕ В ВОЗДУХЕ

О.В. Болотов, В.И. Голота, С.Д. Гуртовой

Проведены исследования катодонаправленного стримера в режиме замыкания им разрядного промежутка без перехода в искровой пробой. Зарегистрированы спектры излучения второй положительной системы азота в диапазоне длин волн 300…400 нм в воздухе. С помощью анализа вращательной структуры спектра азота определена вращательная температура молекул азота в разных участках (с шагом 1 мм) разрядного промежутка. Показано, что вращательные температуры газа на игольчатом аноде и плоском катоде превышают температуру газа в середине разрядного промежутка. Проведены оценки и определена взаимосвязь между вращательной температурой молекул азота и температурой газа.

РОЗПОДІЛ ТЕМПЕРАТУРИ ГАЗУ В УСТРИМЕРНОМУ РОЗРЯДІ В ПОВІТРІ

О.В. Болотов, В.І. Голота, С.Д. Гуртовой

Проведено дослідження катодоспрямованого стримера в режимі замикання їм розрядного проміжку без переходу в іскровий пробій. Зареєстровано спектри випромінювання другої позитивної системи азоту в діапазоні довжин хвиль 300…400 нм у повітрі. За допомогою аналізу обертальної структури спектра азоту визначена обертальна температура молекул азоту в різних ділянках (з кроком 1 мм) розрядного проміжку. Показано, що обертальні температури газу на голчастому аноді і плоскому катоді перевищують температуру газу в середині розрядного проміжку. Проведено оцінки і визначено взаємозв'язок між обертальною температурою молекул азоту і температурою газу.