https://doi.org/10.46813/2021-134-089

GAS TEMPERATURE MEASUREMENT IN THE ACTIVE ZONE OF STREAMER DISCHARGE UNDER DIFFERENT APPLIED VOLTAGES

O.V. Bolotov, V.I. Golota, G.V. Taran
National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: bolotov@kipt.kharkov.ua

The experimental results on the gas temperature measurement in the active zone of streamer discharge in air at the atmospheric pressure are presented. The gas temperature value was obtained by the optical method for measuring the relative intensity of the rotational lines for the radiation of the second positive (II^+) system of molecular nitrogen, transition bands ($C_3\Pi_u(0) \rightarrow B_3\Pi_g(0)$). It was found that in discharge gap d = 8 mm, depending on the applied voltage (in the range of 6.1…7.8 kV with a step of 0.2 kV), the gas temperature varied from 609 to739 K. The unevenness of the gas temperature change in the active zone of discharge with the increase in the applied voltage is shown. This may be related to the possible changes in the rotational state of nitrogen molecules upon excitation of their electronic state by electrons.

PACS: 52.80.Hc

INTRODUCTION

To study the plasma-chemical and physical processes occurring in the gas discharge plasma, in many cases, measuring the gas temperature in the discharge zone is required. By determining the gas temperature, the information on the intensity of ionization processes can be obtained and the boundary conditions, under which the discharge transition to a spark breakdown occurs, can be found. By measuring the gas temperature in the active zone of the discharge at various voltages across the discharge gap, it is possible to optimize the discharge burning mode. By optimizing the discharge mode, it is possible to prevent the transition of the discharge into a spark breakdown, as well as to significantly reduce the energy consumption in the discharge by reducing the energy consumption for ion heating of the gas. This, in particular, allows optimizing the operation of plasma-chemical reactors for ozone electrosynthesis [1], and also provides information for understanding the mechanisms of formation and development of streamer discharge in air [2].

Under the simplest conditions, when thermodynamic equilibrium takes place in the investigated molecular plasma [3], the temperature of the investigated gas is identified with the measured rotational T_R temperature of the molecules. T_R is a parameter characterizing the Boltzmann distribution of molecules over rotational levels. Temperature measurement is carried out by registration of molecular emission spectrum. The gas temperature T_g can be determined using an optical contactless method by analyzing molecular emission spectra in non-isothermal plasma. This method is based on measuring the relative intensities of the rotational lines for the emission spectrum of the second (II^+) positive system of molecular nitrogen N_2. Thus, in [4], using this method, the distribution over the discharge gap for the gas temperature in streamer discharge in air was measured. One of the difficulties in determining the gas temperature in gas discharge from molecular bands is that the distribution of molecules over rotational states corresponding to the temperature of neutral gas can be determined in advance only for stable molecules. The features of excitation for such molecules by electron impact is that, due to the low probability of change in the rotational energy upon excitation of a certain electronic state, the distribution of molecules over the rotational levels of the excited state is similar to the distribution over the rotational levels of the ground state. However, in the absence of thermodynamic equilibrium, significant errors in measuring T_g are possible due to the following reasons. If a molecule takes part in chemical reactions occurring in the discharge, then part of the activation energy can be converted into the molecular rotational energy, distorting the distribution of molecules over rotational levels. This especially refers to free radicals generated during the discharge process. Another possible error in determining T_g is related to the fact that the actual experimentally determined value is the value of B^I/T_g (B^I is a rotational constant of the molecule for the upper electronic state). In the lower electronic state, there is a distribution over the rotational levels with the gas temperature T_g and rotational constant B^{II}. When excited by electron collisions, the level distribution is preserved. However, if $B^I \neq B^{II}$, then it no longer corresponds to the gas temperature T_g, but corresponds to the temperature $T^I = T_g (B^I/B^{II})$. Thus, for the correct determination of T_g in the absence of thermodynamic equilibrium, it is necessary to choose stable molecules with similar values of B^I and B^{II}. To determine T_g, molecular bands for the second positive system of nitrogen are widely used. In this work, the most widespread spectrometric method was used to measure the gas temperature in the discharge. It is based on measuring the relative intensities of the rotational lines for the emission spectrum of molecular nitrogen N_2. The gas temperature of the discharge was determined from the molecular nitrogen band with a quantum wavelength λ=337.1 nm in the emission spectrum of streamer discharge in air at atmospheric pressure.

1. EXPERIMENTAL SETUP

The experimental setup is shown schematically in Fig. 1. It was used to carry out the experiments on determining the gas temperature in streamer discharge. In the experiments, the emission spectra of discharge in air were studied when high voltage was applied to the "needle-to-plane" electrode system. The positive high-voltage potential was applied to the needle, and the flat metal disk was under the ground potential. The discharge gap was d = 8 mm. The voltage applied to the needle was set using a stabilized HV power supply (up to 15 kV). A ballast resistor with a nominal value of 10 MΩ was used in the external circuit, which limited the value of the discharge current. The average discharge current was measured using an M906 microammeter. Digital storage oscilloscope LeCroy WaveJet324A was used to record the waveforms of the discharge current pulses.

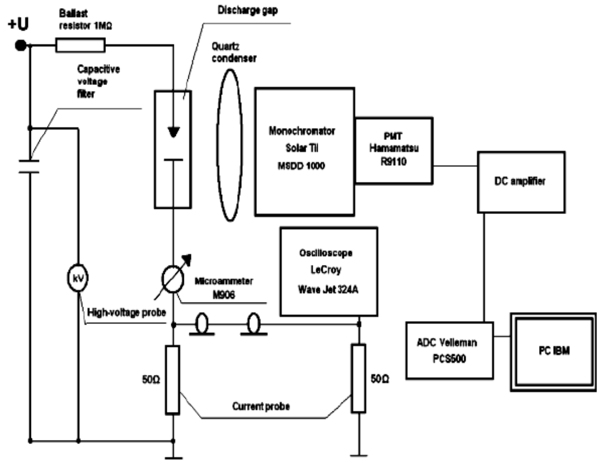

Fig. 1. Experimental setup. PMT is the Hamamatsu R9110 photomultiplier tube, ADC is the analog-to-digital converter; PC IBM – computer; DC – current amplifier

The spectrometric studies of the discharge were carried out using the optical stand based on a Solar-Tii MSDD-1000 monochromator-spectrograph with double dispersion. For radiation emission from the discharge gap, the optical slit system was used. To ensure high spectral resolution, a double diffraction grating of 2400 grooves/mm was installed on the monochromator with the inverse linear dispersion of 0.41 nm/mm. A high-speed photomultiplier Hamamatsu R9110 with a spectral sensitivity band of 185…900 nm was installed at the exit slit of the monochromator. At the output of the photomultiplier, a DC current amplifier (DCA IEC-CA3) was installed. It has the following characteristics: the conversion coefficient range k – (10^{-10}…10^{-5}) A/V. The signal from DC amplifier was sent to the input of the Velleman PCS 500 ADC, which was connected to a computer. The PC-Lab2000 application package made it possible to display the digitized data obtained from the ADC (to visualize the spectrum) on a computer monitor in graphic mode in real time. Also it was possible to record the digitized data into the computer memory.

2. EXPERIMENTAL RESULTS

In the experiments, the emission spectra were registered in the wavelength range of 300…400 nm. The choice of the range can be explained by the presence of intense emission lines for the second positive nitrogen system, which are convenient objects for optical diagnostics. Registration of radiation was carried out from the active (at the distance of ~ 1 mm from the surface of the point anode) zone of the discharge gap, and at different voltage values at the discharge gap (from 6.1 to 7.8 kV with the step of 0.2 kV). The choice of the specified voltage range is related to the fact that in this range, discharge stably burns in the streamer mode, and there is no transition of the discharge to another mode or to the spark breakdown. Below, in Fig. 2, a typical waveform of the current pulse for streamer discharge in air is shown.

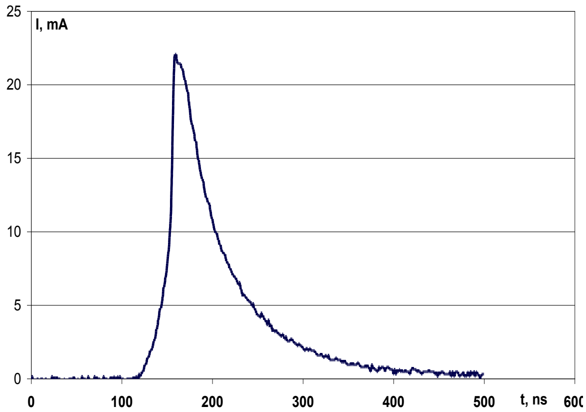

Fig. 2. Waveform of the streamer discharge current pulse. Average discharge current I = 45 μA, applied voltage U = 7.6 kV

It can be seen from Fig. 2 that the discharge current pulse with the characteristic duration $\Delta t \sim 280$ ns and the pulse rise time $\tau \sim 40$ ns is registered in the discharge circuit, which corresponds to streamer development in the discharge gap. The stable shape of the discharge current pulse and the constancy of the pulse repetition rate are indicators of stable discharge burning. Stable discharge is a necessary condition for correct registration of the line intensity in the optical radiation spectra.

To determine the values of the rotational temperature, the rotational spectrum of the (0-0) transition for the $C^3\Pi_u$-$B^3\Pi_g$ band was used. The measurements were carried out at the air pressure p = 1 atm. In the wavelength range λ = 334…337.1 nm, the lines of P, Q and R branches of electronic-vibrational band of molecular nitrogen were identified. The gas temperature was determined from the analysis of relative intensities for the lines of the R-branch for the electronic-vibrational band of N_2.

In Figs. 3, 4, the fragments of emission spectrum of the (0-0) transition in the wavelength range of 334…336 nm are shown. Spectra was registered from the active zone of discharge at various applied voltages.

From the spectra shown in Figs. 3, 4, it can be seen that as the voltage in the discharge gap is increased in the entire investigated range, the radiation intensity in the spectrum is also steadily increased. The origin of changes in the radiation intensity from the discharge active zone can be explained by the dependence of the excitation rate and radiation population of the electronic-vibrational level $C^3\Pi_u(0)$ on the electric field strength. Analysis of the obtained spectra made it possible to determine the gas temperature at different voltage values at the discharge gap.

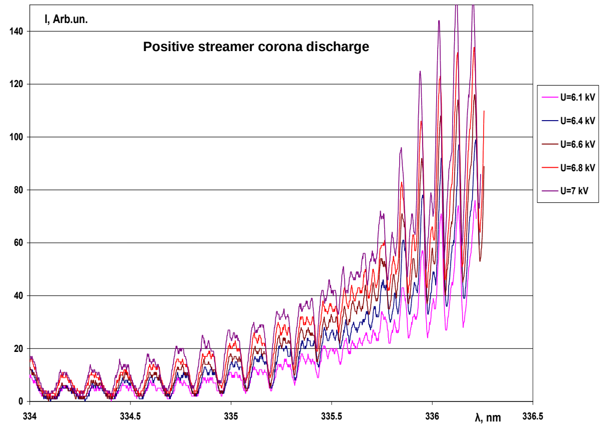

Fig. 3. Fragments of the emission spectrum for (0-0) transition in the wavelength range of 334…336 nm registered from the discharge active zone at different applied voltages. U = 6.1…7 kV. Discharge gap d = 8 mm

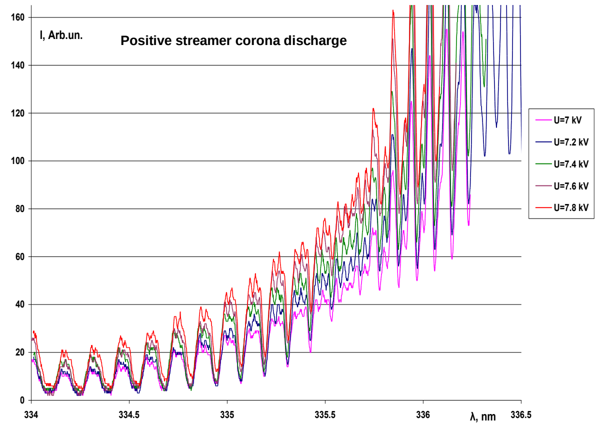

Fig. 4. Fragments of the emission spectrum for (0-0) transition in the wavelength range of 334…336 nm registered from the discharge active zone at different applied voltages. U=7…7.8 kV. Discharge gap d = 8 mm

With the Boltzmann distribution for the population of rotational levels of the excited electronic-vibrational state, there is a simple correlation between the experimentally measured line intensity and rotational temperature T_r of the excited electronic-vibrational state

$$\ln\frac{I(\lambda)}{\nu^4 S_{j'j''}} = -\frac{hc}{kT^*_r}\cdot F(j') + const\,,$$

where F (j´) is the energy of upper rotational level in cm^{-1}, k is the Boltzmann constant, c is the speed of light.

The straight-line dependence of $\ln\dfrac{I(\lambda)}{\nu^4 S_{j'j''}}$ on F (j´) is the experimental confirmation for the existence of the Boltzmann distribution for the population of rotational levels.

In Fig. 5 below, the Boltzmann plots obtained from the analysis of R-branch for the rotational structure of the discharge emission spectrum is shown. The plots show a linear dependence on F (j´) = J (J + 1). The slope of the dependence shown in the plot corresponds to the rotational temperature of nitrogen molecules, which is equal to the gas temperature [4].

In Fig. 6 below, the diagram of the gas temperature distribution depending on the applied voltage is shown. In the diagram, the corresponding values of the gas temperature in the discharge are presented.

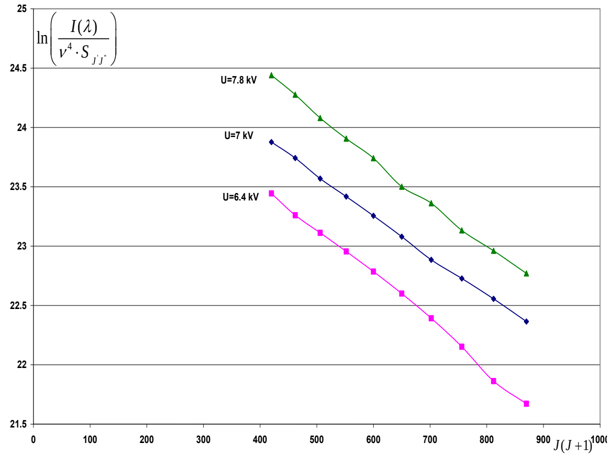

Fig. 5. The Boltzmann plots obtained from the analysis of the spectra for the electronic-vibrational transition C_3P_u (0)→B_3P_g (0). The spectra were registered from the active zone of the discharge gap

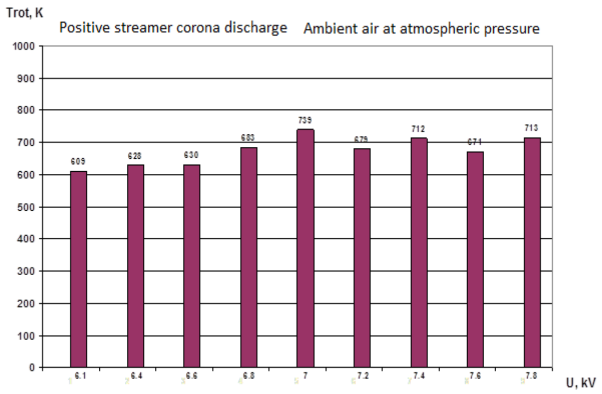

Fig. 6. Diagram of the gas temperature distribution in the active zone of streamer discharge depending on the applied voltage. Positive streamer. Discharge gap d = 8 mm

From the diagram shown in Fig. 6, it can be seen that as the voltage in the discharge gap is increased, the gas temperature is changed in the range from 600 to 740 K. It is worth noting that the gas temperature is changed unevenly as the applied voltage is increased. Thus, at the minimum voltage in the discharge gap U = 6 kV, the gas temperature has a minimum measured value of 609 K. However, the maximum measured temperature of 739 K corresponds to the voltage U = 7 kV, which lies in the middle of the investigated voltage range. This can be associated with both the features of streamer discharge and possible changes in the rotational state of the molecule upon excitation of its electronic state. Firstly, applied voltage does not significantly change the initial parameters of the streamer in the active zone, but mainly affects on the propagation velocity of the streamer in the discharge gap. In the second place, as noted in [5], the origin of the differences in the rotational state of the molecule depends on the electron energy even at the energies much higher than the excitation threshold.

CONCLUSIONS

From the distribution of emission line intensities for the electronic-vibrational bands of the second positive nitrogen system, the gas temperature values in the active zone of streamer discharge in air were obtained. It was found that, depending on the applied voltage (from 6.1 to 7.8 kV with the step of 0.2 kV), the gas temperature varies from 609 to 739 K. It is shown that the rotational temperature is not changed much as the voltage is increased, and is related to the change in the applied external voltage in a complex way. This can be explained by both the features of streamer discharge and the possible changes in the rotational state of the nitrogen molecule upon excitation of its electronic state.

An uncertain dependence of the nitrogen molecule temperature on the discharge macro parameters significantly complicates the use of rotational excitation for nitrogen molecules to control the rates of plasma-chemical processes in gas-discharge plasma. This requires additional studies of the electronic excitation processes for nitrogen molecules. In particular, it is important to identify the processes in which the distortion of Boltzmann distribution over rotational energy levels is possible.

REFERENCES

1. V.I. Golota, L.M. Zavada, B.B. Kadolin. Generatsiya ozona v tleyushchem razryade polozhitel'noy polyarnosti // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration".* 2000, № 1, p. 58-62.
2. O.V. Bolotov, V.I. Golota, B.B. Kadolin, V.N. Ostroushko, L.M. Zavada, A.Ju. Shulika. Experimental investigations of cathode-directed streamer propagation in air at high pressure // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration".* 2008, № 4, p. 204-208.
3. L.M. Biberman, V.S. Vorobiev, I.T. Yakubov. *Kinetics of nonequilibrium low-temperature plasma.* M.: "Nauka", 1982.
4. O.V. Bolotov, V.I. Golota, S.D. Gurtovoi. Distribution of the gas temperature in streamer discharge in air // *Problems of Atomic Science and Technology. Series "Plasma Physics".* 2014, № 6, p. 223-225.
5. V.M. Zakharova, Yu.M. Kazan. About the motion of ions and atoms in plasma // *Spectroscopy of gas-discharge plasma: Collection of articles* / Ed. S.E. Frisch. L.: "Nauka", 1970, p. 291-318.

Article received 07.07.2021

ИЗМЕРЕНИЕ ТЕМПЕРАТУРЫ ГАЗА В ГЕНЕРАЦИОННОЙ ЗОНЕ СТРИМЕРНОГО РАЗРЯДА ПРИ РАЗЛИЧНЫХ НАПРЯЖЕНИЯХ НА РАЗРЯДНОМ ПРОМЕЖУТКЕ

О.В. Болотов, В.И. Голота, Г.В. Таран

Представлены результаты экспериментальных исследований температуры газа в генерационной зоне стримерного разряда в воздухе при атмосферном давлении. Температура газа определялась оптическим методом по измерению относительной интенсивности линий вращательной структуры излучения второй положительной (II^+) системы молекулярного азота, полосы перехода ($C_3\Pi_u(0) \rightarrow B_3\Pi_g(0)$). Установлено, что при межэлектродном расстоянии d = 8 мм, в зависимости от напряжения, приложенного к разрядному промежутку (в диапазоне 6,1…7,8 кВ с шагом 0,2 кВ), температура газа изменяется в пределах от 609 до 739 К. Показана неравномерность изменения температуры газа в генерационной зоне разряда с увеличением приложенного напряжения. Это может быть связано с возможными изменениями вращательного состояния молекул азота при возбуждении их электронного состояния.

ВИМІРЮВАННЯ ТЕМПЕРАТУРИ ГАЗУ В ГЕНЕРАЦІЙНІЙ ЗОНІ СТРИМЕРНОГО РОЗРЯДУ ПРИ РІЗНІЙ НАПРУЗІ НА РОЗРЯДНОМУ ПРОМІЖКУ

О.В. Болотов, В.І. Голота, Г.В. Таран

Представлені результати експериментальних досліджень температури газу в генераційній зоні стримерного розряду в повітрі при атмосферному тиску. Температура газу визначалася оптичним методом по виміру відносної інтенсивності ліній обертальної структури випромінювання другої позитивної (II^+) системи молекулярного азоту, смуги переходу ($C_3\Pi_u(0) \rightarrow B_3\Pi_g(0)$). Встановлено, що при міжелектродній відстані d = 8 мм, залежно від напруги, прикладеної до розрядного проміжку (у діапазоні 6,1…7,8 кВ з кроком 0,2 кВ), температура газу змінюється в межах від 609 до 739 К. Показана нерівномірність зміни температури газу в генераційній зоні розряду зі збільшенням прикладеної напруги. Це може бути пов'язано з можливими змінами обертального стану молекул азоту при збудженні їх електронного стану.