Experimental studies of the spectral characteristics of a free glow discharge in the wavelength range of 340-440 nm

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Abstract. Non-equilibrium air plasma generated in free glow discharge is characterized by optical emission spectroscopy techniques in the wavelength range of 340–440 nm. The rotational and vibrational temperature are studied as a function of distance from the electrode, to find out differences in the distribution of plasma parameters along with the discharge axis. In this work, the rotational and the vibrational temperature is determined from rovibrational spectra of second positive \( N_2^+ \) system. It is observed that \( N_2^+/N_2 \) intensity ratio increases from anode to cathode along the discharge axis.

1. Introduction
Low-temperature plasma discharges are widespread industrial applications, energy applications, and fundamental research, plasma chemistry, gas dynamics [1]. Nitrogen mixture plasma discharges are widely used in modification surface properties, and it is essential in studying atmospheric chemistry. The possibilities of using plasma discharges to modify supersonic flows are investigated, too. The features of the shock waves interaction with plasma discharges are still far from being sufficiently understood [2-3].

Optical emission spectroscopy (OES) in the visible spectral range is one of the primary plasma diagnostic techniques. This method allows for obtaining detailed information on the plasma composition, temperatures, and concentrations of various components of a non-equilibrium plasma [4–9]. The rotational and vibrational temperature can be determined by using OES. The advantages of OES are non-contact, a large amount of information about plasma parameters and the simplicity of its technical implementation.

This paper describes the experimental setup at the Ioffe Institute for the study of free glow discharges in different gases. The study presents preliminary experimental research of spectral emissions in different regions of free glow discharge. This research help understand the physics of free glow discharge.

In this work, a direct current (DC) glow discharge, which is not limited by the working chamber walls are studied. Discharge is generated in the air at average pressures 10–50 torr. The discharge has a diffuse structure with inhomogeneous luminosity along and across the discharge axis. The luminescence intensity increases near the electrodes. It indicates the nonuniformity of the plasma parameters in different regions of the discharge.
2. Materials and methods
The schematic diagram of the experimental setup is illustrated in Fig. 1. The discharge is generated in a cylindrical vacuum chamber with a diameter of 300 mm and a height of 400 mm between two conical 60-degree copper electrodes located vertically at a distance of 100 mm. The upper electrode (cathode) is grounded, and the lower (anode) is powered. The anode is located on a non-conductive plate. The discharge is generated in the air at a pressure of 4 kPa. The power supply provided a constant discharge current of ∼1 A at a voltage of ∼700 V on the electrodes. The shape of the discharge is a rounded cone with a cross-section increasing towards the top. The visible part of the discharge luminosity has a diameter of less than 100 mm.

![Experimental setup diagram](image.png)

**Figure 1.** The experimental setup. 1 — vacuum chamber, 2 — lens, 3 — Seyia-Namioka monochromator, 4 — CCD detector, 5 — PC.

OES is carried out using a spectrometer designed and assembled at the Ioffe Institute with a computer-controlled registration system. The spectrometer consisted of a monochromator constructed according to the Seya–Namioka scheme with a constant deflection angle of 70°30′ (the sum of the angles of incidence and diffraction), and a linear CCD image sensor TOSHIBA TCD1304DG CCD controlled by PC. The linear CCD image sensor is installed in the plane of the exit slit of the monochromator. The monochromator having diffraction grating with 600 grooves/mm and inverse linear dispersion of 3.8 nm/mm spectral resolution of no higher than 0.03 nm. The spectrometer has a simple design in which the only movable element is a diffraction grating. The rotational angle of the diffraction grating determines the central wavelength of the recorded spectral range 100 nm. Measurements of the shape of the spectral line Hg I = 435.8328 nm for different widths of the entrance slit of the monochromator showed that the FWHM of the instrumental response function is greater or equal 0.04 nm. The wavelength of the spectrometer is calibrated using a quartz mercury lamp. Wavelengths of Hg I lines from the NIST Atomic Spectra Database [10] were used. The ribbon filament lamp was used to obtain the spectral response correction.

OES is carried out through the optical window in the vacuum chamber wall. Light from discharge collected lens made of fused silica and transmitted to the slit without light-collecting optics. The width of the entrance slit is 150 μm.

3. Results
Fig. 2 is the OES from the discharge between 300 and 800 nm. This spectra obtained using a low-resolution compact spectrometer. It is the typical spectra of the second positive nitrogen

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system (transition $N_2 (C_3\Pi^+ \rightarrow B_3\Pi^+_g)$, $\lambda = 300 – 470$ nm), the first negative system of the molecular nitrogen ion (transition $N_2^+ (B_2\Sigma^+_u \rightarrow X_2\Sigma^+_g)$, $\lambda = 300 – 500$ nm) and $N_2$ transition ($B_3\Pi^+_g \rightarrow A_3\Sigma^+_u$) in the long-wavelength region $\lambda = 500–800$ nm.

Figure 2. Free glow discharge spectra.

In this work, the range $\lambda = 340–440$ nm was chosen for spectral studies. This choice is because the discharge emits a significant part of the energy precisely in this range. It contains a lot of nitrogen molecular bands of nitrogen second positive system $N_2(2^+)$ (transition $N_2 (C_3\Pi^+ \rightarrow B_3\Pi^+_g)$) and first negative system $N_2^+ (1^-)$ (transition $N_2^+ (B_2\Sigma^+_u \rightarrow X_2\Sigma^+_g)$). The typical spectra of $N_2$ system is well studied, and $N_2$ molecular constants are known with high accuracy [11]. The $N_2$ systems are used in a large number of studies to determine plasma parameters. For example, in [12, 13] methods for determining the rotational and vibrational temperatures from the unresolved rovibrational spectral band of $N_2$ molecules are described.

In [12], numerical simulations of the second positive nitrogen system were performed. It is shown that the intensity of an isolated spectral band with an unresolved rotational fine structure varies exponentially with the wavelength, and the exponent is uniquely related to the rotational temperature of the upper level of the transition. By plotting the one spectral band on a semi-logarithmic scale, it can find the spectral range of linear dependence of the logarithm of intensity on wavelength. Usually, the range of linearity is at least 2 nm. Rotational temperature can be associated with the slope of the approximating straight line. The method’s error is determined by the intensities measurement error of the lines of an unresolved structure and does not exceed 10%. For typical medium-pressure plasma parameters, a Boltzmann distribution in the system of rotational levels is established with a temperature equal to the translational temperature of heavy particles [14, 15]. Therefore, the described method allows one to obtain information on the gas temperature, which is an essential plasma parameter.

According to [13], the vibrational temperature can be found out from the relative band intensities of the second positive $N_2$ system. For that, sequence $\Delta \nu = (0–2$ at 380.4 nm, 1–3 at 375.4 nm, 2–4 at 370.9 nm, 3–5 at 367.0 nm) was chosen. Vibrational temperature is obtained from the equation (1):

$$\ln(I_{\nu',\nu}/A_{\nu',\nu}) = -E_{\nu}/k_BT_v + C$$

(1)

where $I_{\nu',\nu}$ is the relative intensity of the corresponding band, $\lambda$ is the wavelength, $A_{\nu',\nu}$ is the transition probability, $E_{\nu}$ is transition energy, $k_B$ is Boltzmann constant, $T_v$ is vibrational temperature. From the slope of the graph dependence of logarithm of the intensity from energy, one can calculate the vibrational temperature of the corresponding band.
Fig. 3 is the OES from the central and near-electrode regions of the discharge in the air between 340 and 440 nm. The intensity of each spectra is normalized to the maximum intensity in the spectral range. For ease of comparison, the spectres are spaced vertically with step 1. It can be seen that the spectra from different regions of plasma discharge have important qualitative differences. The spectral line intensity ratio and the spectral composition in the range more 400 nm significantly change. The identification of the N$_2$ and N$_2^+$ spectral bands observed in the spectra was carried out. The spectral line intensity ratio 391.4 nm N$_2$ and 380.5 nm N$_2^+$ for the cathode and centre is different. The N$_2^+$ system is not visible in the spectra of the anode.

The results of the assessment of rotational and vibrational temperatures, performed using the methods described above are provided in Table 1.

**Figure 3.** Vibration-rotation band spectra.

**Table 1.** Vibrational and rotational temperature.

| Discharge region | $T_v$(K)   | $T_r$(K)  |
|------------------|------------|-----------|
| Cathode          | 3399±69    | 1556±160  |
| Center           | 4741±576   | 1879±190  |
| Anode            | 7942±1896  | 3392±340  |
4. Conclusions

Spectra of near-electrode regions and the central region of a glow discharge were obtained. The rotational temperature and vibrational temperature have been estimated as a function of distance from the electrode, at 4 kPa filling gas pressure, by using OES techniques. The spectral line intensity ratio of the $\text{N}_2^+ / \text{N}_2$ is maximum in the cathode region. It is associated with an increase in the degree of ionization of the gas near the electrodes. It is shown that the rotational temperature of nitrogen molecules is significantly lower than the vibrational one.

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