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EXPERIMENTAL AND THEORETICAL STUDIES ON THE CHARACTERISTICS OF LOW-PRESSURE GLOW DISCHARGE WITH LIQUID CATHODE

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Abstract. The characteristics of low-pressure air glow discharge with liquid cathode (electrolytic cathode low-pressure discharge, ELCLPD) has been investigated. Distilled water was utilized as a cathode. The electric field strength, gas temperature as well as emission intensity of some bands of $N_2(C^3\Pi_u \rightarrow B^3\ \Pi_g)$ were measured at pressure from 76 to 760 torr at fixed discharge current of 40 mA. Based upon these data, the reduced electric field strength, E/N, effective vibrational temperatures for $N_2(C^3\Pi_u,\ X^1\Sigma_g^+)$ and rotational temperatures for $N_2(X^1\Sigma_g^+)$ were investigated. The electron energy distribution function (EEDF) and some electron parameters (average energy, electron density) were obtained on the base of numerical solution of the Boltzmann kinetic equation.

1. INTRODUCTION

The large number of papers on non-thermal atmospheric pressure plasmas in contact with liquids were published during the last decade. The interest in liquid electrode's discharges are determined by simplicity of discharge production and by the wide range of the possible practical applications The current status of research on non-thermal atmospheric (or high) pressure discharges in contact with liquids was summarized by Bruggeman and Leys (2009).

As opposed to atmospheric pressure discharges in contact with liquids the low-pressure discharges of such types are practically not investigated yet in details. The dependences of the current density versus pressure in "metal anode-liquid cathode" cell that were obtained by Hickling and Linacre (1954), Denaro and Hickling (1958), Mezei et al. (1998) shows violation of the scaling law. Pressure dependence of the some emission lines of the electrolyte cathode glow discharge were studied by Mezei et al. (1997). In large, information on the ELCLPD are scanty. However, these informations are imagined useful from point of view not only fundamental physics but for advanced study of the more practically feasible atmospheric discharge process regularities.

The goal of this study is to obtain information about EEDF form and electron characteristics of ELCLPD from numerical solutions of Boltzmann equation. To obtain solutions, it is necessary to know some related plasma parameters such as mole fraction of main gas-phase components, the total particle density, *N*, and electric field strength, *E* (more exactly, the reduced electric field strength, *E/N*). We experimentally obtained these parameters.

2. EXPERIMENTAL

Fig. 1 shows the schematic diagram of our experimental set-up. The discharge cell was exposed to ambient air and no gas control was applied. DC power supply with a 30 kOhm ballast resistor was used for the excitation of discharge. High voltage (up to 14 kV) was applied between aqueous cathode and copper anode which placed at the position of 10 mm above the liquid surface. The liquid was connected to the negative pole of the power supply with a copper electrode. Discharge current was 40 mA, pressure was varied from 76 to 760 torr. Distilled water was used as cathode. Emission spectra were recorded within the wavelength range of 300-850 nm using compact AvaSpec-2048 (grating of 600 line/mm) and AvaSpec-3648 (grating of 1200 line/mm) spectrometers (Avantes Co., Netherlands).

The intensities of 0→2, 1→3, 2→4, 3→5, 4→6 bands for the $C^3\Pi u \rightarrow B^3\Pi g$ transitions were obtained through integrating appropriate band profile. The distribution of $C^3\Pi u$ molecules on vibration levels was described quite well by Boltzmann relation. Using this relation we determined vibration temperature, T_v, of $C^3\Pi u$ state.

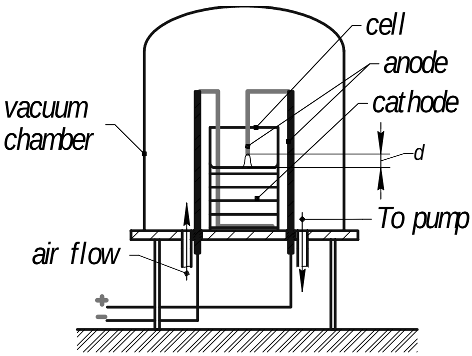

Figure 1: Experimental set-up.

To obtain rotational temperature, the distribution of emission intensity for particullary-resolved rotational structure of N_2 ($C^3\Pi_u \rightarrow B^3\Pi_g$, 0-2) band was modelled by using Cyber-Wit Diatomic modelling software by Xiaofeng (2002, 2004).

Discharge voltage was measured between anode and negative electrode as a function of distance between anode and liquid surface. Voltage drop on water layer was measured in advance. Then, this value was subtracted from voltage measured. The voltage-distance dependence was extrapolated to the zero distance to obtain the cathode drop value and electric field strength (*E*) in plasma.

The EEDF was obtained from the solution of the homogeneous Boltzmann equation using two term expansion in spherical harmonics. Since the solution of Boltzmann equation depends on electron density (through the e-e collisions), on vibration level population of N_2, O_2 and H_2O molecules (via the superelastic collisions), and gas composition we used iterative procedure for calculation. At first iteration, the electron densities as well as effective vibration temperature were equal to zero. After solving the first step of Boltzmann equation, the electron density was obtained from the equation for plasma conductivity, a new value of vibration temperature and new gas composition from reaction set by Smirnov et al. (2002) were calculated up to the convergence of numerical procedure. Details of solution were described by Titov et al. (2006).

The content of the water vapor was changed during calculation in the range of 0.15-0.5%. The N_2:O_2:Ar ratio was the same as for dry air.

3. RESULTS

The electric field strength were sharply increasing functions with respect to the pressure. Fig. 2 shows the reduced electric field strength calculated from the measured values of *E* and *T* and input power density *jE*. The gas temperature obtained on the base of the rotational temperature of $N_2(C^3\Pi_u, V'{=}0)$ did not depend on pressure (Fig. 3), i.e. increase in the input power density doesn't lead to the correspondingly gas temperature growth. The $(C^3\Pi_u\ V')$ vibrational temperatures are shown in Fig. 3. This temperature weak depends on the pressure and changes from ~4800 K at 76 torr to 5700 K at atmothpheric pressure. The calculated $(X^1\Sigma_g^+)$ vibrational temperatures (Fig 3) is close to the $(C^3\Pi_u\ V')$ vibrational temperatures. Let's note that the electric field energy is consumed in the process of excitation from molecular ground states to vibration level through electron impact changes in the range of 90% to 70% as pressure decreases.

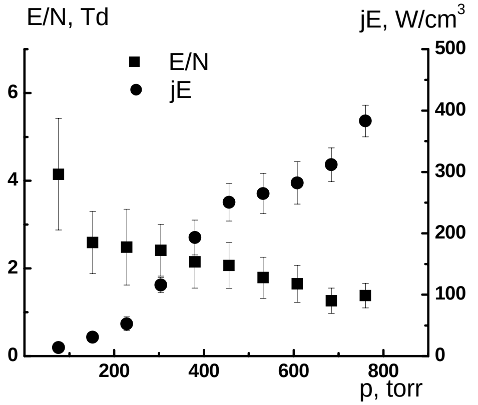

Figure 2: Change of the reduced electric and the input power density field strength with respect to pressure.

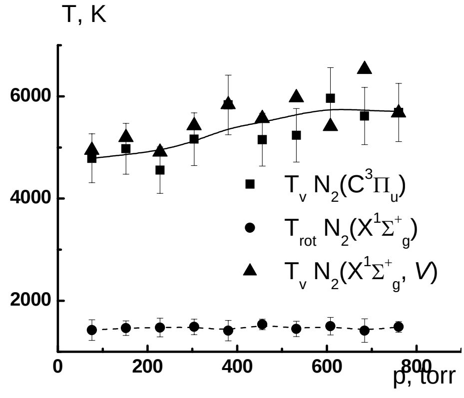

Figure 3: Vibrational temperatures of the N_2 $(C^3\Pi_u)$, $N_2(X^1\Sigma_g^+)$ states and the gas temperatures versus the pressure.

The EEDF calculated are shown in Fig. 4. The decrease of pressure increases the amount of electrons with high energy and decreases the low-energy electrons' amount. The average electron energy E_a shows near-by-exponential growth as pressure decreases (Fig. 5). The Fig. 5 shows sharp decrease of the electron density up to two order of magnitude at the pressure fall from 760 to 76 torr.

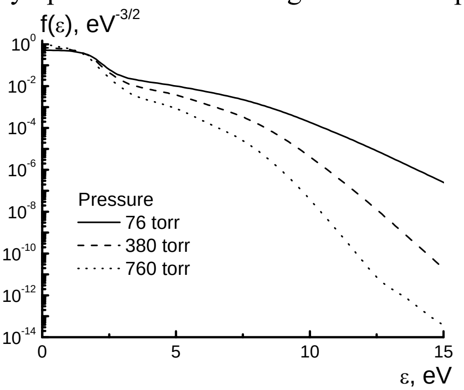

Figure 4: Calculated EEDF.

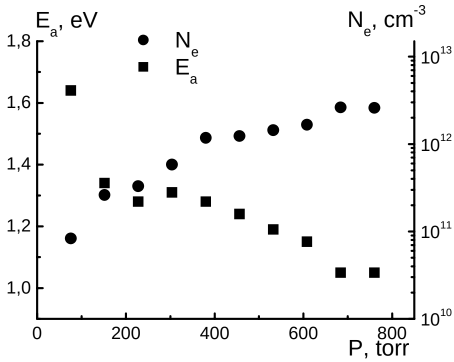

Figure 5: Calculated parameters of electrons: the average energy and electron density.

4. CONCLUSION

Experimental data showed that the low-pressure air glow discharge was non-equilibrium system. Vibrational temperatures of some plasma components are higher than the gas temperatures. The EEDF was different from Maxwell distribution, especially in the region of fast electrons. Plasma properties strongly depends on the pressure.

Acknowledgements

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