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OES Spectroscopic Measurements of Temperatures and Densities of Charged Particles in Micro-Air Plasma for Gene Transfection

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ABSTRACT: The aim was to characterize by optical emission spectroscopy measurements our μ-air plasma discharge successfully used for gene transfection. We estimated rotational Trot and electron T_e temperatures, and densities of charged particles.

KEY WORDS: micro-air plasma, corona discharge, plasma diagnostics, electron temperature and density, ion density

In this study, we aimed to experimentally characterize a μ-air plasma discharge using optical emission spectroscopy (OES) measurments. This μ-air plasma has been successfully used for gene transfection.[1] We estimated rotational temperatures (T_{rot}) and electron temperatures (T_e) as well as densities of charged particles (electrons and N_2^+ molecular nitrogen ions). Figure 1 displays the coronal discharge setup generated from the tip of a pulsed high-voltage microtube placed 2 mm in front of a Petri dish containing deionized water and placed over a grounded copper plate. Table 1 summarizes temperatures and densities for several z positions in the interelectrode space. T_e is equal to

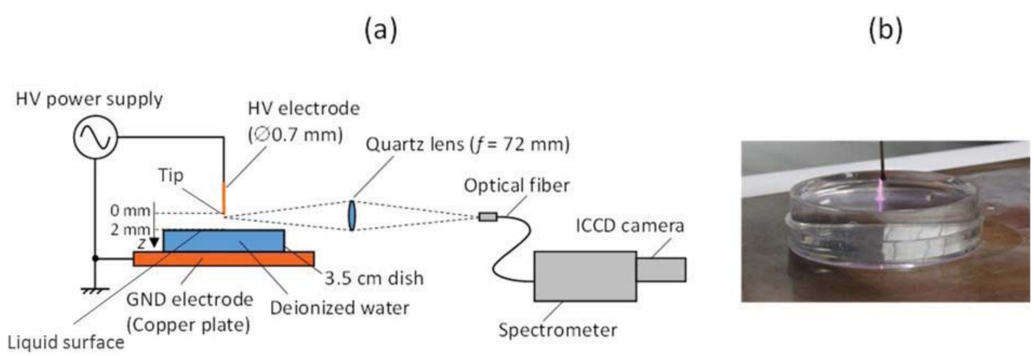

FIG. 1: (a) Schematic of the experimental setup using sinusoidal voltage waveform with frequency of 20 kHz, amplitude of 7 kV and duration of 0.1 s with a repetition frequency of 1 Hz to producing micro-air plasma and (b) a picture of the generated plasma discharge

TABLE 1: Temperatures and densities of charged particles for several z positions

z(mm)	T_{rot}(K)	T_{vib}(K)	T_e(eV) Error bar = 30%	n_e (cm^{-3}) Error bar = 100%	N_2^+ (cm^{-3}) Error bar = 50%
0	2000	2800 ± 500	6.75	10^{15}	1.2×10^{15}
0.5	2000	3500 ± 500	4.85	0.8×10^{15}	1.8×10^{13}
1	2000	4500 ± 500	4.2	1.8×10^{15}	5.8×10^{13}
1.5	2000	5500 ± 500	3.4	2.3×10^{15}	3.1×10^{13}
2	2000	6500 ± 500	3.38	0.8×10^{15}	7.5×10^{14}

~6.75 eV near the electrode tip and decreases to 3.4 eV near the liquid surface. T_e has been estimated from an interesting approach described elsewhere[2] and is based on the experimental ratio of the closest nitrogen emission spectra of N_2^+ (FNS) at 391.4 nm and N_2 (SPS) at 394.3 nm.

Based on the measured Hα spectrum, electron density (n_e) has been estimated from Stark broadening versus the interelectrode position. An n_e of $\sim 1 \times 10^{15}$ cm^{-3} near the tip is in agreement with the usual magnitude of electron density in the streamer head developed near the tip of coronal discharges. T_{rot} estimated from comparison of synthetic and experimental spectra of OH (A-X), N_2^+ (FNS) at 391.4 nm, and N_2 (SPS) at 337 nm are respectively equal to 2350 K, 2000 K, and 700 K in the gap space. This finding clearly underlines a thermal nonequilibrium of the corresponding excited species generated inside the thin streamer filaments. However, due to the high dilution of these species in the background gas, these high rotational temperatures do not affect the mean gas temperature, which remains close to 300 K. N_2^+ (FNS) for (0, 0) and (1, 1) head-band spectra at 391.4 nm and 388.4 nm allowed us to estimate the vibrational temperature (T_{vib}) from ~3000 K near the electrode tip up to ~6500 K near the plate. The density of nitrogen ions has been estimated to be $\sim 10^{15}$ cm^{-3} from the relative intensities of the same close wavelength spectra: N_2 (SPS) at 394.3 nm and N_2^+ (FNS) at 391.4 nm. These experimental plasma characteristics can be used to better understand the mechanisms and processes involved during plasma gene transfection. This model was developed from a specific Monte Carlo poration model[3] to simulate the membrane permeabilization and pore formation when the cells are impacted by micro-air plasma fluxes.

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