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Spectroscopic characterisation of a cross-flow plasma jet

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ABSTRACT

The aim of this work is to study the thermal characteristics and electron density based on atomic and molecular emission of a new plasma jet at atmospheric pressure. The novelty of our jet is its generation with a single electrode, the plasma gas flowing perpendicularly to the RF powered electrode (13.56 MHz, 10^3 V). Optical emission of the plasma was collected in two ways: the normal viewing mode and the axial viewing mode. The plasma characteristic parameters as function of helium flow-rate, plasma power and position of the investigated zone were studied. The excitation, vibrational and rotational temperatures are in the range of 1500–2350 K, 3500–4400 K and 450–1100 K, respectively. The electron number densities are in the range of 10^{13}–10^{14} cm^{-3}. For qualitative observations regarding the atomic and molecular processes in the plasma we used the relative intensities of the most representative lines of He, N_2, O, H and N_2^+.

1. Introduction

Many technological applications of plasmas (etching, thin film deposition, surfaces treatment) are based on gas discharges generated at pressures lower than the atmospheric pressure. Because the atmospheric pressure plasmas (APP) overcome the disadvantages of vacuum operation, the interest for these plasmas, in particular for non-thermal plasmas, is finding increasing attention over the last decade. They offer high excitation selectivity and energy efficiency in plasma chemical reactions. They are also sources of UV, VIS and IR radiations, free radicals (such as O and OH) and active species that can play important roles in various techniques. Many kinds of low power and very low power atmospheric pressure plasma sources for biomedical, environmental and technological applications were designed. The most important of them can be considered: plasma needle [1,2], plasma pencil [3], miniature pulsed glow-discharge torch [4], open-air hollow slot microplasma [5], one atmosphere uniform glow-discharge plasma [6], resistive barrier discharge [7] and dielectric barrier discharge [8] and atmospheric pressure plasma (micro)jet [9–14]. Various types of plasma jets have found wide applications in material surface modification [11], deposition of thin films [12], sterilization [13] or surface modification of polymer fiber [14].

The knowledge of plasma parameters allows us to have information on the elementary processes in the plasma. The plasma temperatures and electron number density can be estimated based on the study of the plasma emission spectrum which represents a non-intrusive and non-perturbing tool. By ascribing of emission lines to atoms and molecules, the atomic and molecular species and their generation and excitation mechanism in different plasma zones were identified and studied [1,4,8].

The purpose of the present research is to study the thermal characteristics and electron density based on atomic and molecular emission of a new atmospheric pressure plasma jet. The novelty of our jet is its generation with a single electrode, the plasma gas flowing perpendicularly to the RF powered electrode.

2. Experimental

The experimental arrangement is shown in Fig. 1. It consists of three main parts: the RF generator, the plasma torch and the feeding with plasma gas system.

The construction of the RF generator used for sustaining of CCP (capacitively coupled plasma) at atmospheric pressure was described in details elsewhere [15]. The torch used for generating the plasma jet consists of a cylindrical sinterized alumina (Al_2O_3) piece (12.8 mm o.d.) with a longitudinal hole (0.9 mm diameter), a glass tube and an insulator support. The RF powered electrode is perpendicularly positioned to the longitudinal axis of the torch, having its tip (1 mm diameter, kanthal made) centered to the exit hole of the alumina piece. Assisted by a flow rate regulator (Cole&Palmer) the gas flow can be adjusted in the range of 0–6 l min^{-1}.

The plasma power was estimated by using an extracting method [15]. It represents the difference between the powers absorbed by the rf generator from its DC power supply in the presence of the plasma jet and in the absence of it, respectively. The uncertainty of this method is about 5–10%.

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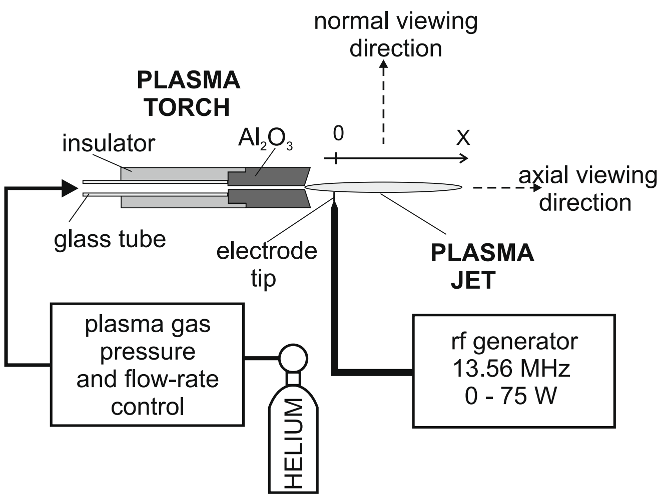

Fig. 1. The experimental arrangement.

Plasma optical emission was collected with two Ocean Optics high-resolution fibre optic spectrometers: HR4000 for wavelengths in the range of 290–429 nm, and HR4000CG-UV-NIR for wavelengths in the range of 254–965 nm. The spectrometers were controlled by the SpectraSuite software. All spectral plots are the result of 3–5 data acquisitions, depending on the total emission intensity of the plasma. For the spectra displaying, labelling and for measuring the relative intensities of the emission lines the Spectrum Analyzer 1.6 software was used [16]. It was also used to calculate the electron excitation temperature of the He atoms, T_{excHe} and the temperature of excitation of vibrational states of the N_2 molecules, T_{vibrN_2} by the Boltzmann plot method [17,18]. For calculation of T_{excHe}, the neutral He atomic lines with the wavelengths of 501.56, 587.56, 667.81, 706.51 and 728.23 nm were used. T_{vibrN_2} was calculated using the heads of the molecular N_2 bands from the 2nd positive system ($C^3\Pi_u \rightarrow B^3\Pi_g$), with the bandheads at 371.05 (2–4), 375.54 (1–3) and 380.41 (0–2) nm. The used spectral data were taken from [19]. The temperatures of excitation of rotational states of the OH radicals, T_{rotOH} and of the N_2^+ ionic molecules, $T_{rotN_2^+}$ were estimated by finding the best fit (chi-square method) of the measured molecular spectra with the synthetic spectra generated by the LIBASE 1.5 spectral simulation software [20]. For OH radical the emission band ($A^2\Sigma^+$, $v = 0 \rightarrow X^2\Pi$, $v' = 0$) with a prominent line at 308.9 nm and for N_2^+ molecule the emission band of the 1st negative system with bandhead at 391.44 nm ($B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$), were used. The electron number density was calculated based on the Stark broadening of hydrogen emission line H_α.

3. Results and discussion

3.1. Plasma appearance and plasma emission

Fig. 2 presents an image of helium plasma jet. It has a visual appearance like a needle with a diameter around 1 mm close to the nozzle exit. Its length (6–15 mm) is function of both plasma power and helium flow rate. For a constant flow rate the length increases with plasma power (3–38 W). The plasma power decreases monotonically when helium flow rate increases, because of the convection and conduction cooling of the gas. As a consequence, in this situation the plasma length will decrease too.

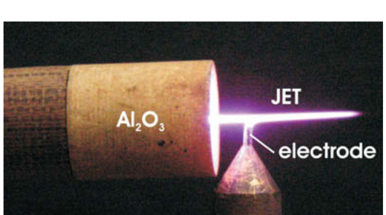

Fig. 2. Photograph of helium plasma jet. Plasma power – 34.85 W; He flow rate – 2.2 l min^{-1}.

This assumption is sustained by the dependence of the OH rotational temperature on the helium flow rate, determined in axial viewing mode (Fig. 3).

A typical emission spectrum of the helium plasma in the range of 200–900 nm is shown in Fig. 4. Beside the above mentioned He emission lines, atomic emission lines of O (777.41 and 844.67 nm) and H (656.27 nm) and molecular bands of NO, OH, N_2 and N_2^+ are presented in the radiation spectrum. Excepting helium, the presence in the plasma of the other atomic and molecular species is inevitable because of the back diffusion of the ambient humid air. Recently, it was demonstrated that even small level of impurity (particularly nitrogen from ambient air) could have an important influence in radiation of noble gas plasmas [21].

The presence of NO is due to the chemical conversion of N_2 and O_2. The OH radicals represent the result of the dissociation of H_2O molecules from air caused by the collisions with accelerated electrons or with long-lived species presented in the plasma, especially with helium metastables, He_m^* [1,4]. Beginning with the

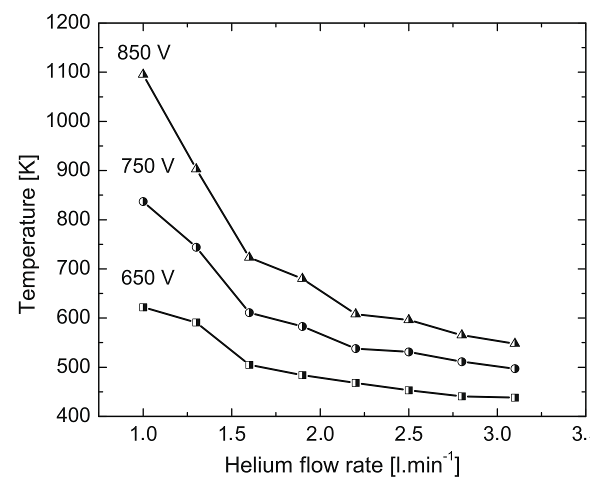

Fig. 3. Dependence of OH rotational temperature on helium flow rate, for different DC supply voltages of the RF generator, in axial viewing direction.

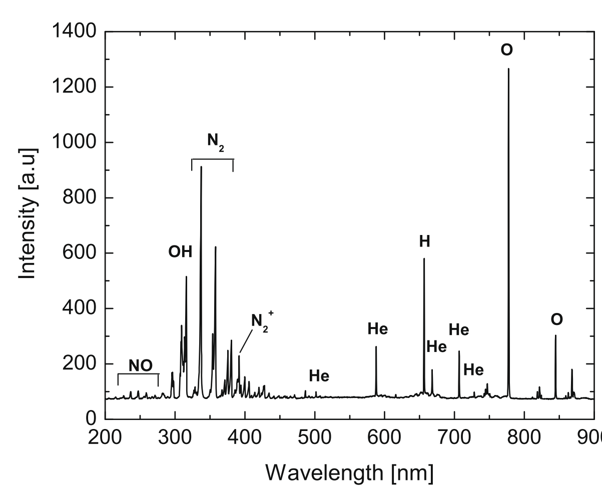

Fig. 4. Emission spectrum of plasma. Plasma power – 34.85 W; He flow rate, 2.2 l min^{-1}; axial viewing direction.