Emission spectroscopy of an atmospheric pressure plasma jet operated with air at low frequency

L Giuliani\(^1\), J L Gallego\(^1\), F Minotti\(^2\), H Kelly\(^2\) and D Grondona\(^2\)
Instituto de Física del Plasma (INFIP), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires (UBA).
Ciudad Universitaria, Pabellón I, C1428EHA, Buenos Aires, Argentina.
E-mail: leandro@tinfp.lfp.uba.ar

Abstract. Low-temperature, high-pressure plasma jets have an extensive use in plasma biology and plasma medicine, such as pathogen deactivation, wound disinfection, stopping of bleeding without damage of healthy tissue, acceleration of wound healing, control of bio-film proliferation, etc. In this work, a spectroscopic characterization of a typical plasma jet, operated in air at atmospheric pressure, is reported. Within the spectrum of wavelengths from 200 to 450 nm all remarkable emissions of N\(_2\) were monitored. Spectra of the N\(_2\) 2nd positive system (C\(_3\)\(^\text{T_u}\)–B\(_3\)\(^\text{T_g}\)) emitted in air are the most convenient for plasma diagnostics, since they enable to determine electronic T\(_e\), rotational T\(_r\) and vibrational T\(_v\) temperatures by fitting the experimental spectra with the simulated ones. We used SPECAIR software for spectral simulation and obtained the best fit with all these temperatures about 3500K. The conclusion that all temperatures are equal, and its relatively high value, is consistent with the results of a previous work, where it was found that the experimentally determined electrical characteristic was consistent with the model of a thermal arc discharge, together with a highly collisional cathode sheet.

1. Introduction
A very active branch in plasma physics is the development of plasma sources able to provide energetic electrons and ions, which produce in turn highly active chemical reactive species, at relatively low gas temperature. This is due to a large number of applications of these sources in plasma biology and plasma medicine, such as pathogen deactivation, wound disinfection, stopping of bleeding without damage of healthy tissue, acceleration of wound healing, control of bio-film proliferation, etc. (see [1] and references therein).

In spite of the existing large amount of experimental work with plasma jets [2-5], the discharge structure and the plasma state are not yet well known. This knowledge is important for the scaling and optimization of the discharge in several potential technological applications.

In a previous work [6], a plasma jet operated with air or argon at atmospheric pressure using the same discharge geometry as used in this work was presented. An electrical study of the discharge, together with a theoretical interpretation, indicated that in some configurations the discharge plasma can be thought of as a low-current arc, in which a relatively large voltage drop occurs mainly in a

\(^{1}\) Fellow of CONICET.
\(^{2}\) Researcher of CONICET.
cathodic, collisional sheath. Also, the possibility of turbulence in the gas flow was considered, and linked to the behavior of the external plasma plume for different gas flow rates.

In this work, a spectroscopic characterization of a typical plasma jet, operated in air at atmospheric pressure, is reported. Within the spectrum of wavelengths from 200 to 450 nm all remarkable emissions of N\textsubscript{2} were monitored. Spectra of the N\textsubscript{2} 2nd positive system band head (C\textsuperscript{3}Π\textsubscript{u}–B\textsuperscript{3}Π\textsubscript{g}) emitted in air were used to determine electronic $T_e$, rotational $T_r$ and vibrational $T_v$ temperatures by fitting the experimental spectra with the simulated ones.

2. Experimental set-up
A schematic of the experimental device used to generate the atmospheric plasma jet is shown in Figure 1. The device consists in two electrodes with a hole of 1 mm diameter, through which the gas flows. The two electrodes are made of stainless steel disks of 20 mm diameter and 3 mm thickness attached to the surface of centrally perforated dielectric disks (Teflon) of 1 mm in thicknesses. The hole in the center of the dielectric disk is 2 mm in diameter.

The ac power supply is a commercially available transformer for neon light (25 kV, 50 mA, 50 Hz) which is connected to a variable autotransformer (Variax) in order to allow voltage control. Neon light transformers are quite interesting sources for the generation of low current plasma jets, because they provide an intrinsic current limitation of reactive origin (thus avoiding the use of external ballasts in the discharge circuit), combined with a low commercial price.

![Figure 1. Schematic of the experimental device.](image1)

![Figure 2. Photograph of the plasma jet.](image2)

The voltage $V$ between the electrodes was measured using a digital Tektronix oscilloscope (70 MHz, 1GS/s), the current $I$ was measured from the voltage drop through a 50 Ω resistor, and the air flow was measured using a stainless steel float flow meter.

The spectroscopic measurements were performed with a monochromator (200-500 nm) attached to a photomultiplier (Hamamatsu 1P28) facing the plasma jet. All along this work, the discharge was operated with the power source at 11.2 kV and an air flow of 11.3 l/min.

A photograph of the plasma jet operated with air under the same conditions used for the spectrum measurements is shown in figure 2.

3. Results and analysis
The current and voltage waveforms of the discharge are shown in figure 3. These measurements show that the discharge current was sinusoidal like the transformer voltage and controlled by the transformer impedance (estimated in $(57 \pm 1)$ kΩ by a linear regression), being almost independent of the
discharge voltage behavior. The voltage between the electrodes shows a quasi-square signal with an amplitude of around 500 V, with a slight concavity opposed to that of the current.

**Figure 3.** Typical voltage and current waveforms of the discharge.

The emission spectrum of the plasma jet can be seen in figure 4. It was found that the spectrum was dominated by emissions of molecular nitrogen containing N$_2$ second positive systems. These excited molecules and energetic UV photons play important roles in the sterilizing properties of plasmas. It is worth noting that this spectrum was obtained with the monochromator facing the jet so that most of the light came from the bright spot within the interelectrode region.

**Figure 4.** Emission spectrum of the plasma jet with all remarkable emissions of N$_2$ monitored within the 300-450 nm range.

Experimental spectra of the N$_2$ 2nd positive system band head at 337.1 nm (dots) and SPECAIR software spectral simulations (lines) are shown in figure 5. It was found that the best adjustment is obtained with $T_e$, $T_r$ and $T_v$ about 3500K. In order to test an alternative discharge mode, an additional simulation is included, corresponding to a streamer discharge with electron temperature of about 1 eV in a cold gas.
The result that all temperatures are equal, and their relatively high value, is consistent with the results of a previous work [6], where it was found that the experimentally determined electrical characteristic was consistent with the model of a thermal arc discharge, together with a highly collisional cathode sheet with a relatively large voltage drop.

4. Final remarks
The emission spectrum was mainly dominated by the presence of excited nitrogen species, containing N$_2$ second positive systems. These excited molecules and energetic UV photons play important roles in the sterilizing properties of plasmas.

The spectroscopic data were consistent with a thermalized plasma with heavy species at high temperature (about 0.3 eV), which is also in agreement with a previous study of the electrical characteristic of the discharge. In contrast, a streamer discharge with higher temperature electrons was not revealed by both studies.

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