

Microwave Plasma Source for Biomedical Applications

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Investigations on plasma interaction with living matter are presently at the frontiers of plasma research and development. Plasmas contain numerous agents that influence biological activity. For example, plasmas can provide essentially two types of biocidal species: reactive species, such as oxygen atoms that lead to lethality of micro-organisms through erosion, and UV radiation that can damage the DNA strands [1]. An important aspect to be addressed is whether the biological objects are exposed directly to the discharge plasma or to its flowing afterglow. Combined, reactive species and UV photons can lead to significant synergistic effects. Furthermore, non-equilibrium plasmas are able to initiate, promote, control and catalyze complex behaviors and responses in biological systems, in a variety of ways different from the thermal effects [2]. Significant advancement in the plasma surgery, wound healing and tissue regeneration has been achieved with the development of the so-called “Plazon” system (a dc arc), based on a jet of hot air plasma which is rapidly cooled and provides relatively high NO concentrations with significant therapeutic effect [3]. Today, it is well established that NO serves a multitude of essential biological functions in the human organism – it regulates blood vessel tone and blood coagulation, the immune system and early apoptosis, neural communication and memory, etc.

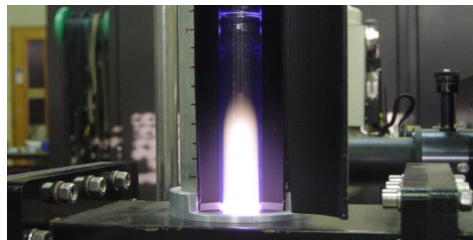


Fig. 1. Microwave air-water vapor plasma source

As low-temperature, non-equilibrium plasmas come to play an increasing role in biomedical applications, reliable and user-friendly sources need to be developed. These plasma sources have to meet stringent requirements such as low gas temperature operation at atmospheric pressure, high concentration of active species of interest and flexible geometry.

In this respect, atmospheric microwave plasma sources driven by surface waves are an attractive alternative to conventional plasma sources, because they are compact, electrodeless, economical, and simple to operate over a wide range of operation conditions [4]. Having an extended zone of operation outside of the field applicator, surface wave discharges and their afterglow plasma jets permit some tailoring of the plasma properties for each specific application.

The aim of the present work is to investigate a surface wave (2.45 GHz) driven air-water plasma source (Fig. 1) as a source of ground state $O(^3P)$ oxygen atoms, NO molecules and UV radiation coming mainly from the $NO(\gamma)$ band radiation. A one-dimensional theoretical model previously developed [4], based on a self-consistent treatment of particle kinetics, gas dynamics and thermal balance, and wave electrodynamics is used to analyze the performance of this plasma source. This model describes both the wave driven discharge zone and its flowing afterglow, as integral parts of the plasma source considered. The predicted plasma-generated $NO(X)$ and $O(^3P)$ concentrations and $NO(\gamma)$ radiation intensity along the source are presented and discussed as a function of two external parameters, *viz.*, microwave power and water vapor percentage in the gas mixture. To validate the theoretical predictions, the relative concentrations of species in the exhaust stream have been detected by mass spectrometry (using a Stanford Research System RGA 200) and Fourier Transform Infrared Spectroscopy (FT-IR). Furthermore, the intensities of the $NO(\gamma)$ radiation (220 -260 nm) and of the atomic oxygen triplet line at 777 nm have been detected by optical emission spectroscopy.

The calculated axial variation of the $O(^3P)$ relative density with respect to the total gas density is shown in Fig. 2 for different powers fed to the launcher, at constant percentage (1%) of water vapor in the mixture and constant total gas flow (1000 sccm). There are small variations in the atomic density along the discharge zone of the source but a sharp decrease of nearly three orders of magnitude occurs in the afterglow zone as seen in this figure. There is a some increase in atomic density ($\sim 40\%$) in the discharge zone when the percentage of water vapor is increased from 1% to 10% at constant power (300 W) and total gas flow (1000 sccm).

The measured and calculated relative integral intensity of 777.4 nm lines of atomic oxygen, corresponding to the transition ($3s^5S \rightarrow 3p^5P$), are presented in Fig. 3 as a function of the power for two different percentages of water vapor in the mixture. The theoretical and experimental values for the line intensities are normalized to the intensity value at $\Delta z = 1$ cm and $P = 200$ Watt power. As seen from this figure, the theoretical and experimental data

follow the same behavior, which provides some confidence for the predicted relative densities of oxygen atoms.

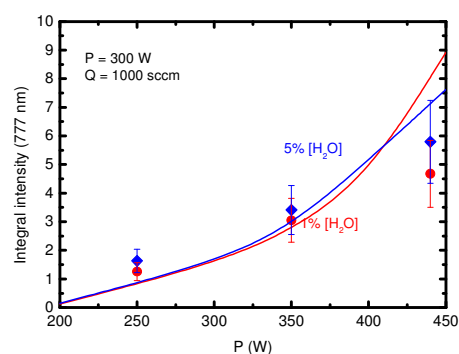
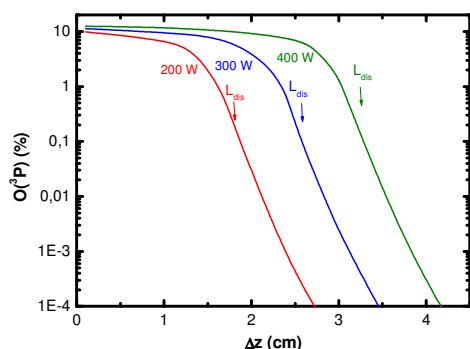


Fig. 2. Axial variation of relative O(3P) atom density. Fig. 3. Integral intensity (777.4nm) vs power.

The calculated NO(X) relative density reaches up to 3.5 % in the discharge zone ($P = 400$ W, $Q = 1000$ sccm, 10% water vapor) and drops close to the end of the discharge zone to a constant (“frozen”) value between 1.2 and 1.25% in the afterglow, depending on power.

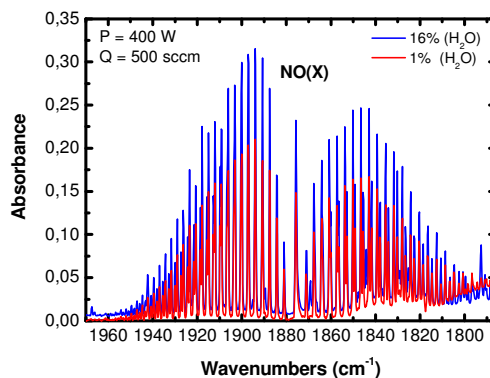
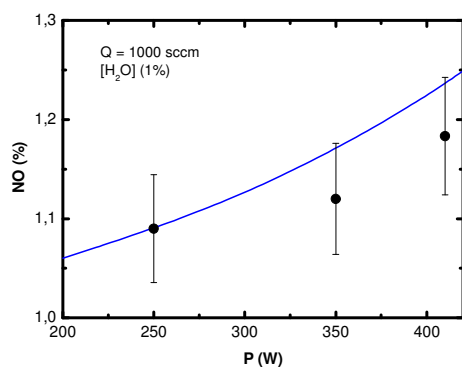


Fig. 4. Relative NO(X) density vs power.

Fig. 5. Fundamental NO(X) ro-vibrational band.

The calculated and measured dependence of the relative number density of NO(X) in the afterglow plasma jet on the microwave power for constant percentage (1%) of water vapor are presented in Fig. 4. In order to validate the predicted dependence, a portion of the output gas stream from the plasma reactor has been channeled to a mass analyzer. The obtained experimental data are relative values. The increase of water vapor from 1% to 10% at constant gas flow (1000 sccm) and microwave power (350 W) results in a small change of the NO(X) relative density in the plasma jet from 1,15% to 1,23%. This trend is confirmed by the measured infrared spectra of the NO(X) fundamental rotation-vibration band in the range $1800 - 1960$ cm^{-1} . The intensity of absorbed rotational lines increases with the quantity of water vapor introduced into the active zone of the plasma source as seen from Fig. 5

The recorded radiation spectrum of NO(γ) [transition NO($A^2\Sigma^+$) \rightarrow NO($X^2\Pi$) + $h\nu$] in the spectral range 230 – 260 nm at two different microwave powers shows an increase of the total intensity with microwave power. According to the model, this is because the main pumping channel of the upper NO($A^2\Sigma^+$) state are the energy exchange reactions $N_2(A^3\Sigma_u^+) + NO(X^2\Pi) \rightarrow NO(A^2\Sigma^+) + N_2(X)$.

The calculated and measured NO(γ) band intensities show that this radiation decreases sharply in the afterglow by many orders of magnitude. In fact, no NO(γ) radiation was detected in the afterglow plasma jet.

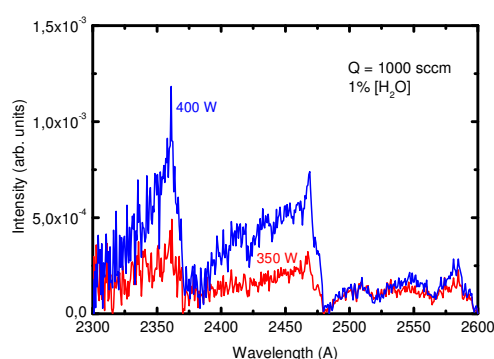


Fig. 6. Ultraviolet NO(γ) radiation spectra for two microwave powers, at distance $\Delta z=1$ cm.

In conclusion, the investigated atmospheric surface wave driven plasma is an effective source of oxygen O(3P) atoms, NO(γ) radiation and NO molecules and has a potential for successful applications in plasma therapy and sterilization processes.

Acknowledgment

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