Radial characterization of electron density and gas temperature in a Helium plasma torch

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Abstract

A complete understanding of Microwave Induced Plasmas (MIPs) is only possible through the detailed characterization of the values of their parameters. This paper deals with the radial distribution of two important parameters ($n_e, T_g$) of the Helium plasma produced by the axial injection torch (Torche à Injection Axiale or TIA). This is performed under different plasma conditions (i.e. HF power and gas flow).

1. Introduction

Microwave Induced Plasmas (MIPs) have nowadays a growing number of applications and are widely used for industrial applications and spectrochemical research. Waste treatment and material processing are some of these applications, together with their use as excitation sources for Atomic Emission Spectrometry (AES). Some advantages of MIPs are the simplicity of their construction and their ability to produce a very stable plasma under a great range of gas flow and power conditions.

Descriptions of the plasmas are necessary to obtain a better understanding of their behaviour and provide a way to compare different types of plasmas, supporting criteria to distinguish between them when applied to a certain task. They can also be used to improve the accuracy and precision of the analysis as well as its detection limits.

Electron number density ($n_e$) and gas temperature ($T_g$) are capital parameters of the

![Diagram](image_url)

Fig. 1: Scheme of the experimental set-up

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plasmas, and the spatial distribution of their values is of great importance for the complete description of MIPs. This paper deals with the radial characterization of these two parameters in a MIP produced at atmospheric pressure via the axial injection torch (Torch à Injection Axiale or TIA), an excitation structure that couples high HF power to the He gas discharge producing a thin plasma flame. This plasma has already been axially described by our group [1], but a radial description has never been performed before, probably because of the problem posed by the small diameter of the flame (aprox. 1 mm). An intensified CCD camera together with an optical image rotation system allowed the lateral resolution of the plasma, while mathematical transformation (i.e. Abel inversion) provided internal description of the parameters in the flame.

<table>
<thead>
<tr>
<th>Components</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave generator</td>
<td>GPM 12K T/t (SAIREM) at 2.45 GHz</td>
</tr>
<tr>
<td>Microwave launcher</td>
<td>TIA (Montreal University)</td>
</tr>
<tr>
<td>Monochromator</td>
<td>THR-1000 (Jovin-Yvon) Grating 1200 grooves mm⁻¹Dispersion: Typically 0.8 nm mm⁻¹ at λ=500nm Computer-controlled Spectralink system</td>
</tr>
<tr>
<td>ICCD camera</td>
<td>Flamestar 2 (La Vision)</td>
</tr>
<tr>
<td>Flow controller</td>
<td>Mass flow controllers FC280 Dynamass control system (Tylan General)</td>
</tr>
</tbody>
</table>

Table 1: Instrumental components

2. Experimental set-up

A diagram of the instrumental set-up used in this work is shown in Fig.1. The description of the set-up components is provided in Table 1.

Plasma generator device: The power supplied by the microwave generator is guided to the launcher by means of a waveguide system (WR-340). At the nozzle tip of the TIA the discharge takes place, generating a 1-2 mm diameter plasma with a height of about 1.5 cm. The HF power was measured by a digital power meter that was coupled to the waveguide, allowing a

![Diagram](image)

Fig.2: The image of the flame, rotated 90° and integrated in the y-axis is dispersed in λ by the monochromator.
precise control of the incident and reflected power together with providing a hint of the plasma stability.

The TIA supports a variety of gases and produces an axially symmetric plasma that expands freely in open air. The flame is highly stable in the lower millimeters, but it becomes turbulent in the upper part. All the measurements have been performed in the stable zone, at the maximum intensity height, about 1 mm above the nozzle.

Detection system: The flame is imaged at the entrance slit of the monochromator, but rotated 90°. This allows the selection of the side-on emission of a transversal slice in the plasma. The image rotation system consists of two convergent lenses and a Dove prism, as seen in Fig. 1. The Dove prism can rotate an image at any desirable angle depending on its orientation.

The rotated image is separated into different wavelengths by the monochromator and then focussed at the bi-dimensional array of photosensitive pixels in the ICCD camera, which is placed at the exit of the monochromator (Fig. 2). The width of a pixel is 29 μm, so the entrance slit width was set with this value to avoid a trapezoidal instrumental function, which would be difficult to deconvolute from the data.

The ICCD camera allowed us to obtain a spectra for each lateral position in the flame, as shown in Fig. 2. It is clear from the figure that the obtained data are line-of-sight integrated intensity values that can be expressed in a matrix form (I(x)), with a different wavelength value for each column and a different lateral position for each row. The resolution in wavelength is limited by the resolving power of the monochromator and by the size of the camera pixels. About 40 pixels/nm is the default resolution, but it can be improved via scanning the wavelengths by moving the grating, which provides the equivalent of a much higher resolution. This last procedure was necessary to perform when the rotational temperature was measured in order to solve the close-in-wavelength peaks of the rotational band. The resolution in lateral position is limited by the pixel width and the size of the image. Due to the small diameter of the flame, it was necessary to magnify the image to improve the lateral resolution.

3. Measurement and data treatment

The Abel inversion method

Let us consider an optically thin light source which is axially symmetric. When a spectroscopic measurement is performed, it is usual to measure the side-on integrated intensity (Fig. 2)

\[ I_\perp(x) = \int_{-y}^{y} \varepsilon_\perp(r)dy \]

An internal description of the light source can be obtained by the deconvolution of the emission coefficient for each radial position \( [\varepsilon_\perp(r)] \). That gives the Abel inversion equation:

\[ \varepsilon_\perp(r) = \frac{1}{\pi} \int_{r}^{\infty} \frac{df_\perp(x)/dx}{\sqrt{(x^2 - r^2)}} dx \]

With discrete sets of data, the Abel integral has to be approximated by a summation. If this is done directly, there will be a discontinuity in \( x = r \), which can be avoided using different approximations [2-4]. Anyway, these approximations were not necessary due to the accuracy of the other method, consisting of expressing \( \varepsilon(r) \) in function of Fourier and zero-order Hankel transformations of \( I(x) \):

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\[ \varepsilon_\lambda(r) = HT^{-1}[FT[I_\lambda(x)]] \]

A typical example of the experimental data for a single \( \lambda \) value is shown in Fig. 3a. Both sides of the plasma differ slightly, so data have to be symmetrized and smoothed. After that, an interpolation based on third grade polynomials with boundary conditions for continuity of the first derivative is performed (Fig. 3b). This method improves the Abel inversion by simulating a higher sampling rate in the lateral position \( x \). An example of Abel inverted data can be seen in Fig. 3c.

![Graph showing different steps in data treatment: (a) Experimental data; (b) Symmetrized and smoothed data; (c) Abel inverted data.](image)

**Fig. 3: Different steps in data treatment:** a) Experimental data; b) Symmetrized and smoothed data; c) Abel inverted data.

**Electron density**

The calculation of the \( n_e \) was performed using the \( H_\beta \) line Stark broadening of the Hydrogen present in the plasma as an impurity. The relationship between electron density and \( H_\beta \) Stark broadening is given by the Czernichowski and Chapelle equation [5].

\[
\log n_e = C_0 + C_1 \log \Delta \lambda + C_2 (\log \Delta \lambda)^2 + C_3 \log T_e
\]

with \( C_0 = 22.578 \), \( C_1 = 1.478 \), \( C_2 = -0.144 \), \( C_3 = -0.1265 \), the full width at half maximum \( (\Delta \lambda) \) expressed in nm, \( n_e \) in cm\(^{-3} \) and \( T_e \) in K (for these conditions \( T_e = 20000 \) K).

In the TIA plasma the intensity of the \( H_\beta \) line is too low while \( H_\alpha \) is a very intense line, so the Stark broadening of \( H_\beta \) was estimated by using the Stark broadening of \( H_\alpha \) after a previous calibration [1].

To obtain the radial distribution of the line broadening, Abel inversion must be calculated for every wavelength, so the inverted data for every radial position can be fitted to a Voigt function.

To know the accuracy of the Voigt fits, the regression coefficient of every fit was also calculated. Bad coefficients appear at the edges of the plasma, where the intensities are small and the signal to noise ratio decreases. At the center of the flame the coefficients are also bad. This can be explained by two different causes: an error introduced by the Abel inversion method, which is higher for \( r \) close to 0, and a diminution in the Hydrogen concentration in this zone, lowering the signal to noise ratio again.
Gas temperature

The very favourable energy exchange between the kinetic energy of the heavy particles and the internal rotational-vibrational states of the N₂⁺ allows us to assume the gas temperature (Tₑ) and the rotational temperature (T₉) to be equal. T₉ was calculated from the R-branch lines of the (0-0) rotational band of the N₂⁺ first negative system.

The rotational temperature has been calculated assuming a Boltzmann distribution for the previously mentioned levels. Maximum intensity values of the R-branch peaks were Abel-inverted, so a Boltzmann plot of ln(I/A) vs. B (Table 2) could be performed for every radial position, being I the line intensity and A and B line parameters related to the population of the upper level of the transition and the energy of such a level respectively [6]. Tₑ is related to the slope of the plot by

\[ m = -\frac{2.983}{T_{rot}} \]

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>K''</th>
<th>A = 2(K'' + 1)</th>
<th>B = (K'' + 1)(K'' + 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>390.29</td>
<td>8</td>
<td>18</td>
<td>90</td>
</tr>
<tr>
<td>390.08</td>
<td>10</td>
<td>22</td>
<td>132</td>
</tr>
<tr>
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<td>12</td>
<td>26</td>
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</tr>
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<td>388.74</td>
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<td>42</td>
<td>462</td>
</tr>
<tr>
<td>388.44</td>
<td>22</td>
<td>46</td>
<td>552</td>
</tr>
</tbody>
</table>

Table 2: Characteristic parameters of the R-branch lines of the (0-0) rotational band of the N₂⁺ first negative system used in the calculation of the Tₑ.

4. Results and conclusions

Measurements were performed under several conditions, i.e. gas flow ranging from 4 to

![Graph](image)

Fig. 4: Variation of the radial distribution of nₑ with a) microwave power and b) gas flow.

10 slpm and HF power ranging from 400 to 1000 W. As can be seen in Fig. 4, nₑ increases with
the microwave power and remains almost without variations when the gas flow increases. This result agrees with previous radially integrated measurements performed on this plasma [1].

As expected, electron density is higher in the centre of the flame, decreasing in the edge direction, where the electrons recombine with the air components. It is interesting to emphasize the high value of the electron density in this flame, which enhances the excitation ability of the plasma.

The results of the measurement of $T_g$ can be seen in Fig. 5. The obtained profiles of the gas temperature show an almost constant behaviour of this parameter with the radial position even beyond the edge of the flame, which is at about 0.45 mm. This can be explained by the high value of the heavy particle conductivity for the conditions of this plasma.

![Graphical representation of $T_g$ variation with radial position for different microwave powers and gas flows.](image)

**Fig. 5:** Radial distribution of $T_g$ for varying **a)** microwave power and **b)** gas flow.

$T_g$ values are only given for radial positions starting far from the axis (0.4 mm). The reason for this is that the calculation of this plasma parameter has been performed using N$_2^+$ lines, a substance present in the surrounding air that enters the plasma. At the tip of the nozzle only the outer layers of the flame are mixed with air, while at the top of the plasma turbulence makes air enter the centre. So weak emission intensity comes from the axis in the lower plasma zone, and no results can be obtained in the center on these conditions. However, some measurements have been performed introducing small samples of N$_2$ in the plasma flow, showing a constant value of the gas temperature also near the axis, so it can be concluded that the gas temperature is almost constant for every radial position.

**References**