Spectroscopic investigation of a plasma jet ignitor

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Abstract

This paper presents a spectroscopic investigation of a low energy plasma igniter. This device makes it possible to produce 10 to 100 mg of high temperature gaseous mixture that can reach several kKelvin, using only 1 or 2 kJ of electrical energy. A first approach using the spectroscopic measurements is presented in order to assess the temperature and the electron density produced by the device. The spectroscopic investigation is performed using copper and hydrogen lines with time-resolved data sampling (Princeton Instruments optical multichannel analyzer).

1 Introduction

Electrothermal (ET) and electromagnetic (EM) launchers are of interest due to their capacity to launch projectiles at hypersonic velocities. During the last decade or so, considerable effort has been made in the study of this kind of launcher and of capillary discharge. The electrothermal chemical (ETC) gun can be considered as a hybrid launcher, which combines chemical energy from a solid propellant and limited electrical energy that creates a plasma jet. The use of a plasma source as an igniter in a gun combustion chamber has shown a substantial advantage of solid propellant burn rate enhancement [1]. A powerful electrical discharge inside a capillary causes the ablation of an organic material. Further heat transfer induces a process of depolymerization and dissociation of this material and then creates a plasma. Due to the high plasma density and the high pressure obtained during the discharge, temperature and species density are difficult to measure. The diagnostic techniques used in this work is emission spectroscopy.

2 Electrical device & Micro-torch design

Capacitor banks are commonly used in plasma discharge physics with energy ranging from a few kJ to a few MJ. Intermediate and low energy banks (1.5 kJ) have been applied to numerous industrial and research processes including exploding wires, microplasma torches and low power...
electrothermal launchers. The micro-torch system has been designed by GIAT Industries. Scaling of the micro-torch has been made according to similar systems operating with higher energy values. The micro-torch design is described in the paper "Plasma material interaction: ablation rates", presented in this symposium.

3 Set-up for spectroscopic investigation

Spectroscopic data are acquired using a Chromexmonochromator of the Ébert-Fastié type, with focal length of 0.5 m. It has a 1200 grooves/mm grating working in the first order. Photodetection is accomplished with a Princeton Applied Physics OMA equipped with a CCD matrix array having 256 rows of 1024 pixels. In the first spectroscopic order, the detector covers a spectral range of 45 nm. In order to study the evolution of a spectral area in the visible range as a function of time, the CCD array is controlled using a kinetic mode. In this mode, only a number of rows are illuminated during an exposure time $t_e$. At the end of the exposure time, these rows are shifted in the CCD array employed as a fast storage memory. The shift of each row is accomplished during a time $t_s$ depending on the kind of CCD controller. In our case, the shortest time shift available is $t_s=6 \mu$s. The number of lines illuminated is $n=2$, and the exposure time $t_e=15 \mu$s, these values have been chosen using the two criteria of a rather good time resolution, and a reasonable signal level. To summarize, data acquisition allows a spectral area to be sampled every $t_e + n \times t_s = 27 \mu$s. Since the typical time of discharge is about 600 $\mu$s, the sampling rate is sufficient to obtain a time resolution of the spectral emission of the discharge.

The transient plasma jet created by the discharge is observed side-on at the exit of the torch nozzle. An image of the plasma jet is formed with a lens (focal length of 75 mm) on the tip of a 200 $\mu$m diameter optical fiber connected on the monochromator entrance. One has to underline that the light collected by the optical fiber corresponds to an averaged value of the plasma emissivity across the torch nozzle diameter.

The OMA acquisition is triggered using a fast time response ($\approx 6 \mu$s) photodiode (Texas Instruments TSL 252) illuminated by the transient plasma jet. Wavelength calibration of the optical acquisition device is provided using mercury spectral lamps and neon lamps (for Hg study). Special care has been taken concerning the spectral position of diatomic molecular emitted by the plasma jet; the Swan molecular band of C$\text{O}_2$ at 516.5 nm and the CH spectrum at 431.5 nm have been directly recorded using an oxygen+acetylen flame.

4 Results and data processing

4.1 Spectroscopic results with copper lines

In all experimental spectra, emission lines of neutral copper are always predominant, and may be used to obtain a temperature value. Figure 1 shows a typical spectral region with CuI lines and its evolution as a function of time. At the beginning of the discharge, it is obvious that the CuI lines at 513.5 nm and at 521.8 nm present a typical self-absorption shape and, consequently
their overall intensity cannot be directly used to obtain a temperature value. However, this self absorption can give useful information concerning the geometry of the emitting source: one can consider a hot emitting area surrounded by a cold copper gas mainly coming from the exploded wire. When time increases, the line shapes lose their self absorption shape, meaning that the emitting area is either colder or more homogeneous or that the copper density ejected from the capillary decrease. In this case, the line intensities can be employed in a Boltzmann’s plot.

![Graph](image)

**Figure 1: Emission spectra evolution for POM material**

The relative intensity of six neutral copper lines in the spectral range [500 — — — 580 nm] is commonly used to estimate the temperature in a capillary discharge with a copper wire [2]. Four of these lines can be observed in our spectra: 510.5 nm, 515.5 nm, 521.8 nm and 529.3 nm. The relative line intensities, when the hypothesis of local thermodynamical equilibrium is checked, verify the relation:

\[
\ln \left( \frac{I_{\lambda}}{Ag_{u}} \right) = C - \frac{E_u}{kT}
\]

where \(I\) is the relative intensity, \(\lambda\) the wavelength, \(A\) the line transition probability, \(g_u\) the statistical weight of the upper level, \(E_u\) the energy of the upper level, \(k\) the Boltzmann’s constant and \(T\) the temperature. The practical determination of the line intensities (in relative values) has been performed using a best fit procedure of experimental line shapes with a theoretical Lorentzian profiles superimposed on a parabolic underlying continuum. The transition probabilities available in the literature both arise from experimental measurements and theoretical considerations; the values presented in table 1 come from the references [3, 4, 5], and are known with a rather large associated error. Let us underline that a weak line (CuI — 522.0 nm) is located on the red wing of the CuI — 521.8 nm. Because of its physical parameters, this weak line can readily be neglected.

For the POM material, the Boltzmann’s plot give us a temperature of about 10000 K, decreasing slightly with the time to 9000 K.

As shows the figure 2, the torch emission isn’t steady. In a first step, the copper wire explodes and is ejected from the torch. The arc plasma is generated. The emission reaches a maximum
Table 1: Atomic parameters of copper lines

<table>
<thead>
<tr>
<th>λ nm</th>
<th>A (10^4 s⁻¹)</th>
<th>gυ</th>
<th>Eυ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>510.5</td>
<td>0.020</td>
<td>4</td>
<td>3.82</td>
</tr>
<tr>
<td>515.3</td>
<td>0.600</td>
<td>4</td>
<td>6.19</td>
</tr>
<tr>
<td>521.8</td>
<td>0.750</td>
<td>6</td>
<td>6.19</td>
</tr>
<tr>
<td>529.3</td>
<td>0.109</td>
<td>4</td>
<td>7.74</td>
</tr>
</tbody>
</table>

Figure 2. Time evolution of spectroscopic emission from 505 nm to 540 nm for 735 J pulse discharge

very rapidly. Afterward, the spectral emission drops slowly to approach a relative long afterglow at approximately 10% of the maximum value. The peak current intensity and the maximum spectral emission appear at the same time.

4.2 Spectroscopic results with Hα line

The time resolved emission spectroscopy has been used to study the electron densities obtained in the microtorch plasma jet. The Hα line is easily observed in the optical emission. The electron temperature were inferred before from Boltzmann plots of the copper emission lines. Electron density nₑ is measured from Stark broadened Hα emission lines. In the range from nₑ = 10¹³ to 10²⁶ e/cm³ the different theories (Kepple-Griem [6], Sholin-Dmura-Liatsa or Ispolatov-Oks [7]) are very close.

Experimental line profiles are successfully fitted with a theoretical Lorentzian profiles, in order to determine the full widths at half maximum. Since the full width half maximum of hydrogen
Table 2: Time varying electron number

<table>
<thead>
<tr>
<th>times (μs)</th>
<th>FWHM in nm</th>
<th>n_e min in e/cm³</th>
<th>n_e max</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>8.66</td>
<td>2.66 \times 10^{18}</td>
<td>2.42 \times 10^{18}</td>
</tr>
<tr>
<td>162</td>
<td>8.62</td>
<td>2.64 \times 10^{18}</td>
<td>2.41 \times 10^{18}</td>
</tr>
<tr>
<td>270</td>
<td>8.87</td>
<td>2.75 \times 10^{18}</td>
<td>2.51 \times 10^{18}</td>
</tr>
<tr>
<td>540</td>
<td>11.48</td>
<td>4.05 \times 10^{18}</td>
<td>3.70 \times 10^{18}</td>
</tr>
<tr>
<td>810</td>
<td>10.45</td>
<td>3.52 \times 10^{18}</td>
<td>3.21 \times 10^{18}</td>
</tr>
<tr>
<td>1080</td>
<td>9.70</td>
<td>3.15 \times 10^{18}</td>
<td>2.87 \times 10^{18}</td>
</tr>
<tr>
<td>1350</td>
<td>8.20</td>
<td>2.45 \times 10^{18}</td>
<td>2.23 \times 10^{18}</td>
</tr>
</tbody>
</table>

lines varies, to a approximation, as n_e^{2/3} and only weakly with the temperature. Hα spectral-width observations provide measures of the electron density. As presented in the figure 3, Hα line reaches a maximum very rapidly. Afterward, the spectral emission drops slowly to approach a relative long afterglow. At the beginning, the density is steady. The density level is high

\[ (> 10^{18} \text{ cm}^{-3}) \]. The ablation of polymer in the micro-torch carries new molecules which are dissociated and ionized. Then the density increases. The electron density variation as a function of time is given for POM material in table 2.

5 Conclusion

In this experimental study, the time evolution of the emission spectra in a micro-torch plasma jet is presented. All spectra are dominated by the presence of the strong emission lines of the neutral
copper coming mainly from the copper wire employed to start the discharge. The presence of
diatomic molecular bands such as C$_2$ Swan bands [1] is not clearly established, mainly because
of the presence of the strong neutral copper lines that decrease the dynamic range of the optical
detector.

The temperature determination from Boltzmann plots is only available at the end of the dis-
charge, because of very strong self-absorption of copper lines at the beginning of the discharge.
This self-absorption decreases with time. The reasons of self-absorption are many and should be
deeply studied. For H$_{\alpha}$ emission line, doesn’t seem to be affected by self-absorption.

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