Optical emission spectroscopy diagnostic of air-plasma produced by a double spark-plug

D. Astanei[1,2], S. Pellerin[1], B. Hnatiuc[3], F. Faubert[1], E. Hnatiuc[2],

[1] *Orleans University /CNRS , GREMI Laboratory – Site of Bourges*
[2] *"Gheorghe Asachi" Technical University of Iași, Faculty of Electrical Engineering*
[3] *Maritime University of Constanța*

The aims of this paper are to present a diagnostic of plasma produced by a new type of spark-plug for internal combustion engines (ICE) using optical emission spectroscopy techniques. In order to optimize the ignition system geometry and control strategy, next to the discharge electrical parameters evaluation and the tests on real engines, the plasma characterization considering the physical properties is required. The analyses were performed for the discharge produced in air, for values of the discharge energy from 20 up 140 mJ and for different values of gas pressures. Using classical methods applied on emission spectra we have determined the plasma temperatures (rotational, vibrational and excitation) as well as the electron density. The results are shown as function of energy consumed, gas pressure and are compared with the ones obtained for the plasma produces by a conventional spark-plug.

1. Introduction

The ignition of the air/fuel mixture into the combustion chamber of the internal combustion engines requires a repeatedly and steady spark discharge produced by a spark plug. The spark should have the largest possible volume and the energy used to supply it should be as high as possible. These are the minimum conditions necessary in order to increase the engine power.

Considering the benefits that can be obtained by using an improved ignition system, and based on the principles previously presented, we designed, manufactured and tested in real conditions, [1], a plasma based ignition system for ICE that increases the volume of plasma (and consequently the interaction surface between the plasma and the mixture) and discharge electrical power, so to encourage the speed and the quality of the combustion initiation. This new spark plug consists into a double spark system, with three electrodes, which produces two simultaneous sparks generated by a pulsed high voltage power supply.

The double spark plug was obtained from a conventional one, by slicing the hook (ground electrode) and a part of the thread and placing a third electrode with floating potential on the ceramic insulator, between the high voltage and ground electrodes, [2]. Using this configuration we obtain two discharges with a total length of around 5.8 mm and a volume of 2.3 mm^3, more than double than in the case of a conventional spark plug were the plasma volume is less than 1 mm^3. In Fig 1, the geometrical dimensions of the plasma channel produced by the double and by conventional spark plugs are presented. The images were recorded using a high speed camera for the discharges produced in air, pressure 3 bar.

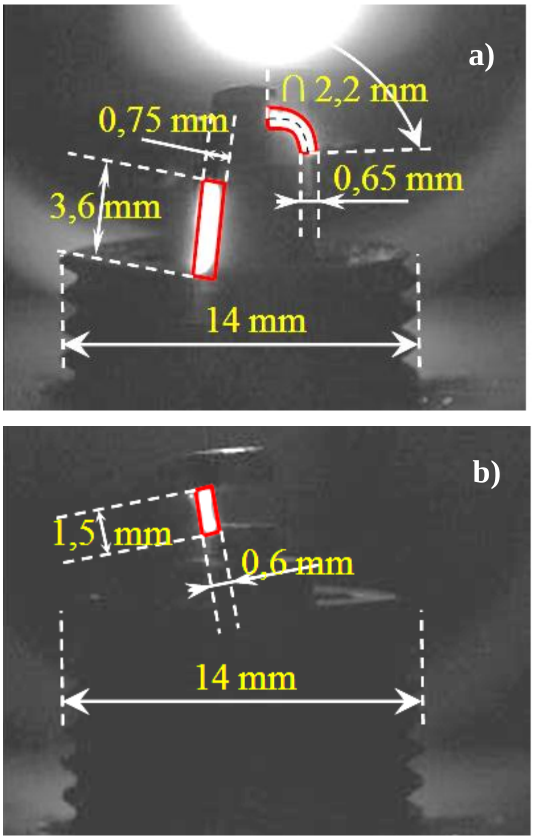

Fig. 1. Geometrical dimensions of the plasma channel: a) double spark plug; b) conventional spark plug (10000 fps, 100 μs exposure time).

The plasma diagnostic was performed in order to be able to find the optimal conditions (spark plug shape and dimensions, electrical supply) for triggering the combustion inside the ICE combustion chamber.

2. Spectra recording

The spectra were recorded for plasma produced inside a test reactor, in air at different pressures (1 bar, 2 bar and 3 bar), for different values of the discharge energy and for different regions of the plasma generation. The experimental setup used to record the spectra consists of a spectrometer ACTON 750i of ROPER SCIENTIFICS (movable tower with 3 gratings: 1200, 2400 and 3600 gr/mm, focal length of 750 mm, resolution less than 0.1 nm) equipped with a two-dimensional intensified charge-coupled device (iCCD) camera (512 × 512 pixels). The plasma image was directly focused on the entrance slit of the spectrometer (set to 20 μm) through a quartz lens (focal length f = 15 cm). The exposition time was adjustable from 2 to 5.6 ms in order to record the spectra corresponding to the entire lifetime of the discharge and was separately chosen for different control pulses used, [3]. The spectra are side-on recorded, providing data easier to be processed, which allowed temporal studies of the plasma with a precise diagnosis, associated with different operating modes. The Abel inversion performed on the recorded frames for setting the zero order of the spectrometer has proved that the plasma channel has a cylindrical symmetry and recording the spectra from one side is enough for the plasma analysis using optical emission spectroscopy methods.

The spectra were recording using step-and-glue method in the range of wavelengths from 200 to 550 nm. An example of typical recorded spectra is shown in Fig. 2.

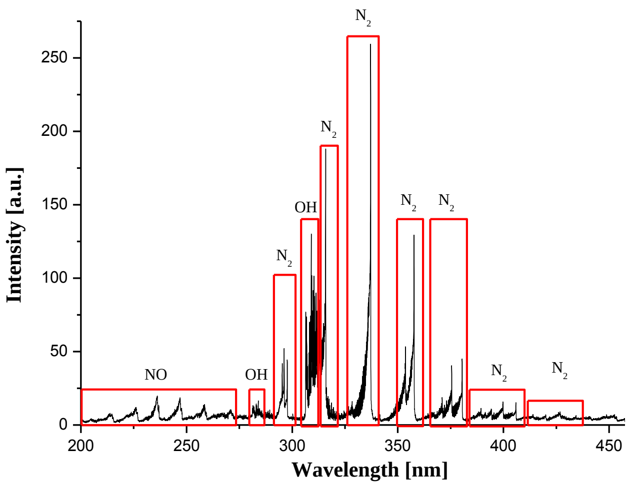

Fig. 2. Typical example of recorded spectrum and identification of the observed molecular bands.

In addition, the UV spectrum of molecular OH 306.357 nm was recorded separately as well as the spectra corresponding to the hydrogen lines of the Balmer series in order to obtain a better resolution to calculate the rotational temperatures and the electronic densities, respectively.

3. Methods used for analysis and results overview

Based on the recorded spectra we have identified the major molecular bands presented in the spectra (NO, OH and N_2) and the atomic lines (Fe I, W I, Cr I and O I) and using appropriate methods we have evaluated the rotational, vibrational and excitation temperatures, as well as the electron density.

The rotational temperature (T_r) was determined using a method based on a comparison between theoretical and experimental emission spectra of UV OH band spectrum at 306.357 nm, by identifying the apparatus function of the optical device, [2], [4].

The values obtained for the rotational temperatures are in the range of 2700 to 3500 K at atmospheric pressure both for using the conventional and double spark plugs, being slightly higher in the first case for the same values of the discharge energy. For the double spark plug the highest values of the rotational temperature were obtained in the vicinity (upper side) of the floating potential electrode. T_r values are increasing with the increase of the energy delivered to the discharge and decreasing with the gas pressure as can be observed in Fig. 3.

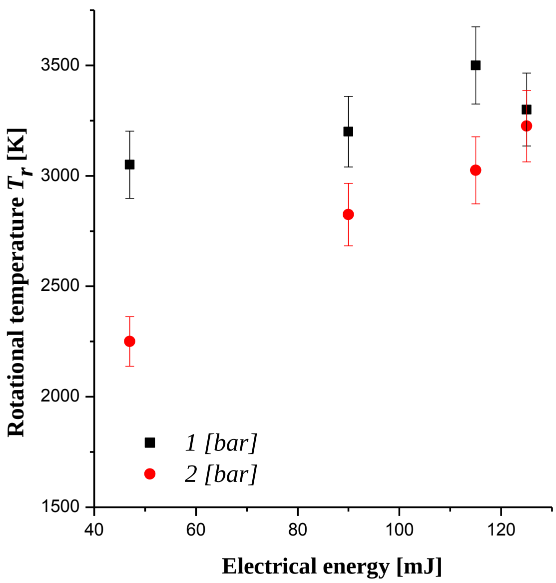

Fig. 3. T_r versus discharge energy – double spark plug, gas pressure of 1 and 2 bar.

The vibrational temperature (T_v) is calculated applying a method based on the second positive system of N_2, using the Boltzmann's plot, [3], [5], [6]. Seven different N_2 transitions (head bands: 350.05, 353.67, 357.69, 367.19, 371.05, 375.56, 380.49 nm) between the electronic levels $C^3\Pi_u$ and $B^3\Pi_g$ – 11.1 eV and 7.39 eV, respectively have been considered.

The T_v values are higher in the case of the double spark plug compared with the conventional one, being strongly dependent on the discharge energy. The results obtained are in the range of 2500 to 6000 K, as can be observed in Fig. 4.

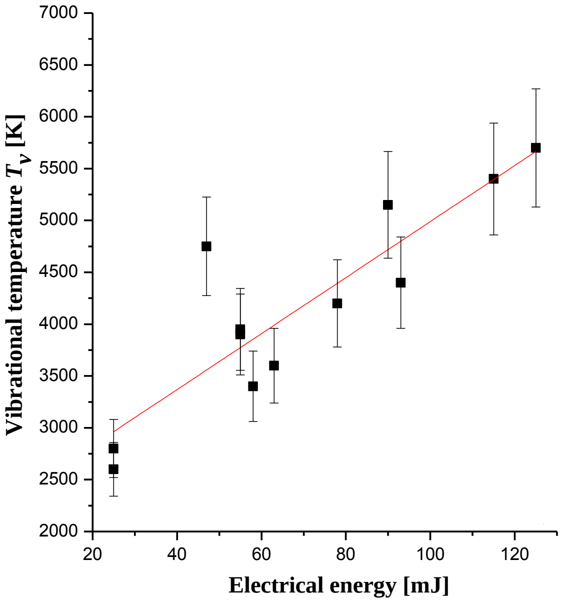

Fig. 4. T_v versus discharge energy – double spark plug, atmospheric pressure.

The electronic temperature was evaluated by classical approach (Boltzmann's plot) and verified through simulation using SPECAIR software. The results obtained are in the range of 9000 to 10000 K and did not envisage considerable differences between the plasma produced by the two spark plugs studied (double and conventional).

The electronic density was determined using the H_α line (656.3 nm) of Balmer series by estimating the Stark broadening, [7], [8]. The emission spectra have been recorded for the plasma generated in an air, Ar, H_2 mixture (60%, 36% and 4% by volume). This mixture has been considered because in the case of spectra recorded for the plasma produced in air, the Balmer hydrogen lines are not enough intense and defined to be used. In the case of the conventional spark plug the electron density has values of around 6 *x* 10^{15} e^-/cm^3 and they are not influenced by the discharge energy. In the case of the double spark plug, the plasma has higher values of the electronic density in the vicinity of the floating potential electrode of around 10^{16} e^-/cm^3.

4. Conclusions

The experimental tests and analyses have proved that the proposed ignition system can assure a more than double volume of plasma with temperatures in the same ranges, compared with a conventional spark plug.

Rotational and vibrational temperatures values of the plasma produced by both the studied spark plugs (conventional and double) are in the range of 2700 to 3500 K and 2500 to 6000 K, respectively and are strongly depending on the discharge energy, increasing with the increase of the energy.

The electronic temperature has values in the range of 9000 to 10000 K, while the highest value of the electronic density of 1.43 *x* 10^{16} e^-/cm^3 was determined in the case of the double spark plug.

The results obtained from plasma diagnostic using optical emission spectroscopy methods, correlated with the ones obtained from testing the double spark plug in real conditions (implementing the spark plug on ICEs) and following the engine performances can help us to determine which are the physical parameters of the plasma that are important for combustion initiation and how to adjust them.

5. References

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