PLASMA VOLUME AND ENERGY INFLUENCES ON THE COMBUSTION EFFICIENCY USING A NEW SPARK-PLUG

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ABSTRACT

The aim of this paper is to present a comparison between a modified ignition system, based on a double spark plug, and a classical one in terms of the exhaust gases composition. The unburned hydrocarbons evacuated by a one-cylinder gasoline engine after the combustion was investigated using gas chromatography-mass spectrometry (GC-MS). A directly sampling method called *solid phase microextraction* (SPME) has been used to collect the organic molecules. The results obtained were also correlated with the values of the electrical energy supplied to the discharge.

1. INTRODUCTION

To ignite the air/fuel mixture into the combustion chamber of a thermal engine it is necessary that an electrical discharge (spark) is ignited between the electrodes of a spark-plug. The combustion evolution is depending on the interaction between the combustion flame and the mixture. However, the plasma produced by a classical spark plug, which has a relatively small volume (~1 mm^3) and remains highly localized, is not always assuring a complete combustion of the mixture of hydrocarbons and air into the combustion chamber.

During the combustion process, the hydrocarbons molecules from gasoline are reacting with oxygen molecules from air and form carbon dioxide and water, when the stoichiometry condition is fulfilled – a ratio of 14.6 kg of air for each kg of gasoline, in the case of the gasoline having the octane rating of 95. As the air/fuel mixture is usually far from fulfilling the stoichiometric condition, after the combustion poisonous gases are released into atmosphere such carbon monoxide (CO), nitrogen and sulphur oxides (NO_x and SO_x), and also volatile organic compounds – usually unburned hydrocarbons (UHC), [1]. Some of the UHC can react with the UV from sunlight and with NO_x to produce ground level ozone which can cause after long exposure some tissue and lung damages. Also, the acute inhalation could cause eyes, throat or nose irritations, [2].

To increase the power of the internal combustion engines (ICE) and to lower the quantity of UHC emitted, it is required to obtain for each cycle a fast and complete combustion of the mixture which also involves providing the maximum quantity of electrical energy to the spark. To be able to "facilitate" and to "speed" the combustion process, it also is necessary to have an ignition spark which provides a higher and more homogenous volume of plasma to increase the contact surface between the plasma and the air/fuel mixture [3 - 5].

Based on the assumptions above we have proposed a new ignition system based on a modified spark-plug having three electrodes (high voltage electrode, *1*, ground electrode, *3*, and a floating potential electrode, *2*, placed between the first ones) which can be adapted to all types of internal combustion engine without requiring any other modifications, *Fig. 1*, [6]. The double spark plug was built from a classical spark plug by slicing a part from the ground electrode (the screw), cutting a small channel into the ceramic insulator, *4*, and placing into it a washer shaped electrode. The system can deliver two quasi-simultaneous discharges having a cumulated plasma volume of up to over 2 mm^3 (more than double than the volume of plasma produced by a classical spark-plug) using the same amount of electrical energy that used to supply a discharge produced with a classical ignition system.

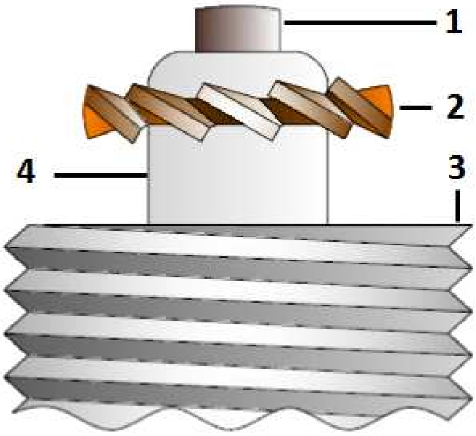

Fig. 1 Double spark plug diagram.

The proposed ignition system has been mounted and tested on a four stroke one-cylinder petrol engine. The exhaust gases resulted after the combustion have been investigated by performing gas chromatography analyses and by using a wide band lambda probe. To run the chromatography test an extraction technique called Solid Phase Microextraction (SPME) has been used, in which the organic molecules (unburned hydrocarbons) are adsorbed onto a fused-silica fiber. For this study only the molecule identification and the analysis of increasing peak area between different chromatograms (for different ignition parameters) was considered. Because the purpose of this study was to compare the two ignition systems (based on a classical and on a double spark plug) a quantitative analysis of the exhaust gases was not required.

2. EXPERIMENTAL PROCEDURE

The ICE used to run the tests is a Honda GX31 engine: four-stroke, overhead valve, single cylinder. The engine displacement (bore $\times$ stroke) is 31 cm^3 (3.9×2.6 cm) and can produce a maximum output power of 1.1 kW at 7000 rpm and a max torque of 1.64 Nm at 5400 rpm. The firing angle and the fuel injection system are electronically controlled. During the tests, both the firing angle and the quantity of the gasoline injected into the combustion chamber were kept constant, 13^0 before top dead center (TDC) for the firing angle and a gasoline consumption of 2.2 ml/min. The engine speed was around 2000 rpm, the engine being loaded using a DC generator connected through a belt to the engine which is imposing a resistant power of 100 W.

Two different values for the electrical energy consumed by the discharge have been chosen for the study, 35 and 100 mJ, which correspond to a width of the control pulses used to command the ignition coil of 1.5 and 3 ms, respectively. The energy transferred to the air/fuel mixture is much less than the consumed energy due to the limited energetic efficiency of the spark ignition systems, [7], [8].

The chromatography analysis was carried out using an *Agilent Technologies* GC-MS system (*6850 Network GC* system coupled with *5973 Network Mass Selective Detector).* The SPME sampling method was chosen for the tests due to its capability to generate chromatograms easier to integrate than the ones produced by using classical methods such charcoal tubes method. Also the sample could be preserved for considerable periods of time before running the GC-MS analysis [9, 10].

To absorb the organic molecules from the exhaust gases a non-polar fiber of Polydimethylsiloxane – 100 μm (PDMS) has been used, placed into a SPME holher for manual sampling. The fiber can retain analytes having the molecular weight between 70 and 320 [11]. The SPME holder has been positioned in front of the ICE exhaust pipe on axial direction, with the exposed fiber placed in the middle of the muffler (Fig. 2). The gases temperature was measured using a thermocouple positioned in holder's place and it was far lower than the maximum utilisation temperature for the PDMS fibre – 280^0C.

The considered absorption time was 4 min and it was established as being the fiber saturation limit for this application. In order to obtain a good resolution, during the tests the parameters which can influence the results have been kept constant: air/fuel mixture richness, engine temperature, engine speed and load, extraction and desorption times and even the period of time between two consecutive experiments.

Fig. 2 SPME holder image captured during the extractive procedure.

The working richness of the air/fuel mixture was $r = 1.05$ and was measured using a Rotronics CMR 101 air/fuel acquisition system equipped with a wide band lambda probe. The high richness values have been preferred for the tests to be able to detect easier the differences between the performances of the two ignition systems studied. For further studies lower richness values will be considered.

After the absorption process, the fiber was manually placed into the GC oven for 5 minutes. The oven is kept for 4 minutes at the initial temperature of 40^0C and is further gradually heated up to 300^0C with a gradient of 10^0C/min. The molecules released into the oven are sent into the GC column (30 m long, 250 µm in diameter). The carrier gas used is He and is having an initial flow rate of 1 ml/min. After they are split into the column, the molecules arrive into the mass spectrometer were they can be identified based on their molecular weight. The GC-MS system used in this study can detect analytes between the limits of the molecular weight from 10 up to 250.

3. RESULTS

Based on the obtained chromatograms (Fig. 3) more than 55 molecules have been identified, from a total of over 200 present. The identified hydrocarbons are commonly founded into the ICE exhaust gases (see [12]). The most common volatile organic compounds identified are: aromatic derivatives of benzene (e.g. 1,2,3-trimethylbenzene, 1-ethyl-2,3-dimethyl-benzene etc.), oxidized derivatives of benzene (e.g. benzoic acid) and polycyclic aromatic hydrocarbons (isomers such naphthalene).

For this study, seven molecules which appear on the chromatograms have been taken into consideration to compare the two ignition systems efficiency. Table 1 shows the selected molecules and the standard deviation determined for 6 consecutive chromatograms corresponding to the utilisation of the classical spark plug for a discharge energy of 35 mJ.

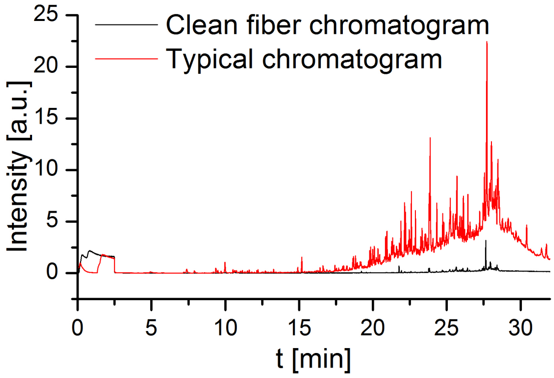

Fig.3 Typical example of obtained chromatogram.

The molecules have been chosen by taking into account their position on the chromatograms and especially a well-defined corresponding peak, important aspect in the integration process.

Table1. The selected molecules.

Compound	Chemical formula	ε [%]
Nonadecane	$C_{19}H_{40}$	15
9H-fluorene, 9 methylene	$C_{14}H_{10}$	5
Dibutylphtalate	$C_{16}H_{22}O_4$	20
Fluoranthene	$C_{16}H_{10}$	9
Oxalic acid, 2-ethylhexyl ester tridecyl	$C_{23}H_{44}O_4$	11
Hexanedioic acid, bis (2-ethylhexyl) ester	$C_{22}H_{44}O_4$	10
1,2-Benzenedi-carboxylic acid, mono (2-ethylhexyl) ester	$C_{16}H_{22}O_4$	12

The peak surfaces corresponding to the molecules (proportional with the quantity of the given molecule) determined on the chromatograms corresponding to the utilisation of the double spark plug (35 and 100 mJ/discharge) have been compared with the ones from chromatograms obtained from using of a classical spark plug and the energy of 35 mJ/discharge. In order to achieve the comparison, a *reduction factor*, σ, has been considered:

$$\sigma = \left(1 - \frac{A_c}{A_d}\right) \cdot 100 \quad [\%] \qquad (1)$$

where A_c is the peak area corresponding to the classical spark plug and A_d is the peak area corresponding to the double spark plug. The results obtained are shown in Fig. 4.

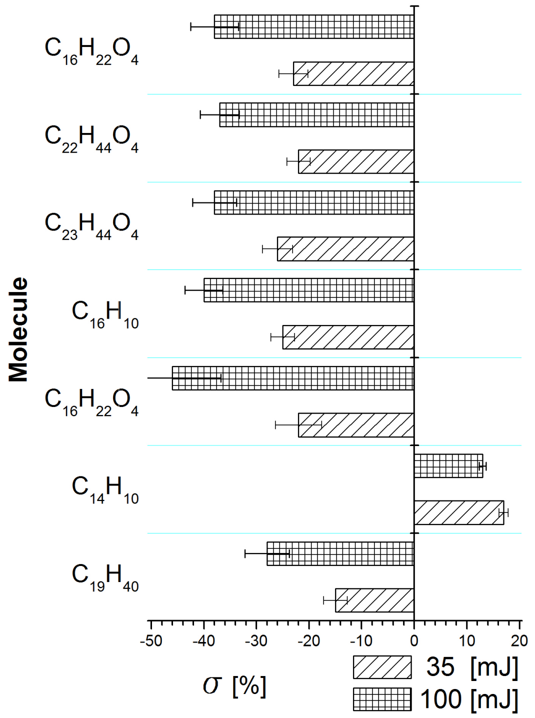

Fig.4 The unburned hydrocarbons reduction factor using the double spark plug for using - 35 mJ and - 100 mJ.

As can be observed in the figure above, by replacing the classical spark plug with a modified one and using the same amount of electrical energy (35 mJ) we can easily obtain a quantitative diminution of some unburned hydrocarbon molecules. This effect can be enhanced by delivering a higher quantity of energy to the discharge (higher values of the plasma temperatures). In the case of the selected molecules only for *9H-fluorene, 9 methylene* we can observe an increasing amount of molecules.

4. CONCLUSIONS

The chromatography tests have shown that the increased volume of plasma given by the double spark plug could assure a better combustion – less unburned hydrocarbons in the exhaust gases. An increased effect of the modified ignition system could be achieved by providing more energy to the discharge. The SPME method provided chromatograms having repeatability within reasonable limits (less than 12% the ICE working parameters are kept steady). This preliminary study will be completed with further tests for which a SPME fiber designed to absorb smaller molecules will be used, the richness of the air/fuel mixture will be varied and the other pollutants from the exhaust will be considered.

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