



Full Length Article

Identification of combustion and detonation in spark ignition engines using ion current signal



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ARTICLE INFO

Keywords:

Ion current
Internal combustion engine
Spark ignition
Knock sensor

ABSTRACT

The identification of combustion and detonation in spark ignition (SI) engines is very important to its control within optimized and efficient boundaries. While they are generally identified respectively by phase and knock sensors, this investigation provides additional evidences that the ion current could be used as a sensing device to replace those two sensors, in order to identify both phenomena. The cylinder under combustion could be determined with the ion current signal, by sampling and computing the area under the signal curve. In order to monitor detonation, the correlation between the energy of a frequency band of the ion current signal and the energy of the knock sensor signal was established. The results indicated the viability to use the ion current to detect combustion and detonation in several situations, such as variations in the fuel mixture, mileage of the spark plug, and area size of the spark plug electrode.

1. Introduction

Over the last decade, automakers have been incorporating new technologies on automobiles, providing better performance, energy efficiency, low pollutants, safety, and comfort. In order to increase energy efficiency and address current international legislations, new control strategies for SI engines must be developed, which require new types of sensors [1,2]. Therefore, it is important to develop new and reliable sensors that could provide better engine diagnostics and identify several important phenomena [3]. For example, detonation could be identified by measuring pressure variations inside the combustion chamber, using a piezoelectric or an optical sensor installed inside the combustion chamber. Alternatively, it could be identified by measuring the ionization of the air/fuel mixture, also labelled as the ion current [4].

Although, an ion current sensor still presents technical challenges that prevent its commercial use, it carries a number of potential applications in automotive industry. This investigation demonstrates the feasibility of using the ion current measurement in an SI engine mounted on a real car, with the specific goal to identify the cylinder that is in combustion and the detonation phenomenon, thus replacing the functionalities of the phase and knock sensors.

Initially, we identified the variables that influence the ion current signal behavior. Then, we computed the area under that signal curve of this current, and correlated this data to the occurrence of combustion. In order to identify detonation, the harmonics of the ion current signal were analyzed and compared with the signals of the knock sensor. The results have shown the conditions in which it is possible to use the ion current sensor to identify combustion and detonation. Those results indicated that it is possible to use the ion current to replace the phase sensor signal, opening opportunities for new applications, such as identification of bad burning (misfire) and the re-ignition of the mixture that did not burn completely in previous cycles during engine operation.

This investigation is presented as follows: Sections 2 and 3 present an overview on recent results associated with the ion current. Section 4 shows the parameters that influence the ion current signal. Section 5 describes the sensors and data acquisition platform. Section 6 shows how the cylinder under combustion can be identified using the ion current signal, while Section 7 shows how to identify detonation with that signal, Section 8 presents an analysis of the results and, finally, Section 9 presents some concluding remarks.

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<https://doi.org/10.1016/j.fuel.2018.04.080>

Received 10 February 2018; Received in revised form 14 April 2018; Accepted 16 April 2018
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2. Review

This section presented a brief review on recent investigations on the ion current in SI engine. The new Ion Current Combustion Control System (ICCS), which can control individual cylinder air fuel ratio and ignition timing, has been recently studied [5]. It has been shown that significant performance improvements could be obtained by adapting this system to a small displacement 3-cylinder engine. The characteristics of this system are: (1) to simplify the system architecture, the ignition plug was used to detect the ion current, while part of the accumulated energy from the ignition coil was used as the bias power supply; (2) to improve the performance for detecting the ion current, the center electrode of the ignition plug was used as the positive pole of the bias power; (3) to overcome the low repeatability of the ion current magnitude, new control variables were introduced for the combustion control; (4) for the air/fuel ratio control, the variation rate of the ion current duration was used; and (5) for knocking control, the variation rates of the ion current, filtered through the frequency band corresponding to knocking, were used.

The gasoline direct injection (GDI) technology has been explored to improve fuel efficiency for spark ignition (SI) engines [6]. The Homogeneous Charge Compression Ignition (HCCI) combustion has the advantages of low fuel consumption and ultra-low NO_x emissions. However, the difficulty in the auto ignition control and the narrow operation region inhibit the practical application of this technology. A hybrid combustion mode, which combines SI and HCCI modes in separated working regions, has been considered as a promising technology for those engines. Additionally, monitoring and providing feedback to the in-cylinder combustion module was found effective to improve and optimize the combustion process. The ion current generated by the in-cylinder combustion carries information that could be used in this combustion feedback. A strategy used in the SI/HCCI combustion mode switch based on ion current was established and experimented on a GDI-HCCI engine assisted by negative valve overlap. During the combustion mode switch process, by adjusting the key factors within switching, such as injection mass, injection timing and throttle opening, the process could be optimized.

Using two numerical models, a recent investigation explored the fundamental processes affecting the phase difference (P_Δ) between Ion_{50} (the crank angle position for the maximum ion current increasing rate) and CA_{50} (crank angle position for 50% burned mass fraction) [7]. A model was used to explore fluid dynamic effects on HCCI engine, while another model was used to explore the mechanisms of P_Δ . The numerical analysis and the experimental results indicated that the ionization process is affected by both flame ionization and fuel heat release. The phase relationship between the ion current signal and combustion phase in HCCI engine, especially the phase difference between CA_{50} and $P_\Delta \text{Ion}_{50}$, was explored.

By analyzing the mechanism that affects P_Δ , three main conclusions were drawn: (1) in HCCI engines, the ion production rate is primarily controlled by the temperature within the cylinder; (2) the change of angle (Φ) equivalence relation affects the P_Δ phase; (3) for hydrocarbon fuel with lower octane value, a higher compression rate and a lower temperature are usually applied in HCCI combustion mode, resulting in a very low ion concentration.

Considering a high exhaust gas recirculation (EGR) rate, the low temperature combustion (LTC) has been explored [8]. The LTC has an application range wider than the HCCI and premixed charge compression ignition (PCCI). Since the high EGR rate influences the condition of intake charge, it would also affect the combustion process and the HC emissions, thus the combustion stability of LTC would be lower than the traditional diesel combustion. The ion current was measured at different EGR rates, along with the combustion parameters, which included the in-cylinder pressure and heat release rate. The CA_{50} and CA_{150} (integrated ion current) were respectively selected as the combustion and ion current phases, and their correlation was analyzed.

Finally, a closed-loop control strategy for LTC was proposed, which was based on the ion current detecting technology. The results showed that, with that control strategy, the combustion stability of LTC and power performance were improved, while the HC emissions were reduced.

Other recent investigations have explored the correlation between the ion current and the NO_x emission in controlled auto-ignition engines [9,10].

3. The ion current

An electric current occurs in solid, gaseous, and liquid phases. While in solids, the real current is associated to free electron carriers, for liquid and gaseous phases, current could be associated to positive and/or negative ions and/or free electrons. Therefore, the electric current that is established in electrolytic and gaseous conductors is labelled as ionic or ion current.

For the SI, the hydrocarbon burning is a chemical process that generates ions, and when subjected to an electric field they move, leading to a current. Since the chemical kinetic mechanisms associated to combustion in SI engines are not fully understood yet, studying the ion current associated with combustion could provide valuable information to understand them.

It is possible to measure the ion current using a spark plug as sensor, by supplying a voltage and generating an electric field inside the combustion chamber [7]. The electrodes are inserted on the ignition plug in the chamber, and a resistor is used to obtain the ion current signal, as shown in Fig. 1.

With this experimental set up, the major challenge is to extract relevant information from the ion current electric signal. In order to measure that current, some nomenclature and definitions are important:

S_{ion} : Ion current signal when the cylinder is in combustion, it is the electric current represented by the letter “I” in Fig. 1

\bar{S}_{ion} : Ion current signal when the cylinder is in admission.

U_{ion} : Inverted ion current signal when the cylinder is in combustion.

\bar{U}_{ion} : Inverted ion current signal when the cylinder is in admission.

P_{ion} : Largest value of the ion current signal when the cylinder is in combustion.

$A_{ion} = \int_{t_0}^{t_f} S_{ion} \cdot dt$: Area under the curve of the ion current signal when the cylinder is in combustion.

$\bar{A}_{ion} = \int_{t_0}^{t_f} \bar{S}_{ion} \cdot dt$: Area under the curve of the ion current signal when the cylinder is in admission.

From experimental results, the ion current has three main phases, as shown in Fig. 2. The first one (Ignition Phase) starts with the coil loading and finishes with the end of the spark. The second one (Flame-Front Phase) appears during the displacement of the flame front in the

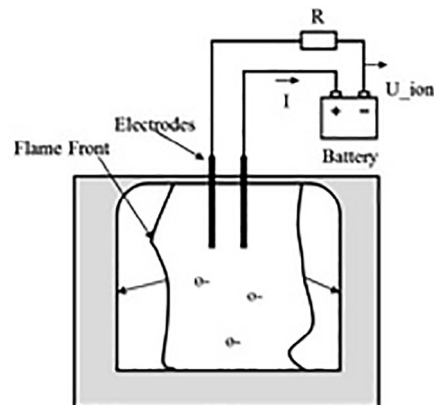


Fig. 1. A measurement schematic configuration of the ion current.

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