Combustion monitoring system on a natural gas fuelled spark ignition engine with high compression ratio using ionization current sensors

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Abstract

The control of combustion development on spark ignition engines is one of the most important international topics under research today. Engines with high compression ratios have higher thermal efficiency than their similars with low compression ratios but have bigger restrictions on cycle-to-cycle variations and knocking. The monitoring of combustion process is a tool that allows for operating these engines with safer conditions and improving their availability through time. This paper shows the implementation of a combustion monitoring system on a natural gas fuelled spark ignition engine with high compression ratio using ionization current sensors. The implemented methodology consisted of measuring chemical and thermal current ionization from natural gas combustion using the ignition spark plug. The experiments were performed at several power outputs and spark advances. The results obtained from the ionization current system was compared with combustion analysis achieved from in-cylinder pressure measurement with piezo-electric sensor (traditional measurement system). This methodology shows results consistent with those reported in the state of the art and it shown to be a reliable tool for the combustion monitoring on these kinds of engines.
Keywords: combustion engines, ionization current, high compression ratios, in-cylinder pressure, natural gas.

1 Introduction

Research efforts on internal combustion engines, during almost four decades, have been guided by requirements of improving thermal efficiency and reducing air pollution. The knowledge of combustion process is even today the most important need to achieve these goals; however, combustion represents the combination of different complicated phenomena in a very short period of time. Different techniques have been developed to extract information from combustion chamber such as laser diagnostics, in-cylinder pressure measurement, and ion-based monitoring systems. Heat Release Analysis, using in-cylinder pressure as main input, is widely used to observe how combustion develops under conditions controlled in laboratories, but this method is still very expensive to implement in engines operating at actual conditions. On the other hand, the measurement of chemical ionization and thermal ionization that are produced during combustion is a cheaper option and provides enough and detailed information as well. Ion-based method has shown to have a good potential to detect knocking and cyclic variability in spark ignited engines [1–3], estimate combustion phasing [4–6] and ringing intensity [7] in HCCI engines, and serve as input for closed-loop engine control. However, the number of ions produced is dependent on factors like fuel composition, engine design, and engine operating conditions, making research on the effectiveness of ion-based method necessary for each specific application.

Gaseous fuels exhibit low carbon-to-hydrogen ratio, hence they have the advantages of emitting lesser CO_2 and particulate matter emissions when compared with liquid fuels. Furthermore, auto-ignition temperature tends to be higher for gaseous fuels; thereby they allow for higher compression ratios. The potential of achieving high thermal efficiencies and low carbon dioxide emissions using gaseous fuels along with high compression ratios is improved when lean fuel-air mixtures are used [8]. However, ionization tends to be lowered with lower equivalence ratios [9] and consequently the implementation of ion-based method to monitor the combustion process is more difficult.

This paper presents the evaluation of a combustion monitoring system using ionization current sensors on a natural gas-fuelled spark ignition engine with high compression ratio operating at lean conditions.

2 Experimental methodology

A compression ignition engine was transformed to a spark ignition engine in order to implement a system for measuring ionization current and validate its performance with high compression ratio (15.5:1) at low equivalence ratios (lower than stoichiometric). The technical characteristics of the engine used are listed in Table 1.

The engine was coupled to an AC generator to run at 1800 rpm. Engine loads were fixed with a variable electrical resistance bank from 3 to 7 kW connected to the generator and power output was dissipated as heat. The fuel used was natural gas with a high percent of methane (97% in a volumetric basis) and the fuel flow

Table 1: Technical engine specifications.

Designation	Lister Petter TR2, two cylinders, air cooled, diesel engine transformed to spark ignition engine
Charge aspiration	Naturally aspirated
Displacement	1.55 L
Compression ratio	15.5:1
Bore x Stroke	98.42 x 101.6 mm
Distance between centers of rod	150 mm
Valves (intake, exhaust)	1.1
Rate power at 2500 rpm	17.3 Kw

rate was measured by a Coriolis sensor (MASS 2100, Siemens A.C.). Air flow rate was determined using a calibrated orifice plate.

A piezoelectric pressure sensor (Kistler 6052) and a spark plug were placed at Cylinder 1 to compare both readings, in-cylinder pressure and ionization current. The reference pressure for in-cylinder pressure traces was estimated by measuring the intake manifold pressure with a piezo-resistive pressure sensor (Kistler 4005B). Both pressure signals were connected to a Signal Conditioning Platform (SCP Kistler 2853) which contains a piezo-electric amplifier (Kistler 5064A) and a piezo-resistive amplifier (Kistler 4665B). The spark plug was used as a sensor for the ionization current system, where a bias voltage allows the ions generated during combustion for flowing through the electrodes. This flow of ions generates a current signal which can be read by the data acquisition board. The pressure traces and the ion-current signal were related with the crank angle position, which was measured by a crank angle encoder (Kistler 2614A1) with a resolution of 0.1 crank angle degrees.

All output signals (pressure, ionization current, angle encoder, etc.) are connected to a data acquisition board (NI-SCB-68) which is connected through a PCI parallel port to a computer where the acquired signals can be displayed and recorded if required for post processing. A schematic of the experimental setup is shown in Figure 1.

The experimental design on this research consisted of collecting data for 300 cycles per sample, using simultaneously both measurement systems and varying power output and spark advance. The throttle was partially opened to set the engine speed at 1800 rpm. Table 2 shows the values evaluated for each operating factor during the experiments. The experimental design was replicated twice.

3 Results

Signals obtained in data acquisition were processed in a model developed in MatLab, which allows conditioning of both signals and performing of detailed

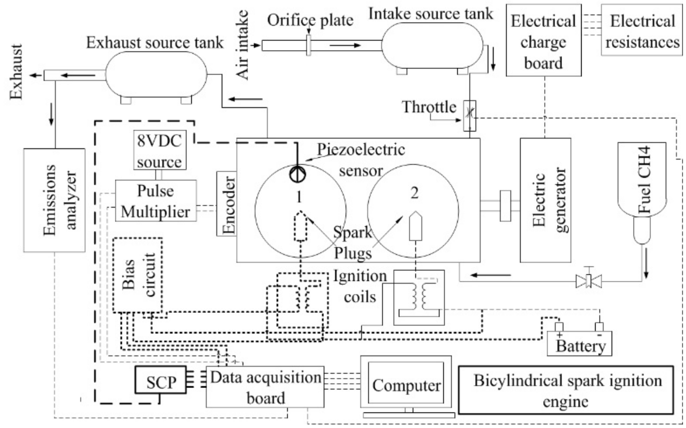

Figure 1: Schematic of the experimental setup.

Table 2: Experimental design for analyzing combustion of CH4.

Power [KW]	Spark plug advance [ºCA]	Throttle opening [%]	Engine speed [rpm]	Number of recorded cycles
3	3,6,9,12,15,18,21	18	1800 +/- 5	300
4	3,6,9,12,15,18,21	22	1800 +/- 5	300
5	3,6,9,12,15,18,21,24	25	1800 +/- 5	300
6	3,6,9,12,15,18,21	25	1800 +/- 5	300
7	3,6,9,12	29	1800 +/- 5	300

off-line analysis of samples. This was done in order to display the results more comfortably and accurately, and in turn be able to compare both signals to determine the validity of the monitoring of combustion process using ionization current sensors. The variables evaluated when comparing the in-cylinder pressure readings with ionization current readings were combustion phases and pressure peak position. Additional to this, the ignition timing using the ionization current signals was also analyzed.

3.1 Combustion analysis

Combustion in spark ignition engines is usually divided in three zones according to the cumulative heat release (CHR). First zone comprises from spark discharge to CA10 (crank angle for 10% CHR), second zone comprises from 10% CHR to 90% CHR, and the last zone comprises the remaining of combustion [10]. Analysis of ionization current and in-cylinder pressure traces allows for identification of these stages of combustion, and consequently information extracted of such analysis can be used to develop strategies to control combustion phasing, improve engine performance, and model emissions control.

Figure 2 shows an average ionization current trace measured during the experiments and divided in three differentiable zones. The corresponding in-cylinder pressure trace is also presented. In this research, the ignition spark plug is used as ion sensor, therefore, the first zone (I) represents the spark discharge duration, the second zone (II) represents the flame-front phase which reflects the early flame development in the spark gap, and the third zone (III) represents the post-flame phase which reflects the ions produced by thermal-ionization behind the flame front. By observing in detail the ionization current signals, it can be seen that the shape and combustion phases obtained are similar to those previously reported by Nielsen and Eriksson [11] and Andersson and Eriksson [12].

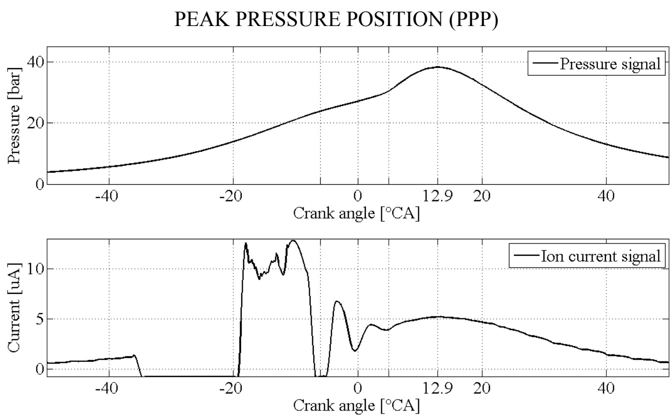

Figure 2: Identification of combustion stages from an average ionization current trace. (I) Ignition phase, (II) flame-front phase, (III) post-flame phase. Power output: 5 kW. Spark advance: 18° BTDC.

Ionization current trace in Figure 2 allows for observing two important features in combustion of spark ignition engines. Flame-front phase is characterized by a peak in ion current that is produced by chemical ionization when flame front passes over the sensor. The ions production during this state is governed by H_3O^+ ion. The post-flame phase is also characterized by a peak in ion current, but this peak is governed by NO formation during thermal-ionization. The crank angle for post-flame peak is usually the same for the peak in-cylinder pressure (as shown in Figure 2).

Combustion phases observed with ion current traces are affected by engine operating parameters. Figure 3 shows the flame-front phase and post-flame phase for power outputs of 3, 5, and 7 kW (increasing from left to right) at spark advances of 3 and 12 BTDC (Increasing from top to bottom). As can be seen in these figures, as the power output and the spark advance increases, the peak of ion current tends to be higher for both combustion phases. Richer mixtures were used when power output was augmented leading to an increase of chemical ionization during flame-front phase, mostly at 3º BTDC spark advance. Higher equivalence ratios also can lead to higher in-cylinder temperatures, which in turn increase thermal ionization. When spark was advanced combustion temperatures tended to be higher producing an increase of thermal ionization and higher peaks of ion current during post-flame phase.

Figure 4 presents in-cylinder pressure and ion current signals related with crank angle for a normal combustion cycle, and Figure 5 shows the same variables for a partial-burned cycle. It is shown that the main difference between

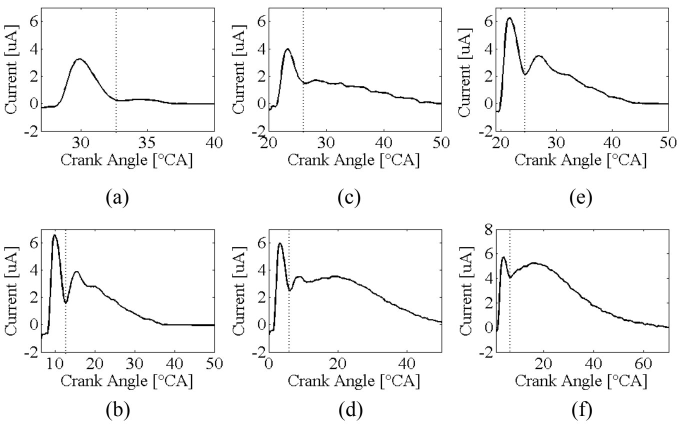

Figure 3: Flame-front phase and post-flame phase from average ionization current traces for different power outputs and spark advances. (a) 3 kW at 3º BTDC spark advance, (b) 3 kW at 12º BTDC spark advance, (c) 5 kW at 3º BTDC spark advance, (d) 5 kW at 12º BTDC spark advance, (e) 7 kW at 3º BTDC spark advance and (f) 7 kW at 12º BTDC spark advance.

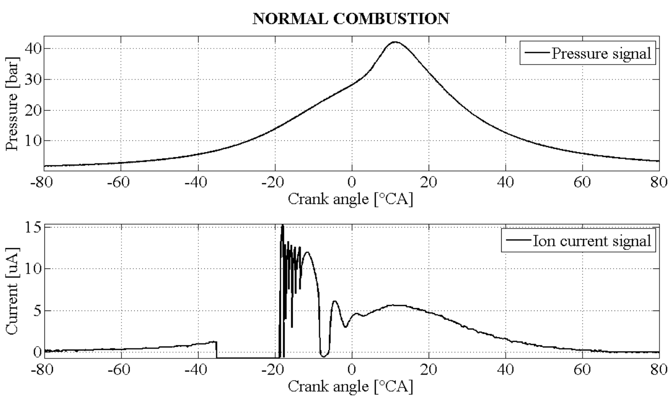

Figure 4: In-cylinder pressure and ionization current traces measured in a normal combustion cycle. Power output = 5 kW. Spark advance: 18° BTDC.

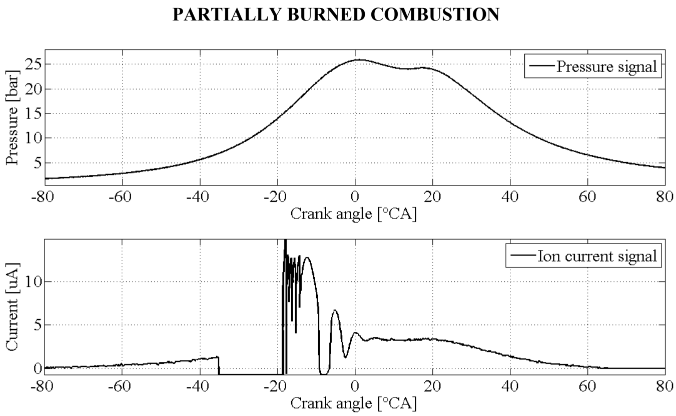

Figure 5: In-cylinder pressure and ionization current traces measured in a partially-burned cycle. Power output: 5 kW. Spark advance: 18° BTDC.

the ion-current traces of both figures is observed in the peak of the post-flame phase. Cycle-to-cycle variations on combustion process of spark ignition engines are related with partial burning which is reflected on in-cylinder pressure variations. A cycle with partial or total misfire is identified by a lower pressure peak when compared with a normal combustion cycle. This phenomenon can be detected with the ion-sense method because the time for a peak in post-flame current is usually the same for the peak in pressure trace and the ion-current peak is augmented for higher peaks of in-cylinder pressure.

The fact that peak ion-current in the post-flame phase correlates with the peak gas pressure can be used as input to control spark advance in order to achieve the maximum brake timing. A peak pressure below the maximum pressure at motored conditions represents cycles with partial or total misfire; therefore, the spark timing should be advanced to achieve normal combustion. Accordingly, a peak ion-current lower than the peak for normal combustion in the post-flame phase means that spark timing should be advanced. This statement is illustrated using Figure 6, in which the average peak ion-current in the post-flame phase and the average peak in-cylinder pressure for different power outputs have been related. The lower values of peak ion-current are achieved at lower spark advances and lower peak in-cylinder pressures for the power outputs tested. Similar results were obtained by Byttner and Holmberg [13].

3.2 Spark advance analysis

Ionization current traces allow for identifying crank angle for spark timing and how dielectric resistance of intake charge affects pre-ignition process. It can be observed in the first phase of the ion-current trace (as illustrated in Figure 2). Four ionization current curves acquired for a power output of 5 kW and different theoretical spark advances are shown in Figure 7. It can be seen that the actual spark advance occurred before the theoretical spark advance. Additionally, the

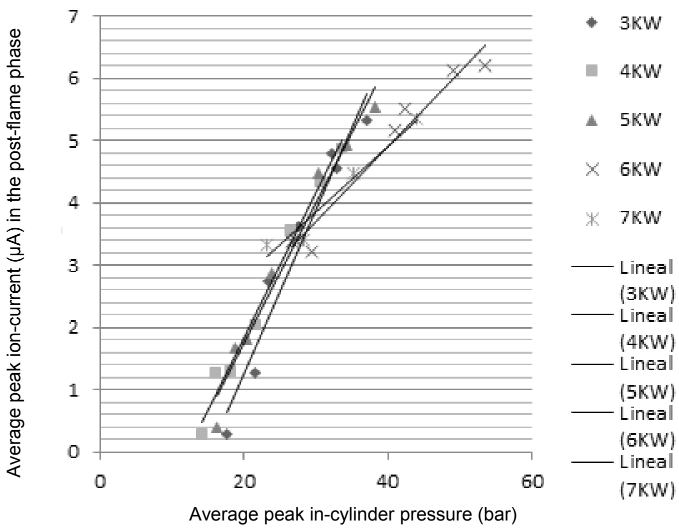

Figure 6: Average peak ion-current (µA) in the post-flame phase related to the average peak in-cylinder pressure (bar) for several power outputs and spark advances.

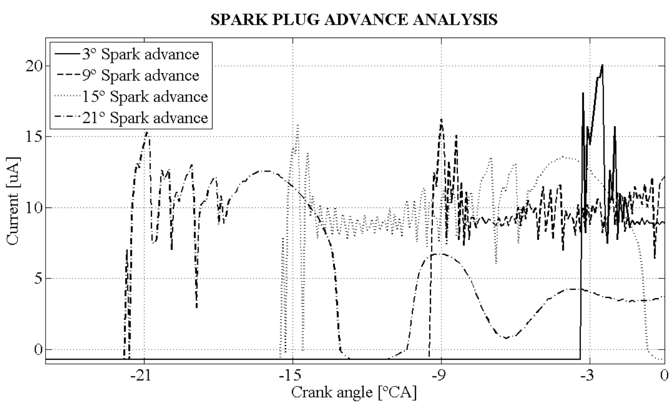

Figure 7: Measured spark advances for a power output of 5 kW and several theoretical spark advances (3, 21, 15, and 21° BTDC).

way how the current develops across the electrodes presents differences according to the spark advance.

To evaluate the precision for the measurement of the spark advance using the ionization current system, the measured value was plotted against the theoretical value in Figure 8 for all power outputs tested. The first number of each point represents the theoretical value of spark advance, the second one is the spark advance measured at 3 kW, the third one is the spark advance measured at 4 kW, the fourth one is the spark advance measured at 5 kW and the last one is the spark advance measured at 6 kW. It shows a linear regression determination coefficient of 1 for 3 kW, 4 kW and 6 kW and 0.9999 for 5 kW. This result indicates that the implemented ion-based current sensor allows identifying spark timing with high accuracy.

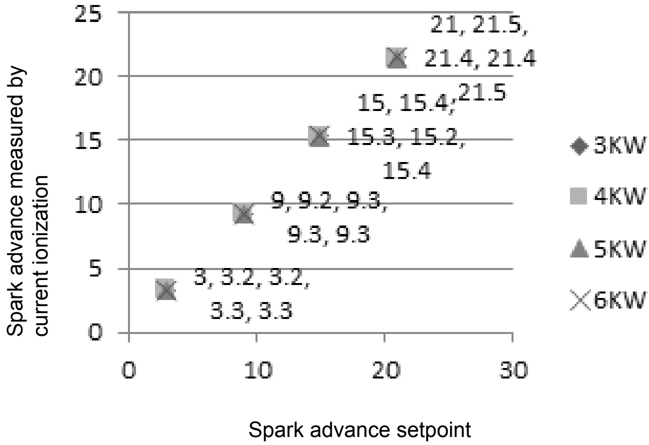

Figure 8: Measured spark advances related with theoretical spark advances for power outputs of 3, 4, 5, and 6 kW.

4 Conclusions

A combustion monitoring system using ionization current sensors was implemented on a natural gas-fuelled spark ignition engine with a compression ratio of 15.5:1. The results obtained from ionization signal were compared with the in-cylinder pressure and related with the crank angle rotation. The ion-current based system was able to identify the ignition phase, chemical ionization during the flame phase, and thermal ionization during the post-flame phase. The engine was tested using lean air-fuel mixtures at several power outputs and spark advances to evaluate the effectiveness of the ion-based monitoring system to detect normal and partial burning cycles under different operating conditions. The ion-based system was able to detect when peak current diminishes during the post-flame phase for cycles presenting partial and total misfire. Peak in-cylinder pressure and peak ion-current during the post-flame phase were related by a linear regression for all power outputs tested showing the high potential of the ion-based monitoring system to implement a combustion control when natural gas is used in spark ignited engines with high compression ratio.

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