Monitoring of the combustion process through ion current measurement in flex fuel spark ignition engines

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ABSTRACT

The aim of this work is to analyze the technique of measuring ion current through experiments as a means of monitoring the combustion process directly within the cylinder of spark ignition (SI) flex fuel engines. The quality of combustion has a direct impact on both engine performance and pollutant emissions, making monitoring of this process crucial. The spark plug was used as a sensor element in the experiments. The resulting ion current signal curve from combustion was sampled and numerically integrated, with data being validated through correlation with the pressure signal of the combustion chamber. Results demonstrated the feasibility of utilizing ion current to monitor the combustion process across varying engine operating conditions, including fluctuations in gasoline-ethanol fuel mixture, rotation, torque, and ignition timing.

Keywords: Ion current; Spark ignition (SI) engine; Flex fuel; Combustion process monitoring.

INTRODUCTION

With the growing global concern for environmental issues and the imposition of increasingly stringent government regulations to limit pollutant emissions and improve the energy efficiency of automotive vehicles, the automotive industry is facing new technological challenges. One of the main challenges is the monitoring of the combustion process in internal combustion engines, which has become crucial for improving engine control and increasing its energy efficiency. While combustion pressure analysis is often used for monitoring the combustion process during engine development and calibration, the high cost of these sensors makes their widespread application by automakers impractical. Therefore, the use of ion current has been widely investigated as a more accessible and efficient alternative for monitoring the combustion process, enabling the extraction of valuable information such as the occurrence of phenomena like misfire and knocking [1][2]. The objective of this study is to demonstrate the feasibility of using ion current as a monitoring tool for combustion in internal combustion engines compared to conventional pressure sensors. The investigation addresses the application of different fuel mixtures, such as gasoline and ethanol, as well as variations in engine speed, torque, and ignition timing.

REVIEW

Ionic current is an electrical phenomenon commonly associated with the movement of charged carriers, such as free electrons, positive ions, and negative ions present in an ionic compound [3]. These charge carriers move in response to an electric field, generating an electric current flow that can be measured through an electrical circuit [4].

In an internal combustion engine, the charge carriers are formed during the combustion of the air-fuel mixture. This process occurs in two distinct stages of ionization. The first stage, known as chemical ionization, occurs at the beginning of combustion and is related to the composition of the mixture. During this phase, the initial reactions between the hydrocarbon and oxygen result in an increase in the charge concentration in the cylinder, which then decreases in subsequent reactions.

The second stage, called thermal ionization, occurs when high temperature and pressure are reached inside the cylinder. This promotes the ionization of NO molecules, increasing the charge concentration once again [5]. Research has indicated that the position of the peak of the thermal phase is related to the position of the pressure peak inside the cylinder. Both phases of the ionic current reflect the combustion behavior and therefore provide valuable information for the purpose of this study.

In practice, the measurement of ionic current in spark-ignition engines is commonly performed through the spark plug. The electrodes of the spark plug are polarized with an electric potential of several hundred volts, which is sufficient to generate the electric field inside the cylinder. The resulting signal from the measurement of the ionic current is illustrated in Figure 1, where the three characteristic phases of the signal can be observed.

The initial phase, referred to as the ignition phase, corresponds to the effects generated by the ignition system in the ionization circuit. These effects include the start and end of coil charging, as well as the release of the electric spark in the combustion chamber. The ignition phase is typically not considered useful for combustion analysis and is therefore often excluded from the signal [4].

The subsequent phase, called the chemical phase, corresponds to the process of chemical ionization, where the release of charges in the combustion gas occurs through the reactions of the hydrocarbon with oxygen. The chemical phase is typically more pronounced in the ionic current signal at low engine speeds [1].

The final phase, known as the thermal phase, corresponds to the process of thermal ionization, where charges are released due to the high temperature of the combustion gas. The thermal phase reflects the development of combustion in the cylinder and, therefore, contains relevant information about the occurrence of knocking, the combustion phase, and the occurrence of ignition failures [1].

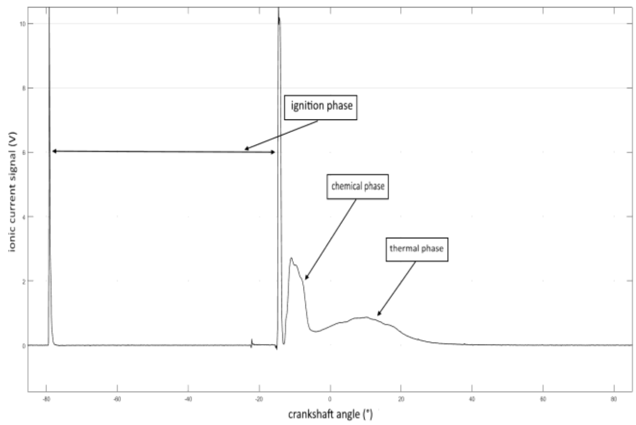

Figure 1: Characteristic signal of ion current during a combustion cycle.

There are basically two types of circuits used to apply this electrical potential: the circuit with a direct current (DC) power source and the circuit with a capacitive power source. In the present study, we chose to use the circuit with a capacitive power source, which uses a capacitor to generate the high voltage required. The advantages of this circuit include its lower production cost, as it does not require the use of a DC power source, and its easy adaptation to conventional ignition systems [6].

IONIC CURRENT CIRCUIT

An electrical spark is produced by the ignition system to initiate the combustion of the air-fuel mixture. The ignition system consists of a control circuit with a switching device for ignition command, ignition coil, spark plug cable, and spark plug. The primary side of the ignition coil is connected between the positive terminal of the 12V battery and the ignition command, and its grounding is controlled by the electronic control unit (ECU). The primary side of the coil stores energy through inductance when the switching device is in the closed state. As soon as the switching device changes its state to open, a voltage is produced in the primary side of the coil. When the voltage in the primary side increases, a high voltage of about 25-30 kV is generated in the secondary side of the coil. The high voltage in the secondary side generates an electrical spark between the electrodes of the spark plug.

When the electric current generated by the high voltage decreases, the current of the ion current circuit flows between the spark plugs and the combustion gases. To measure the ion current, the circuit shown in Figure 2 was used. The circuit consists of a capacitor (C1) in parallel with a Zener diode (D1), which limits the charging voltage to approximately 600 V. The diode (D1) allows the capacitor to charge during the release of the electrical spark at the spark plug (D), while the diode (D2) suppresses the high voltage from the ignition coil, protecting the measurement components of the circuit. The output signal of the ion current is measured between resistors (R1) and (R2), allowing the detection of the electric current generated by the combustion inside the cylinder.

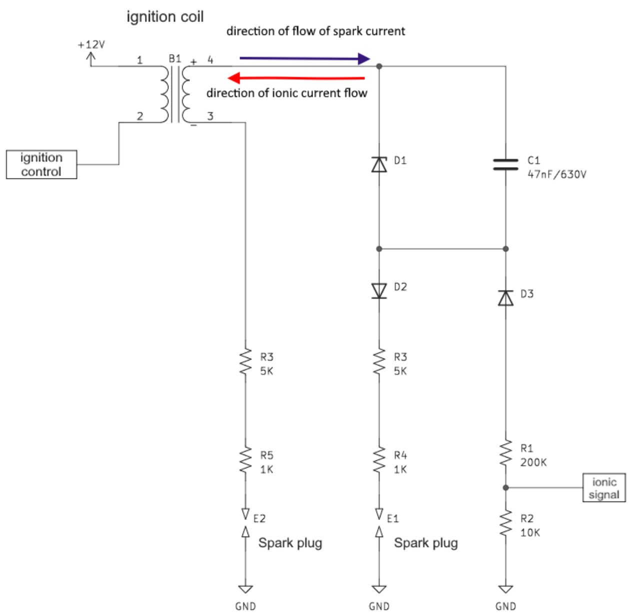

Figure 2: Ion current circuit.

EXPERIMENTAL SETUP

The experiments were conducted on a naturally aspirated 1.6-liter flex fuel engine. The engine specifications are presented in Table 1.

Displacement /L	1,6
Bore (mm)	76,5
Stroke (mm)	86,9
Number of cylinders	4
Compression ratio	12,1
Power	101 cv (gasoline) / 104 cv (ethanol) @ 5250 rpm
Torque	143,18 Nm (gasoline) / 141,22 Nm (ethanol) @ 2500 rpm
Ignition system	Dual ignition coil (Wasted spark)

Table 1: Engine specifications.

The schematic diagram of the test bench is shown in Figure 3. The experiments were conducted using a multi-fuel spark-ignition (SI) engine coupled to a hydraulic bench dynamometer. The engine is equipped with a cylinder pressure sensor and an ion current sensor installed in cylinder #1. To measure the combustion pressure, a pressure sensor integrated into a commercial spark plug was used. This sensor has a measurement range of 0 to 206 bar, with good linearity. The engine speed sensor was used to measure the rotation and angular position of the crankshaft. The ion current circuit was integrated into the ignition system to measure the ion current.

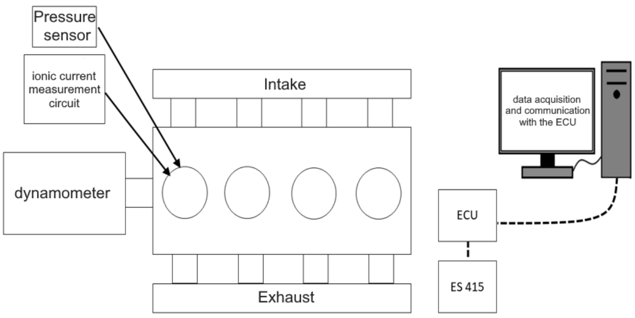

Figure 3: Test bench diagram.

The electrical signals from the sensors were collected using the ES415.1 module, which was configured with a vertical resolution of 16 bits and a sampling frequency of 100 kHz. The ES415.1 module processes the signals and sends them in digital form to a programmable electronic control unit (ECU). Subsequently, the digital signals are transmitted from the ECU to the computer and displayed in the INCA® software. The throttle valve control and ignition timing of the engine were performed through the INCA software, which in turn sends control signals to the actuators via the ECU. The torque and rotation control were carried out by the management system of a dynamometer.

METHODOLOGY

To correlate the signals of the ion current with the proposed variables, the method of numerical integration of the signal curve between the top dead center and bottom dead center regions of the cylinder was adopted. These regions correspond to the combustion phase, where the air-fuel mixture burns inside the cylinder. The computational tool MATLAB was used to perform the integration, employing the following equation:

$$Ision = \int_{ang2=90^{\circ}}^{ang1=0^{\circ}} SION(\theta)\, d\theta$$

In this equation, Ision represents the value of the integral of the ion current signal, SION(θ) represents the ion current signal as a function of the crankshaft angle (θ), and ang1 and ang2 are the limits of the integration window, corresponding to the top dead center (ang1 = 0°) and the bottom dead center (ang2 = 90°), respectively.

The experiments were conducted with the engine preheated to approximately 90 degrees Celsius, and controlled variables such as fuel, ignition timing, engine load, and engine speed were tested by manipulation. Table 2 presents the controlled variables along with their levels and specifications.

Variables Controlled	Levels	Specifications
Fuel	3	Ethanol, Commercial Gasoline and pure gasoline
Ignition timing	4	20°, 30°, 40° e 50° before top dead center
Load (torque)	3	40, 80 e 120 Nm.
Engine speed	6	1500, 2000, 2500, 3000, 3500 e 4000 RPM
In-cylinder pressure	6	17, 25, 33, 40, 47 e 51 Bar

Table 2: Variables specifications.

EXPERIMENTAL RESULTS

In this section, the results obtained according to the presented methodology will be discussed. The results of the integration of the ion current signal and its correlation with the tested variables in the experiment will be presented.

IN-CYLINDER PRESSURE

In order to investigate the characteristics of the ion current signal during combustion and its absence, we conducted a comparison between the ion current and pressure signals during the combustion and exhaust cycles of the engine. This comparison is presented in Figure 4.

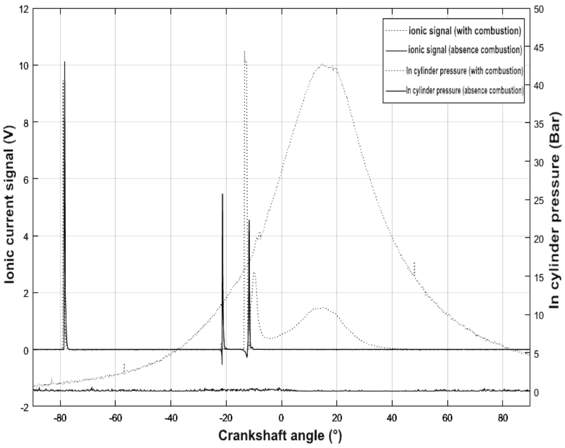

Figure 4: Comparison between ion current signals (with and without combustion) and cylinder pressure signals (with and without combustion).

It is possible to observe that during the absence of combustion in the cylinder, the ion current signal only shows the characteristic peaks of the ignition phase, which are located around -80º, -20º, and -10º of the crankshaft angle. This occurs due to the operation of the ignition system, which even in the absence of combustion, allows the measurement circuit to continue operating normally. However, since there is no air-fuel mixture to be ionized, there is no release of charges in the combustion chamber, preventing the formation of the chemical and thermal phases, resulting only in the ignition phase.

Figure 5 shows the comparison of the integral of the ion current signal for six average combustion pressures, taken over 300 consecutive engine cycles.

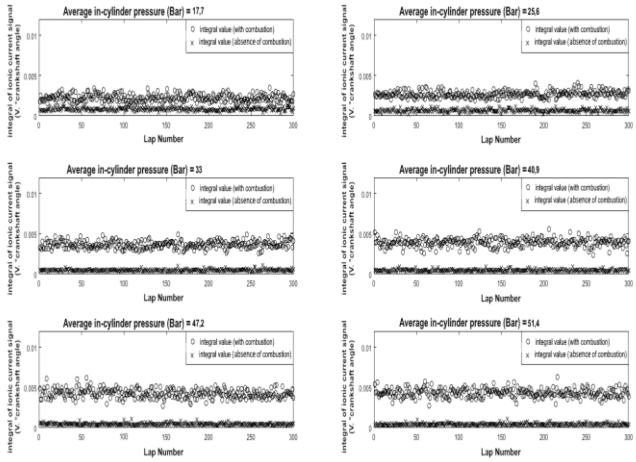

Figure 5: Comparison of the results of numerical integrations of the ion current signals as a function of pressure.

From the visualization of Figure 5, two important characteristics for monitoring the combustion process can be noted. The first one is the difference between the integral values during combustion and its absence. This difference is sufficient for identifying the occurrence of combustion in the cylinder, as the dispersion region between the data does not overlap.

The second characteristic is the increase in the average amplitude of the integral values during combustion compared to the average pressures. As the average pressure inside the cylinder increases, the amplitude of the integral also increases. This correlation is shown in Figure 6, where the correlation coefficient is 0.86.

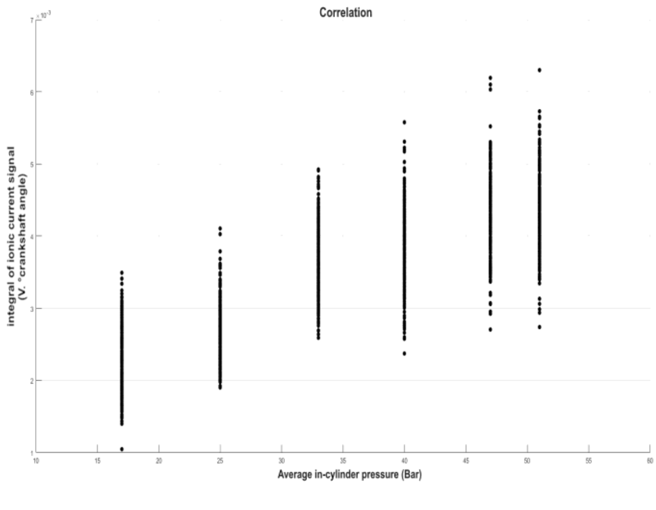

Figure 6: Correlation of the values of the integral of the ion current signal and the average pressure inside the cylinder.

FUEL

Figure 7 shows the comparison of the integral of the ion current signal for three fuel mixtures: gasoline without ethanol addition, gasoline with 27% ethanol, and pure ethanol.

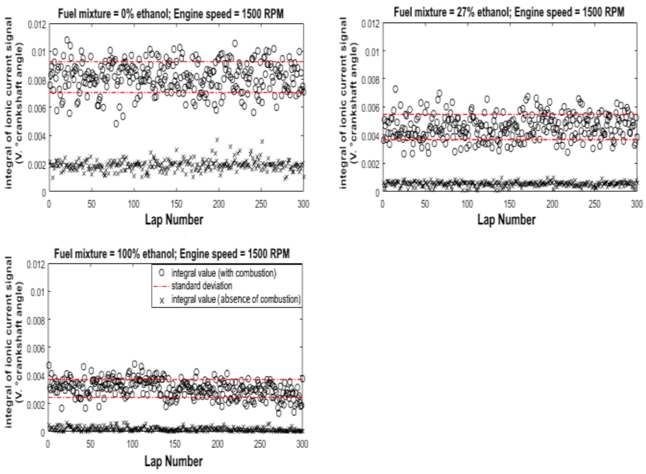

Figure 7: Comparison of the results of numerical integrations of ion current signal with respect to the fuel.

It can be observed that the amplitude of the integral of the ion current signal decreases as the percentage of ethanol in the fuel composition increases. This effect is also reflected in the data dispersion, as indicated by the standard deviation.

The figure 8 shows the correlation between the amplitude of the integral of the ion current signal and the percentage of ethanol in the fuel composition, with a correlation coefficient of -0.69.

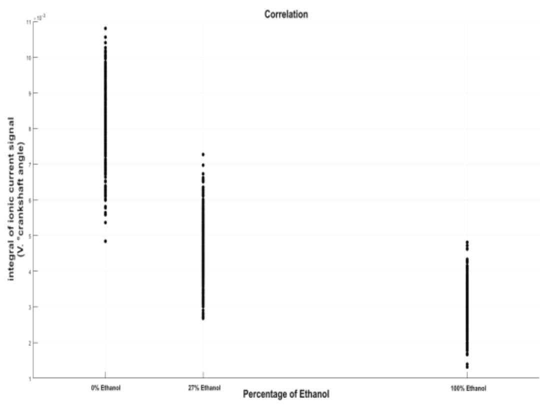

Figure 8: Correlation of the values of the integral of the ion current signal and the fuel mixture.

ENGINE SPEED

The figure 9 presents the comparison of the integral of the ion current signal for six different engine speeds: 1500, 2000, 2500, 3000, 3500, and 4000 rpm.

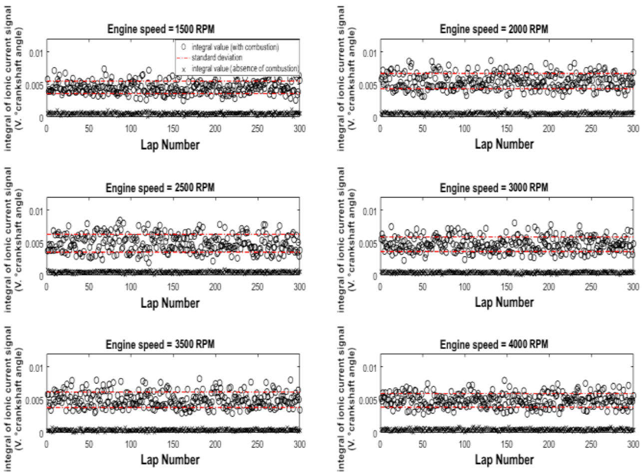

Figure 9: Comparative results of the numerical integrations of the ion current signal with respect to the engine speed.

From Figure 9, it can be observed that there was no significant change in the amplitude of the integral of the ion current signal with respect to the variation in engine speed. This effect also applies to the dispersion, as shown by the standard deviation.

Figure 10 highlights that, in the conducted experiments, there was no correlation between the amplitude of the integral of the ion current signal and the engine speed, with a correlation coefficient of 0.06.

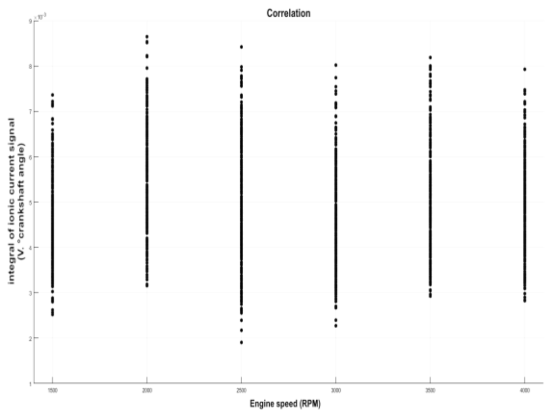

Figure 10: Correlation between the values of the integral of the ion current signal and the engine speed.

TORQUE (LOAD)

Figure 11 shows the comparison of the integral of the ion current signal for three load levels, 40 Nm, 80 Nm, and 120 Nm.

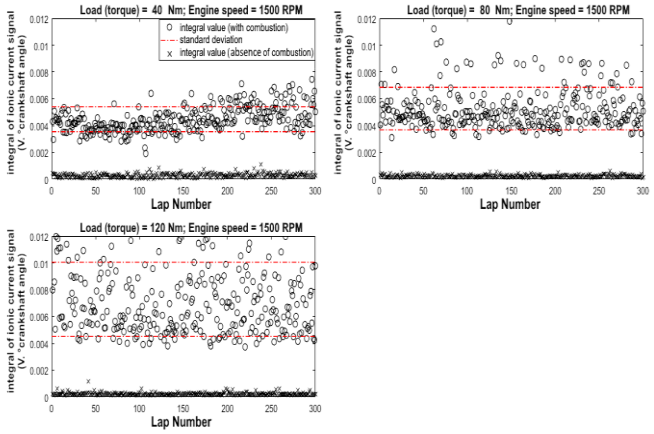

Figure 11: Comparison of the results of numerical integrations of ion current signal in relation to engine torque.

From Figure 11, it is possible to observe a strong influence of the motor load on the amplitude of the integral of the ion current signal, as well as on the data dispersion. As the motor torque increases, the amplitude of the integral and its dispersion also increase.

Figure 12 illustrates the correlation obtained between the amplitude of the integral of the ion current signal and the motor load, with a correlation coefficient of 0.51.

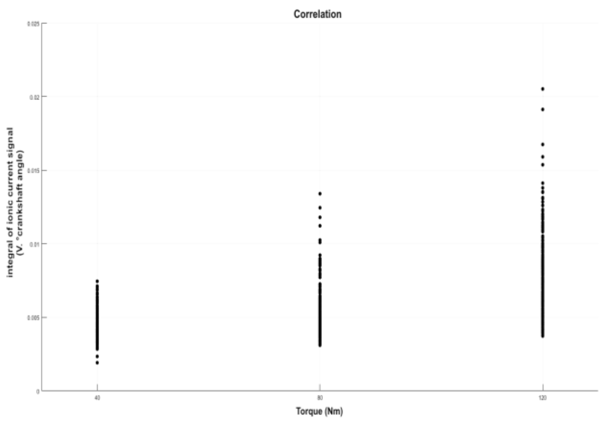

Figure 12: Correlation between the values of ion current signal integral and engine torque.

IGNITION TIMING

Figure 13 shows the comparison of the integral of the ion current signal for four ignition timing points of the engine, which are 20°, 30°, 40°, and 50° before top dead center (BTDC).

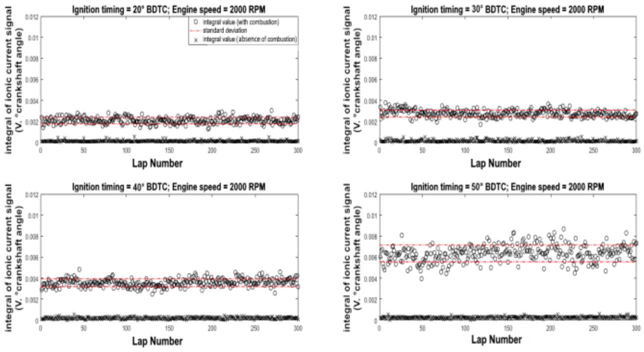

Figure 13: Comparison of the results of numerical integrations of ion current signal in relation to ignition timing.

From Figure 13, it can be observed that the amplitude of the integral of the ion current signal increases as the ignition timing angle is increased. In the experiments, the data dispersion remained relatively constant at all angles, except for the largest ignition timing angle. One possible explanation could be the effects caused by detonation events on the ion current signal, as this phenomenon tends to occur with excessively advanced ignition timing.

Figure 14 shows the correlation obtained between the amplitude of the integral of the ion current signal and the ignition timing angle of the engine, with a correlation coefficient of 0.90.

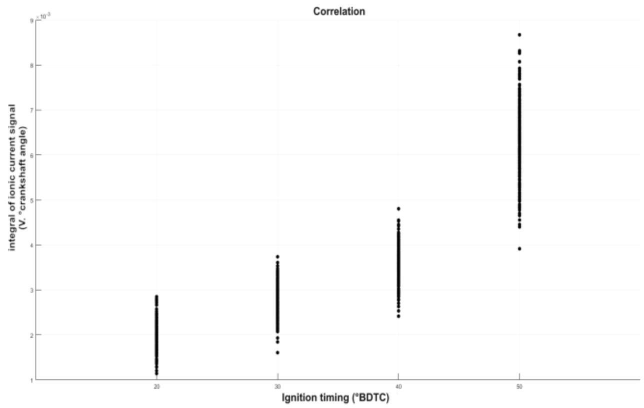

Figure 14: Correlation between the values of the ion current signal integral and the ignition timing.

CONCLUSION

The application of ion sensors in monitoring the combustion process in internal combustion engines is a challenging field of research. In this article, we have presented theoretical considerations and experimental results that demonstrate the feasibility of using ion current sensors to identify and estimate different fuel mixtures, torque, and ignition timing, even with the existing ignition system in the engine. This approach utilizes the spark plug as a sensor element.

The results of the conducted experiments have revealed the sensitivity of the ion current signal to the chemical and physical effects resulting from the combustion process, confirming the potential of this technology as a valuable tool. By analyzing the amplitude and integration of the ion current signal, it was possible to correlate it with different engine parameters, providing a deeper understanding of combustion characteristics.

This research opens up new possibilities for real-time monitoring and control of the combustion process, enabling optimized engine performance, improved fuel efficiency, and reduced emissions. The ongoing development and enhancement of ion current sensor technology can lead to advancements in engine diagnostics, combustion control strategies, and overall engine performance optimization.

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