

Impact of A/F Ratio on Ion Current Features Using Spark Plug with Negative Polarity

Ahmed A. Abdel-Rehim

Benha University, Egypt

Naeim A. Henein

Wayne State University

Ed VanDyne

Woodward Governor Co.

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ABSTRACT

The increasing interest and requirement for improved electronic engine control during the last few decades, has led to the implementation of several different sensor technologies. The process of utilizing the spark plug as a combustion probe to monitor the different combustion related parameters such as knock, misfire, Ignition timing, and air-fuel ratio have been the subject of research for some time now.

The air-fuel ratio is one of the most important engine operating parameters that has an impact on the combustion process, engine-out emissions, fuel economy, indicated mean effective pressure and exhaust gas composition and temperature. Furthermore, air-fuel ratio affects the ion produced during flame kernel initiation and post flame propagation. In this paper, an investigation is made to determine the effect of air-fuel ratio on ion current, using gasoline and methane under different spark plug designs and engine operating conditions. The ion current is produced by using a negative bias and proved to contain enough information about the air-fuel ratio.

I. INTRODUCTION

Ion current produced by applying a voltage, constant DC voltage, across the gap of the spark plug, instantly after the spark discharge,

has been proven to be reliable and inexpensive tool for automotive engines control, misfire and knock detection. The main advantage is the use of a component already present inside the combustion chamber. Many sensors are considered to obtain information about the A/F ratio in internal combustion engines, such as the Exhaust Gas Oxygen sensor (EGO), the Universal Exhaust Gas Oxygen sensor (UEGO) and the cylinder pressure transducer [1, 2, and 3]. Other approaches have been considered to determine A/F ratio from exhaust gas analysis [4, 5]. The ion current measured in the combustion chamber contains enough information about A/F ratio. One of the earliest studies to estimate λ from the ion current was performed by Clements and Smy [6] and from the decay time of the spark discharge [7]. Many others have attacked this area by different degree of success [8-14].

A typical ion current trace from a spark ignition engine is given in figure (1). The trace is characterized by two peaks: the first peak is caused by chemi-ionization produced by the flame front as it moves across the two electrodes of the spark plug. The second peak is caused by thermal ionization produced by the increase in the temperature and pressure of the combustion products around the electrodes, as the flame moves through the rest of the charge in the combustion chamber. The two peaks are explained in some details in references [15, 16 and 17]. The effect of A/F ratio on the characteristics of the ion current

signal, using spark plugs of different designs, will be investigated.

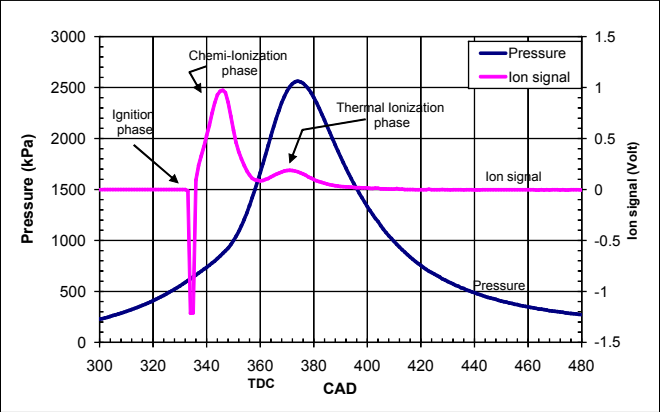


Figure (1) Typical ion current and cylinder gas pressure traces in a spark ignition engine [speed = 1300 rpm, torque = 22 Nm, $\phi = 0.89$, TDC at 360].

II. EXPERIMENTAL SETUP

The experiments were conducted on a single-cylinder Briggs & Stratton VanGaurd, 9 HP engine with a cylinder bore of 59 mm and a stroke of 80 mm. The compression ratio of the engine is 8.1. The engine was coupled to an electrical dynamometer to start and load the engine. A SmartFire system made by Adrenaline Research Co. was used for ignition and ionization detection. SmartFire provides negative bias of -380 volt on the center electrode of the spark plug. Accordingly, the central electrode of the spark plug represents the cathode, and the ground electrode represents the anode. Appendix (1) shows a schematic diagram of the experimental setup. The ion current is measured as a voltage drop across a resistor and the output is expressed in volts where one volt represents 0.1 ampere.

III. ION CURRENT SIGNAL CHARACTERIZATION

There are more than 50 features of the ion current signal that can reflect the combustion process. An illustration of some of these features reported earlier in the literature, and others developed in the present work are given in figure (2) and described in appendix (2).

Eleven of the most important features are defined and summarized in table (1).

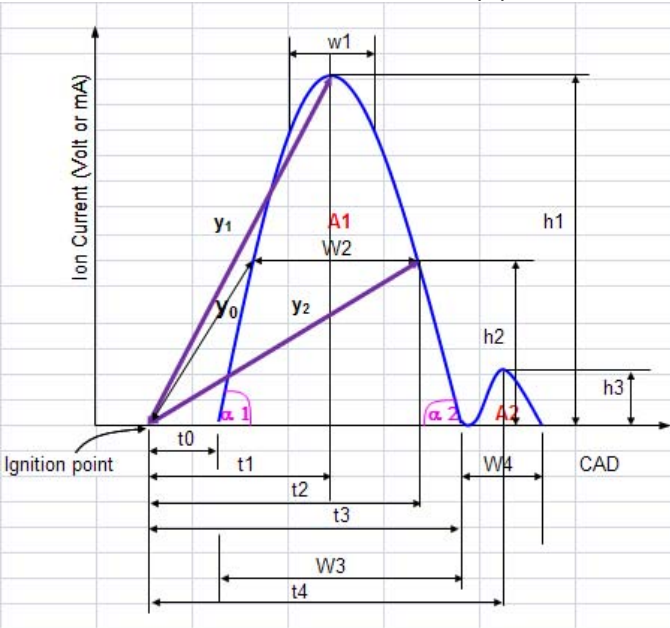


Figure (2) Different Ion current features used to study the correlation between combustion and ion current signal.

No	Parameter	Description
1	h_1	Flame front ion current absolute peak value
2	h_3	Post-flame ion current absolute peak value
3	A_1	Area under flame front peak (First Peak Integral)
4	A_2	Area under post -flame peak (Second Peak Integral)
5	A_3	Ion current integral in 5 CAD window around peak position
6	t_1	First ion current peak position from ignition point
7	t_4	Second peak ion current position from ignition point
8	α_1	Rising edge slope of the first peak
9	α_2	First peak declination slope
10	IC 0.67	Ion Current absolute value after 0.67 ms from ignition
11	CAD 0.1	CAD position on the first peak declination slope where the current absolute value reaches 0.1 volt.

Table (1) some of the Ion current features and their definitions.

IV. EFFECT OF A/F RATIO ON FIRST PEAK

Figure (3) shows ion current traces at different A/F ratios, at 1100 rpm, 18.8 Nm torque, and 26 CAD spark advance. The following can be observed from the figure: (a) the amplitude of the first peak, its timing and total duration change with the A/F ratio. As the mixture moves from the richest mixture, $\lambda = 0.77$, to $\lambda = 0.9$ the amplitude increases, and is reached faster, and its total duration decreases, (b) as the mixture gets leaner the ion current takes a longer time to reach its peak, the amplitude drops, and its total duration is longer.

The first peak is caused by the chemi-ionization in the flame front as it reaches the electrodes of the ionization probe. The change in electrons concentration can be attributed to the change in the concentration of the CH radical, oxygen concentration, and gas temperature, all of which change with A/F ratio. The timing of the first peak after the main ignition is a reflection of the flame speed. The total duration of the first peak is a reflection of the period of time where the flame front is filling the gap between the two electrodes.

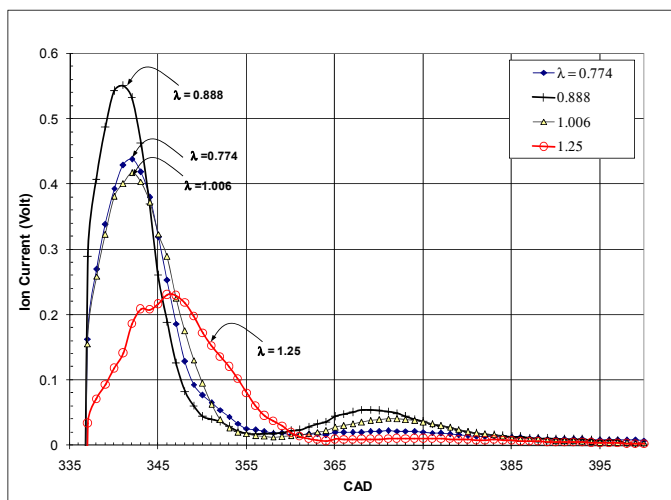


Figure (3) Ion current traces for different AF ratios at: speed:1100 rpm, torque: 18.8 Nm, spark timing: 26°bTDC]

V. A/F DETERMINATION FROM FIRST PEAK PARAMETERS

Knowledge of the in-cylinder A/F ratio is critical in electronic engine controls to meet certain goals in performance, fuel economy and emissions. Since A/F ratio affects the ion current, as expressed earlier, it is evident that some of its trace characteristics can be used to determine the in-cylinder A/F ratio. In the next section, the effect of some chosen characteristics of the ion current signal on the engine A/F ratio will be discussed.

V.1 Amplitude of First Peak

Figure (4) is a plot of the amplitude of the first ion current peak and A/F ratio. The ion current signal has maximum amplitude in the range of $\lambda = (0.86-0.88)$. Earlier studies [6, 18 and 19] showed that the maximum positive ion concentration for several hydrocarbon–air flames is close to the rich side of the stoichiometric point. Recently several publications indicated that the maximum amplitude of the first peak lies between $\lambda = 0.85$ and $\lambda = 0.95$, depending on fuel properties, engine geometry and some running conditions. This can be explained by the fact that the laminar flame speed reaches its maximum, around an equivalence ratio of 1.1 ($\lambda = 0.9$), which shortens the combustion duration and enhances the combustion efficiency.

The first peak amplitude drops with mixtures leaner or richer than that at which the ion current reaches its maximum, due to the drop in combustion temperature. Another factor that might contribute to the drop in ion concentration in the flame front for the lean mixtures is the presence of extra oxygen atoms and molecules and their affinity to the electrons.

Figure (5) shows the locations of some specific points in the ionization current trace, where 10%, 50% and 90% of the fuel is burned. It is clearly seen that at the same range of λ (0.86-

0.88) the combustion takes less time for the three percentages.

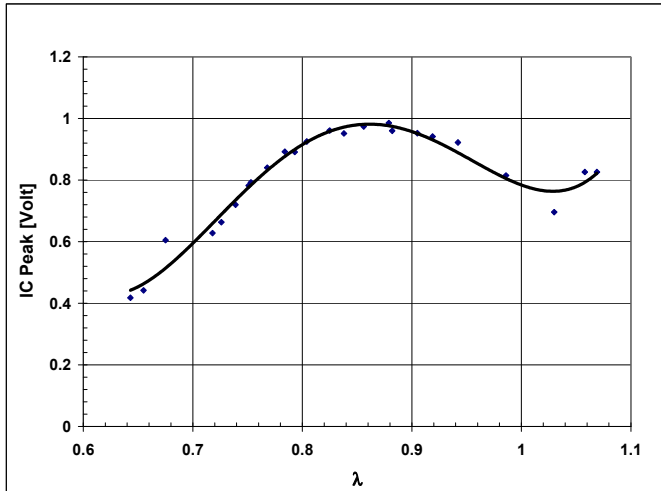


Figure (4) Effect of A/F ratio on the ion current first peak caused by chemi-ionization.

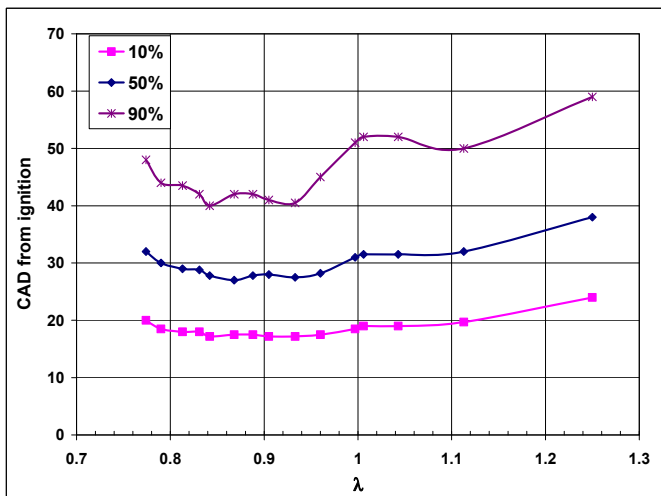


Figure (5) Location of 10%, 50% and 90 % burn at different A/F ratios.

V.2 Integrated Ion Current

Another parameter, used to study the effect of A/F ratio on ion current, is the integral of the area under each of the two peaks. But, in some cases it is difficult to identify the division between the two areas. So, it seems that it is appropriate to determine the area in a window in the ion current trace. Figure (6) shows the integral of the ion current in a window of five crank angle degrees on both sides of the peak position. Here, also, the peak occurred at λ equal to (0.86-0.88).

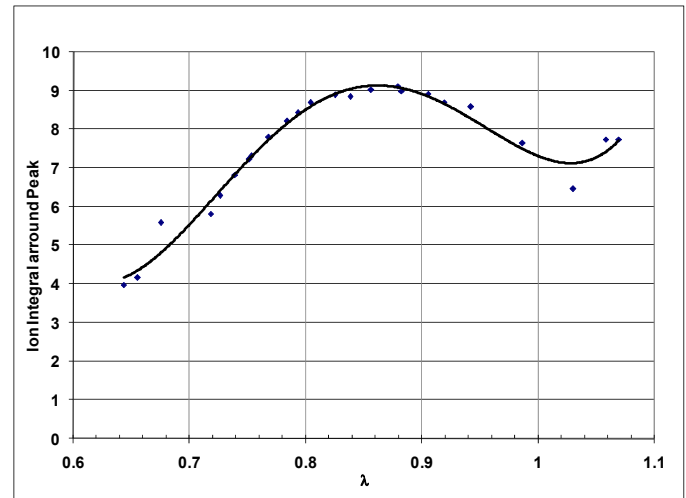


Figure (6) Integral of the ion current over a window 5 CAD before and after the first peak position.

The use of the first peak, or its integral over a window, is useful as long as it is separated from the peak caused by the electric spark, shown in figure (1). But in some cases the peak of the chemi-ionization is very close, or even overshadowed by the main spark ignition signal, as illustrated in figure (7). The trace in this figure was obtained at 16.6 Nm torque, 1400 rpm and $\lambda = 0.95$. As clearly seen the peak ion current is at 340 CAD and there are two points (two CAD) only recorded before the peak point which belongs to the chemi-ionization current. Accordingly, the chemi-ionization peak integral in a window of ± 5 CAD will be hard to obtain in such cases.

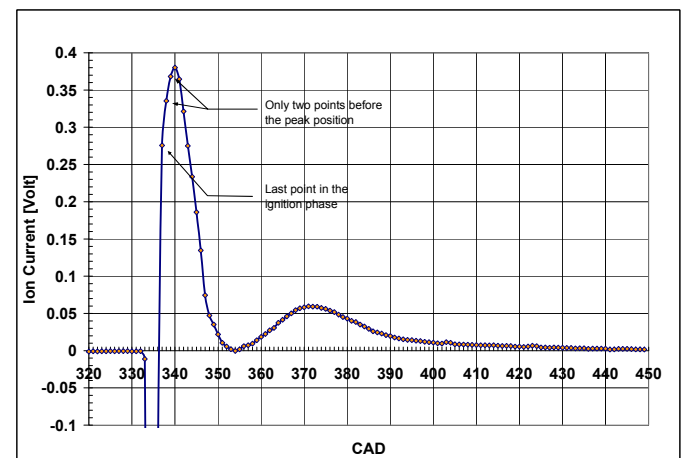


Figure (7) Ion current trace showing early ionization process in the flame front, shadowed by the electric spark signal.

V.3 Ion Current Arrival Time

One of the ion current characteristics is the period for the flame kernel to develop and fill the gap between the two electrodes. This period is known to be heavily dependent on the mixture properties including the A/F and the geometry of the spark plug. This period is 0.67 ms in our engine. The ion current value after 0.67 ms is plotted versus λ in figure (8). It is noticed that the resolution of this trace is better than the previous traces in the rich side of the mixture, $\lambda < 0.85$. Here a change in λ from 0.65 to 0.85 produced a change of about 300% in the ion current value.

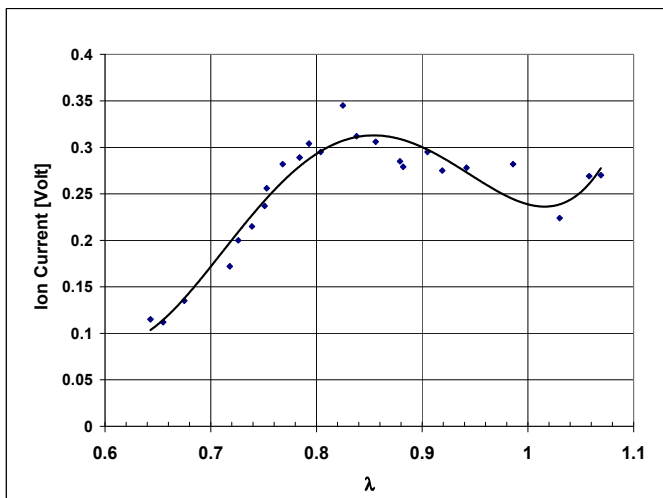


Figure (8) Ion current level 0.67 ms after ignition.

Another ion current characteristic is the rate of increase in the ion current at 5 CAD after ignition, shown in figure (9). This rate is an indication of the flame speed in the early stage of its propagation, which is strongly dependent on A/F ratio. It is noticed that the resolution of the ion trace in figure (9) is even better than that of figure (8). A change in λ from 0.65 to 0.85 increased the ion current by a factor of 4 in figure (9) compared to 2.8 in figure (8). However, this slope might be difficult to determine if there is interference from the main electric spark ignition signal as mentioned earlier in figure (7).

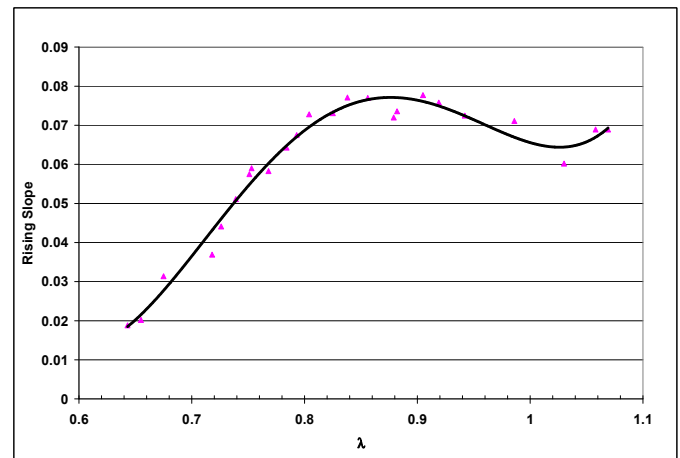


Figure (9) Rising slope of the ion current first peak.

V.4 Ion Current rate of Increase

Another A/F ratio indicator is the average slope of the ion current between its start and its first peak, y_1 shown in figure (2). This parameter contains information about the total number of ions (peak value) as well as the timing of the first peak with respect to the main ignition event. This is plotted in figure (10) and shows a change in λ from 0.65 to 0.85 which increases the ion current by a factor of 2.8, similar to that in figure (8). This parameter represents an indicator that is easier to determine than the rising edge of the first peak, explained earlier.

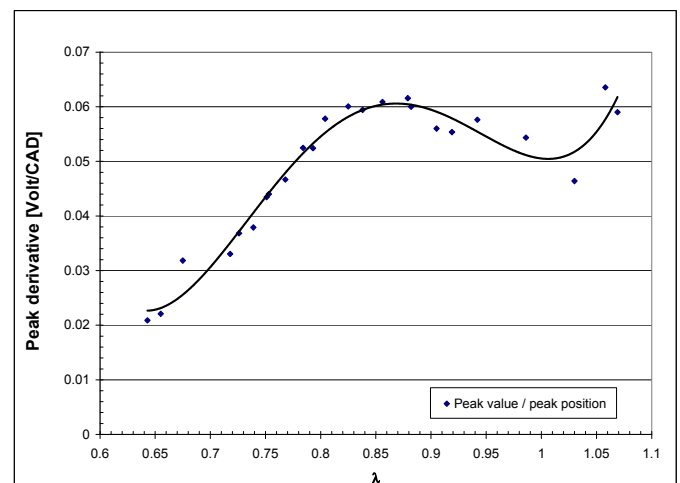


Figure (10) Ion current first peak derivative