

Characteristics of Ion Current Signals in Compression Ignition and Spark Ignition Engines

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Naeim A. Henein and Walter Bryzik
Wayne State Univ.

Ahmed Abdel-Rehim
The British Univ. in Egypt

Ashish Gupta
Cummins Inc.

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ABSTRACT

Ion current sensors have been considered for the feedback electronic control of gasoline and diesel engines and for onboard vehicles powered by both engines, while operating on their conventional cycles or on the HCCI mode. The characteristics of the ion current signal depend on the progression of the combustion process and the properties of the combustion products in each engine. There are large differences in the properties of the combustible mixture, ignition process and combustion in both engines, when they operate on their conventional cycles. In SI engines, the charge is homogeneous with an equivalence ratio close to unity, ignition is initiated by an electric spark and combustion is through a flame propagating from the spark plug into the rest of the charge. In diesel engines, the charge is heterogeneous with equivalence ratios that vary from zero to infinity, gas pressures are much higher than the pressures in gasoline engines, autoignition starts the combustion process in a premixed charge followed by combustion controlled by mixing and diffusion processes.

This paper examines the sources of ionization in hydrocarbons-air flames and the characteristics of the ion current signals in SI and CI engines under their conventional and HCCI operating modes. Some concepts have been introduced on the ionization in diesel engines, based on the limited publications in this area and the experimental results of this paper. Experiments are obtained on three engines. The first is a single cylinder gasoline engine equipped with different types of spark plugs used as ion current sensors. The

second is a single-cylinder diesel engine equipped with a glow plug converted to a glow-ion current sensor. The third is an optically accessible diesel engine where images are taken to show the interaction between the different sprays and their impact on the ion current. The similarities and differences between the ion current signals in SI, HCCI and CI engines are explained.

INTRODUCTION

Spark ignition (gasoline) engines and compression ignition (diesel) engines are required to meet stringent emission standards, without penalty in performance and fuel economy. Furthermore, the concern about global warming is adding another demand on engine manufacturers to reduce carbon dioxide emissions. To meet these demands, close loop engine control strategies are needed. Many sensing techniques have been used to produce signals indicative of the combustion process in both engines. These techniques include the use of pressure sensors [1, 2], glow plugs modified to measure cylinder gas pressure [3], optical sensors [4,5,6] and ion current sensors. Ion current sensors have been used in SI engines for in-cylinder combustion diagnostics [7,8,9], to determine the flame speed [10], to determine A/F ratio [11,12,13,14], to determine mass fraction burned [15], to detect knock [16,17,18], to detect misfire [16,19, 20], to detect combustion variability [21], to detect partial burn [17], to control combustion stability with lean and EGR operation, [22,23,24,25] and ultimately for gasoline engines feedback control [25,26,27,28,29,30,31,32,33,34]. In addition to its use for in-cylinder diagnostics, the ion current was measured in the exhaust of a gasoline engine for the late cycle combustion

analysis during Idling [35]. The above investigations used the spark plug as the ion sensor. Other types of ion sensors were developed and inserted in a ring to monitor combustion in a spark ignition engine at 16000 rpm in a racing car [10].

The ion current was used in HCCI engines to monitor start of combustion [36], to detect misfire and pre-ignition [37] and as a feedback signal to control combustion [37,38,39,40,41,42].

The use of ion current sensors in diesel engines has been limited compared to their use in spark ignition and HCCI engines. Schweimer insulated a part of the exhaust manifold and used it to measure the ion current in the diesel exhaust [43]. Glavmo et al. were the first to modify a glow plug to measure the ion current produced during combustion and to use it as a feedback signal to control the start of combustion in diesel engines, while applying EGR [44]. Kessler investigated the effect of different operating parameters such as load, EGR and injection pressure on the ion current in diesel engines using pilot injection strategy [45]. Kubach et al. investigated the effect of the probe design and its location in the combustion chamber on the ion current produced in a diesel engine with pilot injection [46].

The limited research on the ionization in diesel engines is partially caused by the complexity of the combustion process. The combustible mixture in diesel engines is heavily heterogeneous compared to the homogeneous charges in both gasoline and HCCI engines. The heterogeneity of the charge in diesel engines is not limited to the premixed charge where the equivalence ratio varies from zero to infinity, but the fuel can be present in the liquid phase while combustion is in progress in several parts of the combustion chamber. The liquid fuel can be in the form of droplets of different sizes and number densities, or in the form of a liquid film of different thicknesses deposited on the walls.

Comparing the capabilities of different combustion indicators, it has been reported that the ion current sensor is as able as the pressure transducer in detecting misfire [20], partial burn and inaudible knock [17], and knock [17, 47,48] in gasoline engines. But, in favor of the ion current sensor, several combustion parameters can be correlated with ion current signal which is not the case with the pressure sensor. These parameters include the A/F ratio [12, 29, 49,50,51,52]. In addition, the cylinder pressure can be determined from the ion current signal [53,54,55]. Furthermore, the ion current sensor is less expensive than the pressure transducer and does not require an additional fitting in the cylinder head. In SI engines the spark plug, already installed in the engine, can be used without any additional equipment. In diesel engines, the glow plug which is already installed in many diesel engines can be used as an ion sensor.

The main shortcoming of the ion current sensor is that it measures local properties of the combustion products, rather than the global properties of the gases in the whole combustion chamber [56]. In addition, both the ion current shape and magnitude depend on the design of the sensor, its location in the combustion chamber [16,36,46,57,58,59], and many engine operating parameters such as A/F ratio, speed, load and EGR [46]. Since these parameters vary from one engine to another, strategies developed for one engine cannot be used for other engines particularly if the strategies are based on absolute values, such as the absolute cylinder pressure [56]. Another drawback of the use of ion current sensors is their inability to detect small cylinder-to-cylinder variations in multi-cylinder engines, particularly when EGR is applied [56].

It is important to find out if one or more of the ion current parameters are related to the combustion process and is independent on the engine design parameters

SOURCES OF THE ION CURRENT IN HYDROCARBON-AIR FLAMES

Ionization in flames has been the subject of many early investigations [60, 61]. In hydrocarbons air flames, the main sources of the ion current are chemi-ionization and thermal ionization.

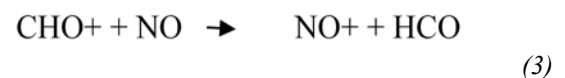
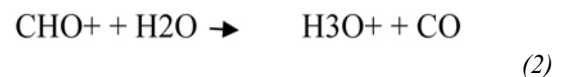
CHEMI-IONIZATION

The following chemi-ionization formation and recombination reactions have been applied to combustion engines running on hydrocarbon fuels [62,63,64,65,66]:

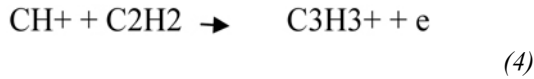
The ions formation reactions are:



The initiation of the ion formation by the CH radical has been established from the results on an experiment conducted on a gasoline engine where no ion current was detected when the engine ran on hydrogen [11]. Reaction (1) is slow compared to the following charge transfer reaction:

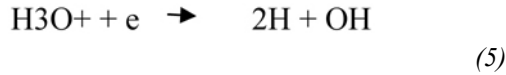


Reaction (2) is dominant in lean and slightly rich hydrocarbon air flames and produces H_3O^+ ions [64]. In rich and sooty hydrocarbons air flames, reaction (4) is dominant [64, 67] and produces C_3H_3^+ ions.



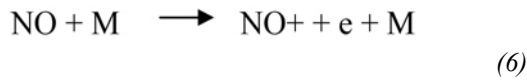
In sooty flames, charge transfer may occur between small ions such as C_3H_3^+ and H_3O^+ and large poly nuclear aromatic hydrocarbons. The ionization potential of these large molecules is small enough so that the charge transfer is thermodynamically favorable [68]. In addition negative ions can be formed and contribute in the ion current.

The ions recombination reactions is:

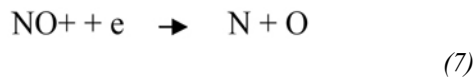


THERMAL IONIZATION

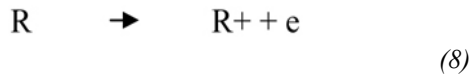
The formation of ions at high temperatures in close-to stoichiometric hydrocarbon air flames is mainly by the following reaction



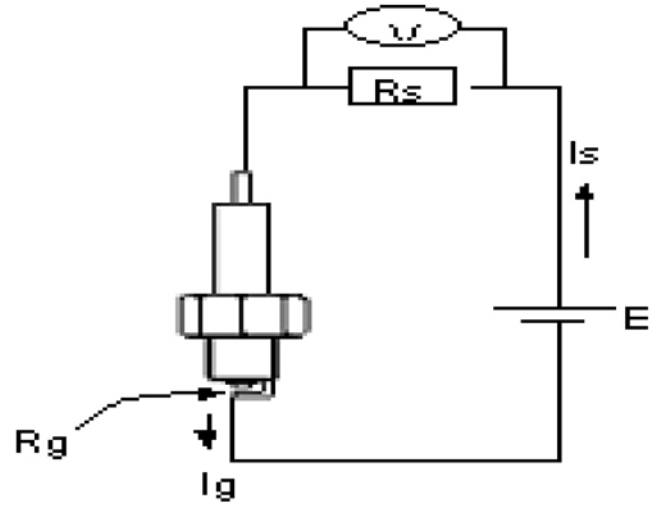
The destruction of NO^+ ions is by



In fuel rich hydrocarbons air flames a fraction of the large hydrocarbon molecules and soot particles, both presented by R, can be ionized directly by reaction (8) [68].



CHARACTERISTICS OF THE ION CURRENT SIGNAL IN SI ENGINES



$$I_s = V/R_s, \quad I_g = E/(R_s + R_g)$$

$I_g = I_s =$ Ionic Current.

Figure 1. Electric circuit for ion current measurement in SI engines.

Figure 1 shows the electric circuit for measuring the ion current in SI engines. A DC voltage, V, is applied across the spark plug gap, directly after the discharge of main electric charge to produce the spark required to ignite the mixture and start the combustion process. In the current investigation, the central electrode is the cathode.

Figure 2 shows typical traces of the cylinder gas pressure and the ion current. The ion current starts to increase at 24° bTDC, immediately after the discharge of electric spark. The ion current signal has two peaks. The first peak is at 14° bTDC and the second peak is at 12° aTDC. The two ion current peaks in SI engines have been reported by many investigators, (69- 71]. The two peaks may merge in one, as reported in two stroke engines under high EGR rates [72-73].

There is a general agreement that the first ion peak is the result of chemi-ionization produced in the reaction zone of the flame kernel that is present in and around the electrodes gap at that time [11, 74,75,76]. The amplitude of the first peak depends mainly on the equivalence ratio of the mixture [11, 74, 75] which affects the concentration of the ion producing species, (CH and O), and the temperature of the combustion products. In addition to the effect of the equivalence ratio, the gas temperature depends on the thermal capacity of the charge immediately after the discharge of the electric spark

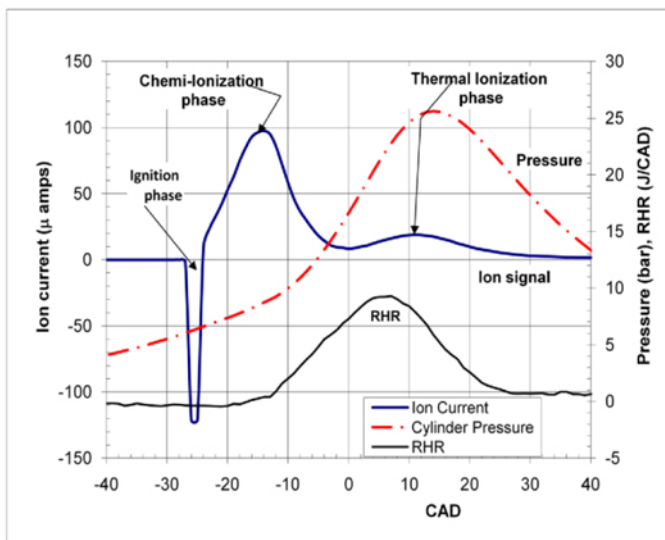


Figure 2. Typical ion current and cylinder gas pressure traces in a spark ignition engine at speed = 1300 rpm, torque = 20 Nm and $\lambda = 0.89$.

The thermal capacity of the charge depends on its density, composition and specific heat of its components, all of which depend on the operating variable of the engine, such as throttle valve opening, engine speed and EGR rate. High EGR rates reduce the amplitude of the first ion current peak because of the drop in combustion gas temperature caused by the higher specific heat of EGR components. As the flame front moves away from the spark plug zone the recombination reactions cause the ion current to drop and reach a minimum, after which it increases again toward the second peak.

There is also general agreement that the increase in the ion current leading to the second peak is due to thermal ionization caused by the increase in the temperature of the gases around the spark plug. This increase in temperature is caused by the combined effects of the energy released from the progressive burning of the charge as the flame front propagates through the combustion chamber and piston motion. The thermal ionization is mainly in NO, according to [reaction \(6\)](#) [53, 54, 70]. NO has the lowest ionization energy of all the other combustion products. Alkali metals in the air have much lower ionization energy than NO and may contribute in the second ion current peak [55]. Many researchers observed that the amplitude of the second ion current peak follows the cylinder pressure, and its location correlates well with the time when the maximum burnt gas temperature is reached, [7]. Some researchers suggested that the contact between the flame front and the cylinder walls contributes in the second peak [7, 55].

Mathematical models have been developed to determine the sources of the two ion current peaks in S.I. engines. One model assumed non-equilibrium ionization of combustion products [74, 75] and the other model assumed equilibrium ionization using Saha's equation [11]. The non equilibrium model [75] showed the following: (a) the mole fractions of both H_3O^+ and NO^+ start to increase after ignition, (b) the first ion peak coincides with H_3O^+ peak mole fraction and (c) the second ion peak coincides with the NO^+ peak mole fraction.

CHARACTERISTICS OF THE ION CURRENT SIGNAL IN HCCI ENGINES

The study of ion current formation in HCCI would help in identifying the sources of ion current in diesel engines because of the similarities between the autoignition process and early stages of combustion in the two engines. The charge is premixed in both cases and the differences are in the equivalence ratios. The equivalence ratio in HCCI is relatively uniform all over the combustion chamber. In diesel engines, the equivalence ratio, in the premixed part of the charge, varies between zero and infinity. But in diesel engines autoignition will occur only within certain limits, close to stoichiometric ratio where some studies of HCCI have been made.

[Figure 3](#) shows traces for the ion current, cylinder pressure and the ARHR around TDC in an HCCI engine at $\phi = 0.35$ and an inlet air temperature of 176°C [77]. The engine is a four cylinder, 1.9 L turbocharged direct injection diesel engine, having compression ratio of 17:1. The ion current starts to increase at a high rate, reaches a peak after which it drops at a slower rate during the expansion stroke. As expected, the ion current in HCCI engines has one peak because of the homogeneity of the charge and the volumetric combustion [58, 77, 78]. The magnitude and timing of the ion current peak depends on the location of the probe in the cylinder head [58]. [Figure 4](#) shows the traces for the ion current and the cylinder pressure at three equivalence ratios. The increase in the ion current due to combustion at $\phi = 0.3$ is fairly small. The ion current peak increased by one order of magnitude as ϕ increased from 0.3 to 0.35, and more than doubled in value as ϕ increased from 0.35 to 0.40.

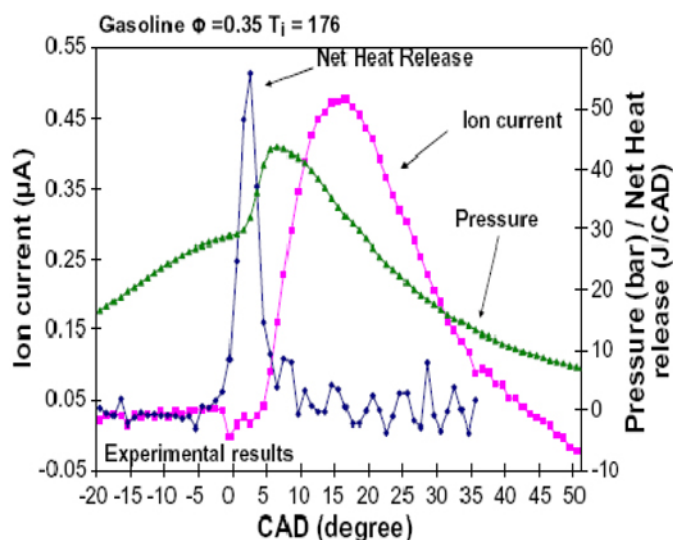


Figure 3. Cylinder gas pressure, ARHR and ion current traces for an HCCI engine [77, 78].

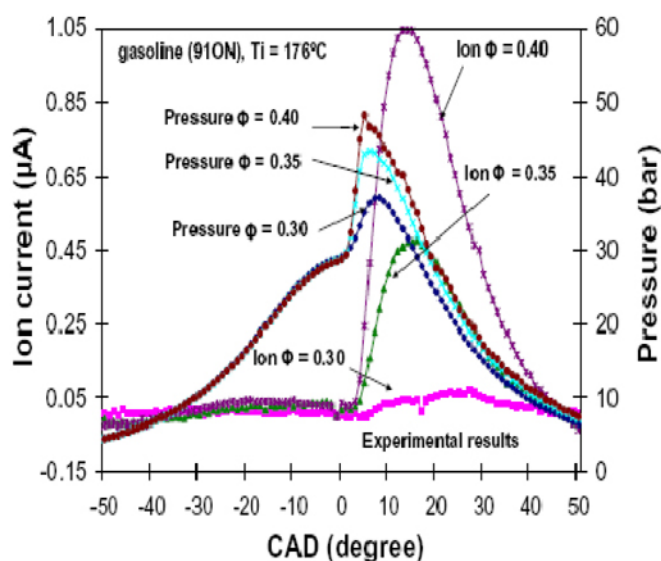


Figure 4. Cylinder gas pressure and ion current traces of an HCCI engine at three equivalence ratios [77, 78]

The increase in ion current at the higher ϕ is caused by the increase in the combustion products temperature along with the higher concentration of the CH radical [77, 78].

In other investigations where higher ϕ values are used, the maximum cycle ion current increased from a low level in lean mixtures ($\phi = 0.3$) at a high rate as the equivalence ratio increased to the stoichiometric and reached a peak with a slightly rich mixture ($\phi = 1.1$). For richer mixtures the ion current dropped sharply [35, 39, 59].

Mehresh et al. numerical investigations show clearly that the ion current in HCCI operation is caused by chemi ionization

from the reaction between CH and O, according to reaction (1), forming HCO^+ ions [39]. This is followed by reaction (2) forming H_3O^+ . In HCCI, ionization increases at higher EGR rates as the mixture approaches the stoichiometric due to the higher concentration of the CH molecule in spite of the drop in O atom concentration at the high EGR rates. The sharp drop in the amplitude of the ion current at higher ϕ is mainly due to the lower O atom concentration, in spite of the increase in CH. In HCCI, the contribution of NO^+ produced by thermal ionization in reaction (6) was found to be insignificant (four order of magnitude lower) compared to HCO^+ produced from equation (1). This is caused by the low in-cylinder NO formation and low combustion temperature. The above analysis shows that chemi ionization plays a key role in the early stages of combustion in diesel engines.

CHARACTERISTICS OF THE ION CURRENT SIGNAL IN COMPRESSION IGNITION ENGINES

A limited number of investigations have been conducted to identify the sources of the ion current in compression ignition engines. Also, the ionization mechanisms developed in gasoline engine cannot explain all the ionization mechanisms in diesel engines because of the differences in the combustible mixtures in the two engines. In spark ignited gasoline engines, the mixture is fairly homogeneous, ignition starts by a high energy electric spark and combustion is achieved by a high temperature flame front that propagates through the whole combustion chamber. In diesel engines, the combustible charge is heterogeneous. Combustion starts with an autoignition process that depends on the properties of the local fuel-vapor air mixture and its temperature and pressure. In addition, with short ignition delays, combustion may occur in the presence of liquid fuel that is still being delivered by the injector, or is in the form of liquid droplets, or a liquid film on the walls. Furthermore, the temperature is spatially different all over the combustion chamber. Accordingly, the chemi-ionization caused by the flame kernel, responsible for the first peak in gasoline engines, cannot explain the first ion current peak in diesel engines. Similarly, the thermal ionization caused by the increase in the temperature of the combustion products around the spark plug, cannot explain the peaks of the ion current in diesel engines.

In diesel engines, the ion current signal can have one, two or more peaks. Unfortunately, the processes responsible for these peaks have not been clearly identified yet. In the following sections the possible sources of the ion peaks in diesel combustion will be explained, based on information available in the literature, data obtained in an optically accessible engine and results of an investigation on a single-cylinder diesel engine

FUEL-AIR DISTRIBUTION IN A DIESEL SPRAY, WITHOUT IMPINGEMENT ON THE WALLS

Figure 5 is a schematic of a fuel spray injected in swirling air in the combustion chamber of a direct injection diesel engine, without impingement on the walls [79]. The small droplets in the spray are carried away by the swirling air and their number concentration decreases as we approach the leading edge of the spray, downstream of the swirling motion. The volumetric combustion of the premixed charge of the different sprays results in the high rate of heat release responsible for the sharp rate of pressure rise and the combustion-produced noise common to conventional diesel engines. The combustion of the rest of the spray depends on the extent of fuel evaporation and mixing with the fresh charge. The heterogeneity of the charge depends on the turbulence caused by the charge swirl and squish motions, in addition to the turbulence produced by the liquid spray as it penetrates through the combustion chamber. The difference in the injection pressure and the cylinder pressure, in addition to other injection system parameters, determine the effect of the spray developed turbulence and its contribution in the combustible mixture formation. The ion current formed in different parts of the spray depends mainly on the local fuel air ratio, charge temperature and pressure. On the lean side of the combustible mixture in the spray, positive as well as negative ions can be formed [81]. On the rich side polycyclic aromatic hydrocarbons ions (PAH⁺) with any number of C atoms up to more than 300 can be formed [61, 82].

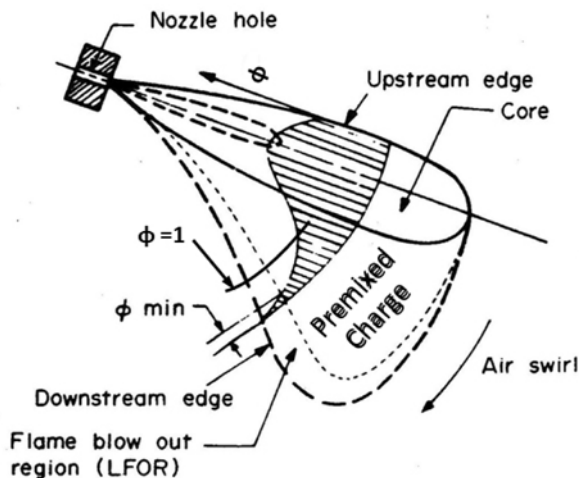


Figure 5. Schematic of the equivalence ratio distribution in a diesel engine fuel spray without wall impingement [79].

The ion current formed in different parts of the spray depends mainly on the local fuel air ratio, charge temperature and pressure.

The above discussions are for fuel sprays without wall impingement. In small bore diesel engines, the fuel spray impinges on the walls. Parts of the spray with high momentum bounce off the wall and form the wall jet. Some of the fuel sticks and spreads on the wall and forms thin liquid films of different thicknesses. The degree of atomization of the wall jet depends mainly on the speed and angle at which the spray hits the wall, which in turn depends on the pressure differential across the nozzle holes and the design of the combustion chamber. The presence of a swirling motion increases the spread of the atomized droplets away from the impingement area as well as the spread of the liquid film on the walls. The combustion of the wall spray depends mainly on the ignition delay. With short ignition delays, autoignition occurs in the free spray before it reaches the wall, and the reflected wall spray would burn by the existing flame in a diffusion type turbulent flame. With long ignition delays, autoignition starts in the wall spray and the flame spreads into the premixed charge produced from the free spray as well as produced from the wall jets. The last part of the spray to burn is the liquid film formed on the walls.

From the above discussion it is clear that the combustion process in diesel engines is quite different from the combustion process in spark ignition engines. Accordingly, the discussions used to explain the sources of the two ion current peaks in spark ignition engines cannot be used to explain the sources of ion current peaks in diesel engines.

ION CURRENT AND ITS RELATIONSHIPS WITH DIFFERENT COMBUSTION PARAMETERS IN CI ENGINES

Figure (6) shows an electric circuit used to measure the ion current by applying a glow plug, modified to act as an electrode [44]. In the current investigation the ion-glow plug is the anode and the rest of the engine is the cathode. The plug plays three roles. The first is to act as an electrode together with the rest of the cylinder block as the second electrode. The second is to assist in the cold start of the engine. The third is to periodically clean up its tip by burning any soot accumulated during engine operation.

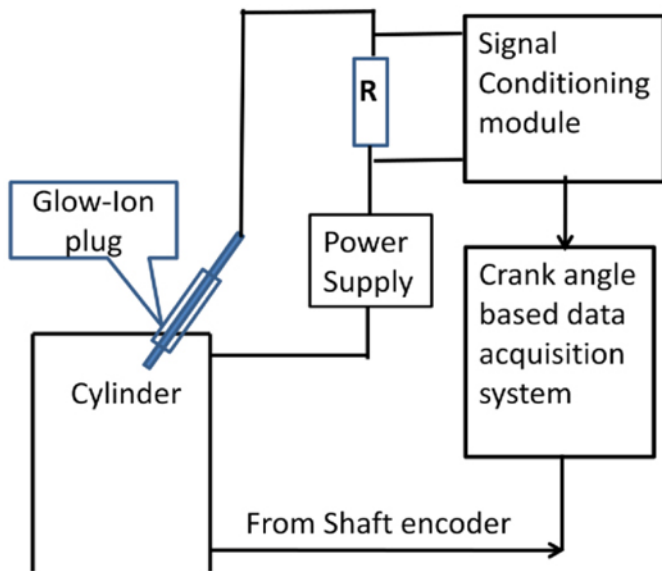


Figure 6. Ion current electric circuit for a diesel engine with a modified glow-plug-ion probe.

Figure 7.a is a view of the cylinder head showing the locations of the pressure transducer and the glow-ion plug relative to the fuel sprays and the walls of the bowl in the piston. The injector nozzle has six orifices, symmetrically drilled around the cylinder axis. The swirl motion is clockwise. The glow-ion plug is constructed in our labs, from parts of two regular spare glow plugs. The glow plug was energized before each test for a few seconds to burn any accumulated carbon deposits.

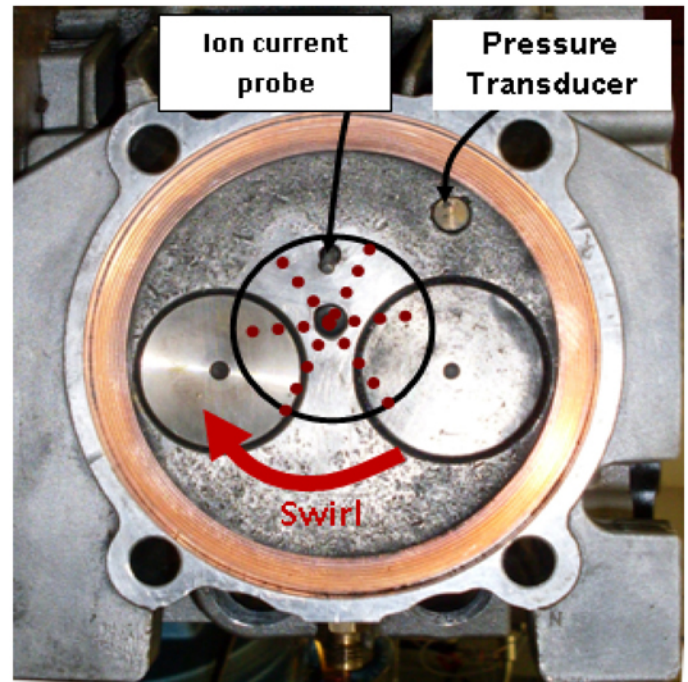


Figure 7.a. A view of the cylinder head showing the locations of the ion current probe and pressure transducer, and the direction of the swirl motion.

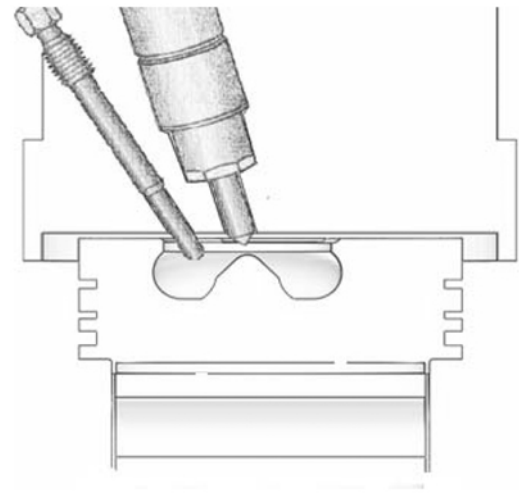


Figure 7.b. Cross section in the piston top.

Figure 7.b is a cross section of the piston showing the location of the ion-glow plug in the bowl. This is the same location of the production glow plug.