

A New Technique to Determine the Burning Velocity in a Gasoline Direct Injection Engine

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ABSTRACT

Many approaches have been taken to determine the burning velocity in internal combustion engines. Experimentally, the burning velocity has been determined in optically accessible gasoline engines by tracking the propagation of the flame front from the spark plug to the end of the combustion chamber. These experiments are costly as they require special imaging techniques and major modifications in the engine structure. Another approach to determine the burning velocity is from 3D CFD simulation models. These models require basic information about the mechanisms of combustion which are not available for distillate fuels in addition to many assumptions that have to be made to determine the burning velocity. Such models take long periods of computational time for execution and have to be calibrated and validated through experimentation.

This paper presents a new technique to determine the burning velocity in a production engine without making any modification in its structure, or use of high speed imaging equipment. This technique is based on the combustion produced ionization measured at two defined locations in the combustion chamber. In the engine used in this investigation, the spark plug is used as an ion current sensor which indicates the time the flame kernel is formed around the spark plug gap. In addition, the fuel injector is used as an ion current sensor, after it is electrically insulated from the cylinder head. The time between the start of ionization at the two locations is used to calculate the burning velocity. The use of this technique to determine the cycle to cycle variation in the burning velocity and other combustion parameters is demonstrated with engine operation at a steady speed and load.

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INTRODUCTION

Demands for improved fuel economy and high power density, in addition to reduced emissions require an improved understanding of the combustion processes in direct injection gasoline engines, which are widely used in passenger cars and light duty vehicles. This requires a detailed analysis of complex fluid dynamic, thermodynamic and chemical processes which affect the combustion process. Due to changes in these processes during the engine cycle, there is a need of computer simulations to determine the effect of different design and operating variables on combustion. Computer simulations enhance the development of strategies for the engine control unit (ECU) to optimize engine operation and achieve the production targets. Of primary importance is the validation of the simulation predictions with experimental data to ensure the validity and accuracy of the models. One of the key parameters that would indicate the quality of a simulation model is the burning rate of the fuel-air mixture.

The burning rate is often expressed in terms of a turbulent burning velocity which is strongly influenced [1, 4] by physico-chemical parameters embodied in the laminar burning velocity [2, 3] and gas dynamics.

The effect of burning velocity on the peak cylinder gas pressure and rate of heat release is reported by Baratta [11] in a naturally aspirated multi-valve gasoline engine using CNG. Yuji Ike [8] applied the infrared (IR) absorption and chemiluminescence technique to measure the burning velocity in a PFI (port fuel injection) racing engine. Rosati and P. G. Aleiferis [9] measured the flame propagation in an optically accessible gasoline direct injection engine running at part load on hydrogen. They reported that the flame speed in hydrogen air mixtures is nearly one order of magnitude higher than that of gasoline and other hydrocarbon fuels.

Yoshiyama [1] used the cylinder head gasket as an ion sensor to detect the combustion quality in a production spark ignition engine. He used 8 electrodes distributed equally around the combustion chamber to get a complete picture about the flame propagation around the combustion chamber.

Simulation of combustion in direct injection gasoline engines includes making many assumptions in the model. Conte [14] considered the combustion process to begin with the formation of a laminar-burning kernel. The kernel grows and the flame surface departs from the ignition source and interacts with the turbulent motion field of the cylinder charge. The flame surface is progressively corrugated and wrinkled by turbulence and after a transition the flame becomes fully turbulent. As the reacting surface is increased, the rate at which the fresh mixture is consumed is increased, making the flame surface advance in the unburnt region at a higher global speed - called turbulent flame speed - although, locally, the combustion process is still taking place at the laminar flame speed, which is determined by the chemistry and by pressure and temperature [14].

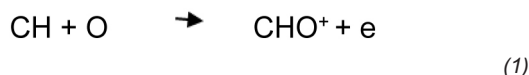
This paper presents a new approach to determine the burning velocity in a GDI engine under different steady speeds and loads. The burning velocity is derived from the time taken by the flame to move from the spark plug to the fuel injector and the distance between the two locations, which can be measured accurately. This technique is used to determine the cycle to cycle variation in the burning velocity and other combustion parameters at a steady speed and load.

SOURCES OF THE ION CURRENT IN HYDROCARBON-AIR FLAMES

In hydrocarbons air flames, the main sources of the ion current are chemi-ionization and thermal ionization [12, 15, and 16].

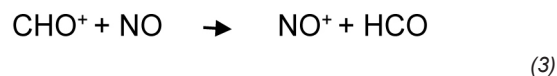
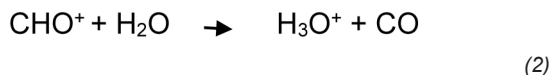
Chemi-Ionization

Chemi-ionization in hydrocarbon-air flames is mainly caused by reactions between the CH radical and the oxygen atom and other combustion intermediates according to the following reactions: [17, 18, 19, 20, and 21]:

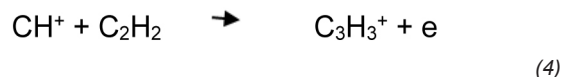


It should be noted that the initiation of ionization is by the CH radical from the hydrocarbon fuel. The ion current was not detected in a gasoline engine fuelled by hydrogen [22].

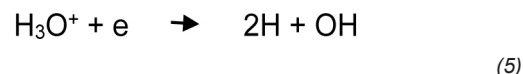
Reaction (1) is slow compared to the following charge transfer reactions:



Reaction (2) is dominant in lean and slightly rich hydrocarbon air-flames and produces H_3O^+ ions [23]. In rich and sooty hydrocarbons air flames, reaction (4) is dominant [23, 24] and produces C_3H_3^+ ions.

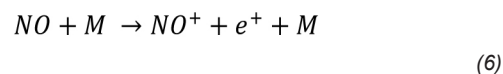


In sooty flames, charge transfer may occur between small ions such as C_3H_3^+ and H_3O^+ and large poly nuclear aromatic hydrocarbons. The ionization potential of these large molecules is small enough so that the charge transfer is thermodynamically favorable [26]. In addition negative ions can be formed and contribute in the ion current. The ions recombination reactions are:

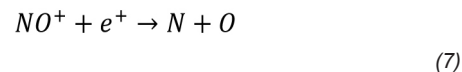


Thermal Ionization

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



"M" is any species that can chemically interact with the NO molecule at high temperature to produce an ionized NO molecule. The destruction of NO^+ ions is by



In fuel rich hydrocarbon-air flames a fraction of the large hydrocarbon molecules and soot particles, both presented by R, can be ionized directly by reaction (8) [25].



CHARACTERISTICS OF ION CURRENT SIGNAL FROM THE SPARK PLUG

Figure 1, shows the electric circuit for measuring the ion current in SI engines using the spark plug as an ion sensor. 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

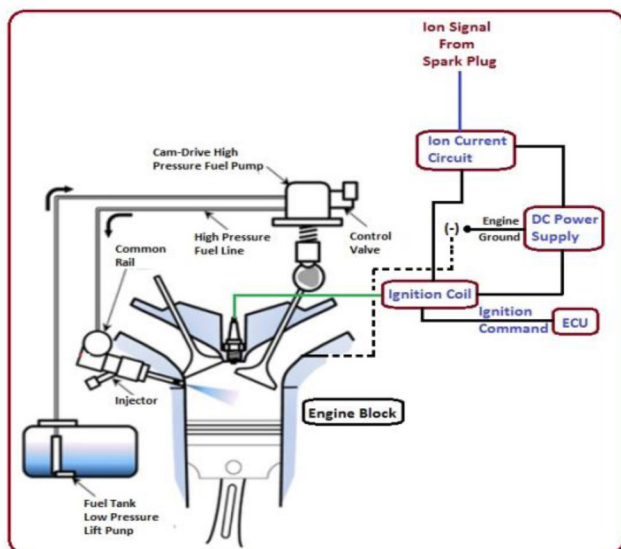


Figure 1. Electric circuit for ion current measurement in Spark plug.

Figure 2 shows sample traces of the ion current, cylinder gas pressure, rate of heat release and integrated rate of heat release. The figure shows spark breakdown occurred at 18° before TDC and the positive rate of heat release started at 12° before TDC, at which the chemi-ionization is detected. There are two major peaks in ion current signal. The first peak indicates the formation of a high concentration of chemi-ionized species around the spark plug gap, caused by the flame kernel in the very early stages of the combustion process. The first peak, caused by reactions (1), (2), (3), (4), is followed by a drop in the ion current produced by the recombination reaction (5). The second peak is due to thermal ionization of combustion products, such as NO, caused by the increase in the local temperature.

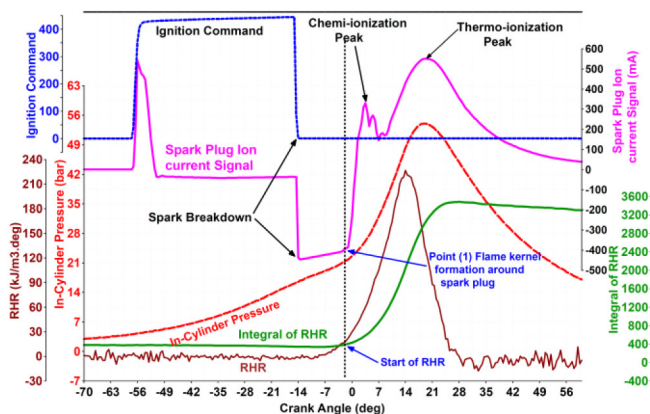


Figure 2. Sample of cylinder gas pressure, ignition command, and the ion current signal from the spark plug. Zoomed in traces at 1500 rpm, 175 N.m (11.0 BMEP)

The increase in the local temperature is caused by the increase in the cylinder gas temperature associated with the increase in cylinder gas pressure,

CHARACTERISTICS OF ION CURRENT SIGNAL FROM THE FUEL INJECTOR

Figure 3 shows a schematic sketch of the multi-sensing fuel injection (MSFI) system. The system consists of a pair of electrically isolated electrodes separated by a gap where the fuel injector nozzle acts as one electrode and the engine block acts as the other electrode. The fuel injector, located within the combustion chamber of the GDI engine, is electrically insulated from the rest of the engine body using non-conducting material.

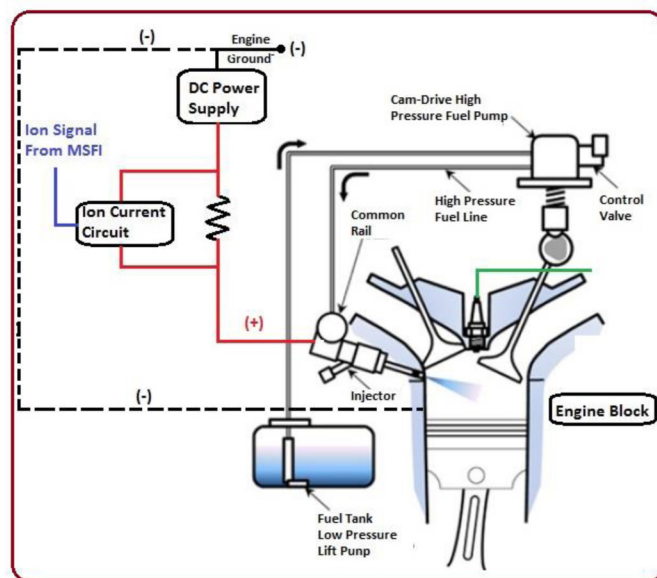


Figure 3. Electric circuit for use of the injector as an ion current sensor.

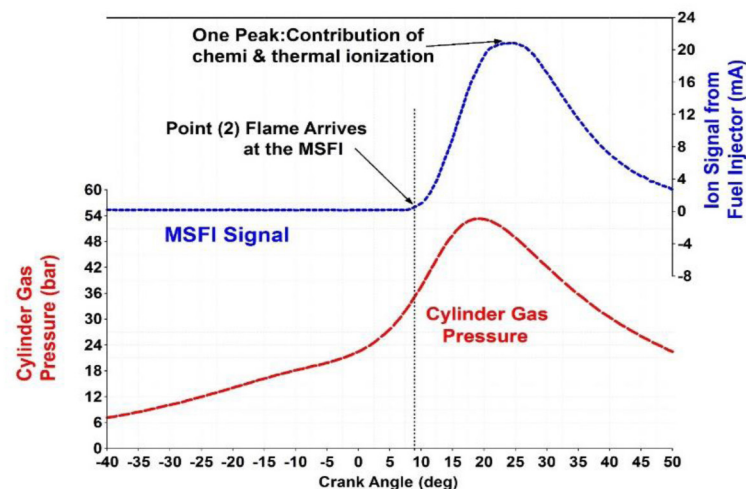


Figure 4. Sample of cylinder gas pressure and the ion current signal from the fuel injector. Zoomed in traces at 1500 rpm, 175 N.m (11.0 BMEP)

The electric circuit for the injector includes a 100 V DC power supply. The negative potential terminal is connected to the engine body. The ion current signal from the MSFI is measured in terms of voltage drop across a resistor. A signal conditioning

unit and an amplifier are included in the circuit. The amplifier can be integrated with low pass, high pass filters to reshape the incoming sensor output signal for control purposes.

Figure 4 shows sample traces obtained from the MSFI and the cylinder gas pressure. The rise in the signal indicates the time of arrival of the flame at the tip of the injector. The phase ship between the ion current signals from the injector and from the spark plug is the time taken by the flame to travel between the two locations.

ENGINE SPECIFICATIONS

Experiments were conducted on a GM dual scroll turbocharged gasoline direct injection 2.0L engine with dual continuously variable cam phaser (D-CVCP). The engine is a 4-cylinder Ecotec engine with 86 mm bore, 86 stroke, and 145 mm connecting rod length. The engine has a compression ratio of 9.2. A multi-hole injector is side mounted in the cylinder and is mated with a common rail fuel injection system operated by a production ECU. Table 2, shows engine specifications.

Table 1. Engine specifications

Engine Type	2.0 L ECOTEC SIDI Turbo
Displacement	1998 Cm3
Bore / Stroke	86/86 mm
Conn. Rod	145.5 mm
Stroke/2/Con. Rod Length	0.294 "λ"
Valvetrain Type	DOHC w/ RFF
Valve Lift Ex/ In	30.1 / 35.1 mm
Cam Drive (Phasing Authority)	D-CVCP (50° / 50°)
Opening Duration Ex / In	221 / 231 °CA (top of ramps)
Compression Ratio	9.2
Max. Torque @ engine speed	350 Nm/ 2000 rpm
Max. Power @ engine speed	194/260 KW/HP / 5300 rpm
Fuel Quality	87 & 95 RON

EXPERIMENTAL SETUP

Figure 5 is a layout of the experimental set up. The engine is connected to an AC electric dynamometer for power absorption and motoring. The dynamometer is controlled by an AVL PUMA system. Intake and exhaust temperatures are recorded for each test as well as coolant temperatures. An optical encoder is installed on the front end to acquire the crank angle position with a resolution of 0.1 CAD. Data such as engine load, speed, intake pressure, and throttle position were recorded using an AVL data acquisition system. The engine-out soot is measured using an opacity meter installed on the tailpipe.

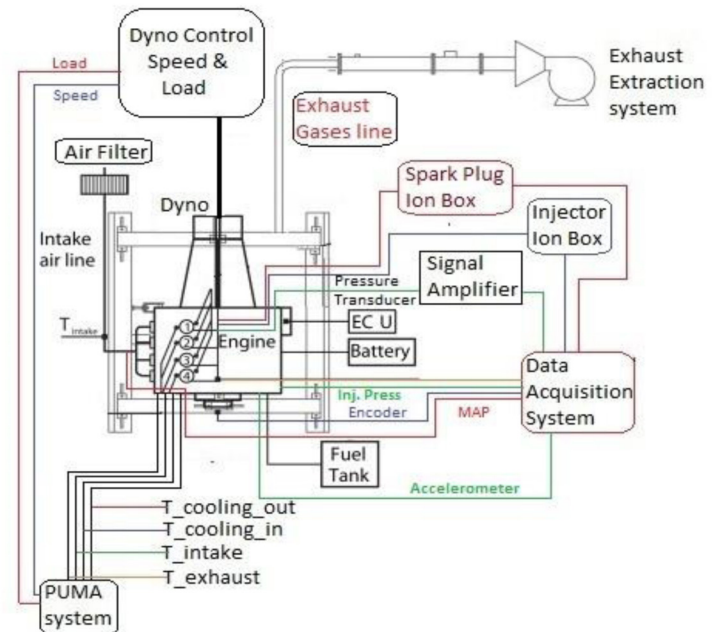


Figure 5. Layout of experimental setup.

Cylinder one is fitted with a spark plug pressure transducer, the spark plug and the injector of the four cylinders are used to measure the ion current

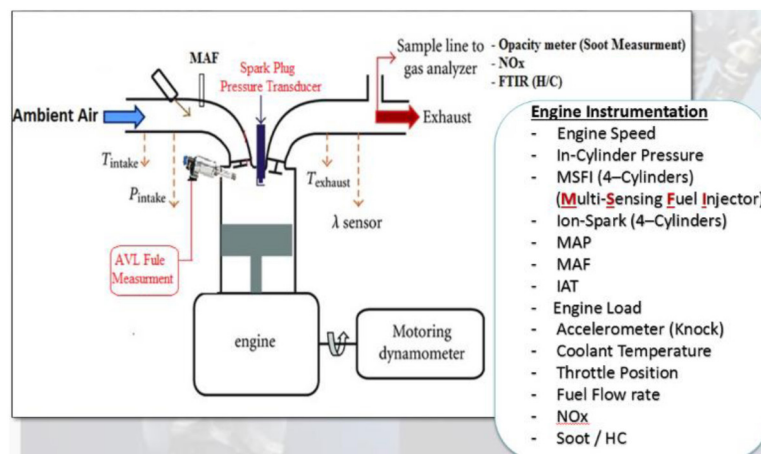


Figure 6. Schematic diagram for engine instrumentation.