

# Homogeneous Charge Compression Ignition (HCCI) Engine

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## ABSTRACT

Ion sensors have been shown to be a low-cost and robust method of measuring start of combustion (SOC) in Homogeneous Charge Compression Ignition (HCCI) engines. The combustion event in an HCCI engine is governed by temperature sensitive chemical-kinetics and is highly fuel dependent. Autoignition variability between various fuels can also affect emissions, efficiency, and overall operating range of the HCCI engine. Ion sensors (i.e. modified spark-plugs) can be used pragmatically to detect the combustion event for various fuels in HCCI engines over a wide range of operating conditions. An investigation of the ion currents produced from the combustion of gasoline, ethanol, and n-heptane in a 1.9L 4-cylinder VW TDI diesel engine (converted to run in HCCI mode) is conducted over a range of equivalence ratios, intake temperatures, and intake pressures. Gasoline, ethanol and n-heptane have diverse autoignition characteristics which affect the overall operation of the HCCI engine. Experiments show that detecting ions during combustion is a sufficient and reliable technique used in measuring SOC for various fuels in a HCCI engine. The ion currents for gasoline and ethanol are comparable, while n-heptane produces a much weaker ion current. The fact that gasoline and ethanol have comparable ion currents has huge implications in regards to the use of fuel blends consisting of 85% ethanol and 15% gasoline (E85) in HCCI engines. Additionally, the ability to measure ion currents using n-heptane fuel suggests ions may be measurable in diesel fueled HCCI engines.

## INTRODUCTION

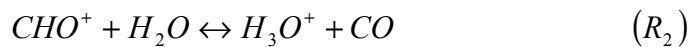
A Homogeneous Charge Compression Ignition (HCCI) engine has the distinct characteristics of high efficiencies (high compression ratio) compared to gasoline engines, low NO<sub>x</sub> (low peak temperature), low Particulate Matter (PM) (homogeneous air/fuel mixture), and the ability to operate on a variety of fuels (i.e. gasoline, ethanol, diesel, n-heptane, and others). These characteristics make HCCI an ideal candidate for the next generation of passenger vehicles. However, a main obstacle in the introduction of a fully automated HCCI engine into a production vehicle is the lack of control of the combustion process. In order for HCCI to become a viable production engine, the issue of controlling combustion timing with a cost-effective system is extremely important, thus the use of an ion sensor using a standard spark plug is ideal. Ion sensors using standard spark plugs are inexpensive sensors which are also ideal for production engines switching between Homogeneous Charge Spark Ignition (HCSI) and HCCI mode.

The current study looks into the effects of ion production in the combustion chamber with respect to three different fuels. The three fuels chosen are gasoline, ethanol, and n-heptane. These three fuels are chosen for very distinct reasons; gasoline is selected for its prominent use in the United States, ethanol is selected for its potential use as a fast-growing alternative fuel, and n-heptane is used because of its diesel-like characteristics (in regards to auto-ignition) and simplicity for both experiments and modeling. A sufficient understanding of the effect of fuels on the ion current is required if the ion detector is to successfully replace the pressure transducer for measuring SOC in an HCCI engine.

## ION PRODUCTION

Ions produced in flames have been studied for many years [1-3]. Ion sensors have been used in HCSI (gasoline) engines to measure misfire and knock [4-6]. The high combustion temperatures and near stoichiometric fuel concentrations in a HCSI (gasoline) engine produce strong ion currents. Ion detection in HCCI engines has only recently become a potential combustion diagnostic tool. HCCI unlike HCSI is a relatively lean and low temperature combustion event, which leads to small quantities of ions being produced during the combustion event [7-9].

The ions produced in a HCCI engine are due to a chemi-ionization process described by three principle reactions [6,10].



Results from numerical models indicate that  $H_3O^+$  is the most dominant ion and the associated electron is responsible for the current that can be used to detect the combustion event [11-13]. Experiments have identified  $CHO^+$ ,  $H_3O^+$ ,  $C_3H_3^+$  using spectrometric techniques [7]. Using the ion current produced from the reactions shown above, a sensor is designed that measures the small current for detecting the combustion event in a HCCI engine.

## EXPERIMENTAL SETUP

### TEST ENGINE

The HCCI engine used in the current experiment is a modified 1.9L Volkswagen (VW) 4-cylinder Turbo-charged Direct Injection (TDI) diesel engine with a compression ratio of 17:1 operating at 1800rpm (+/- 5 rpm). Detailed specifications are listed in Table 1. The glow-plug holes originally located on the cylinder head were replaced with standard (16mm) spark-plug holes for ion sensors. The ion sensors are located between the intake and exhaust valves.

TABLE 1. VW TDI ENGINE SPECIFICATIONS

|                               |                        |
|-------------------------------|------------------------|
| Compression ratio             | 17:1                   |
| Intake valve opening (IVO)    | 16 ATDC                |
| Intake valve closing (IVC)    | 25 ABDC                |
| Exhaust valve opening (EVO)   | 28 BBDC                |
| Exhaust valve closing (EVC)   | 19 ATDC                |
| Overlap                       | 3°                     |
| Valve lift (Intake & Exhaust) | 1.0 mm                 |
| Cylinder Bore                 | 79.5 mm                |
| Stroke                        | 95.5 mm                |
| Volume BDC                    | 504.73 cm <sup>3</sup> |
| Volume TDC                    | 29.69 cm <sup>3</sup>  |

Gasoline, ethanol, and n-heptane are the three fuels used in these experiments. The gasoline has a 91 octane rating (R+M/2) obtained commercially in California, thus the gasoline is expected to contain some percentage of ethanol ( $\leq 6\%$ ). This quality of gasoline is used for a realistic comparison with what is currently used in our automobiles, based on the goal of using ion sensors on production engines. The ethanol and n-heptane fuels are both 100%.

The turbocharger is removed from the engine due to poor performance associated with the low exhaust temperatures produced during operation of the engine in HCCI mode. The intake air is heated approximately 1 meter before the intake manifold to temperatures of 150°C to 170°C (depending on operating conditions). The fuel is injected upstream of the intake valves, using standard gasoline fuel injectors (8.62 kg/hr). The fuel injectors are located on a custom intake runner system which provides separate intake pathways for each cylinder, so fueling and intake temperature to each cylinder is independently controlled. The fuel and air is pre-mixed approximately 18 cm upstream of the intake manifold to ensure proper mixing before entering the combustion chamber. The typical emissions of 1-5 ppm of NO<sub>x</sub> for equivalence ratio of 0.25-0.4, suggests that the mixture is homogeneous, since such low NO<sub>x</sub> at these lean conditions would be unlikely if the mixture is not homogeneous.

### DETECTION SYSTEM

The ion detection system consists of a resistor (820 kOhm) and a bias voltage source (140V) as shown in Fig. 1. The entire system is contained in a portable aluminum box (L = 17.8 cm, W = 12.7 cm, H = 5.1 cm) that is connected to the spark plug (ion sensor). This self-contained ion detection system is connected to a data acquisition board and computer where the ion current is analyzed and compared with the pressure signal (acquired from AVL® QH33D quartz piezo-electric pressure transducers).

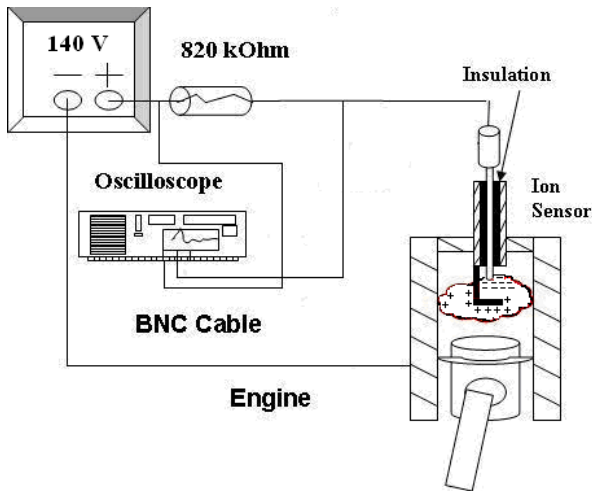


Figure 1. Schematic of the ion detection system consisting of a spark plug (ion sensor), a resistor, and a bias voltage source.

A bias voltage is applied to the ion sensor and the ion current through the resistor is read; essentially, the more ions that are produced, the larger the electron current that is conducted through the resistor. The spark plug has an electrode spacing of 1.27mm, the surface area of the positive electrode is 29.26 mm<sup>2</sup> and the surface area of the four side electrodes is 167.72 mm<sup>2</sup>. The center electrode of the spark-plug was chosen as positive and the side electrodes as negative due to a stronger ion current [6,14].

## NUMERICAL MODEL

HCCI process has the interesting characteristic of being relatively insensitive to turbulence and mixing effects compared to a HCSI (gasoline) or CI (diesel) engine, in large part because the mixture is homogeneous [15]. Auto-ignition chemistry is the main controlling parameter in determining ignition. This homogeneous feature eliminates the need of including the treatment of fluid dynamics, by modeling the combustion chamber with a Well-Mixed Reactor (WMR) with a time dependent variable volume. WMR does not account for the inhomogeneity of the temperature; therefore, the model tends to under-predict burn duration. Consequently peak pressure is over-predicted by using WMR. A WMR-model [16] with Woschni [17] heat transfer equations was used as the basis of the model. The engine wall temperature is assumed fixed at 430K (157°C) throughout the simulations. Additional engine parameters (bore, stroke, EGR, swirl, etc.) were included in the WMR model to resemble as closely as possible the actual engine used for the experiments [16,18-19]. Intake temperatures and intake pressures from the experiments were also input parameters for the model. The modeled and measured pressure traces were compared to ensure the validity of the model. The model predicted ignition 1° to 4° crank angle degrees (CAD) before measured ignition, providing a good level of agreement as shown in Figs. 2-4.

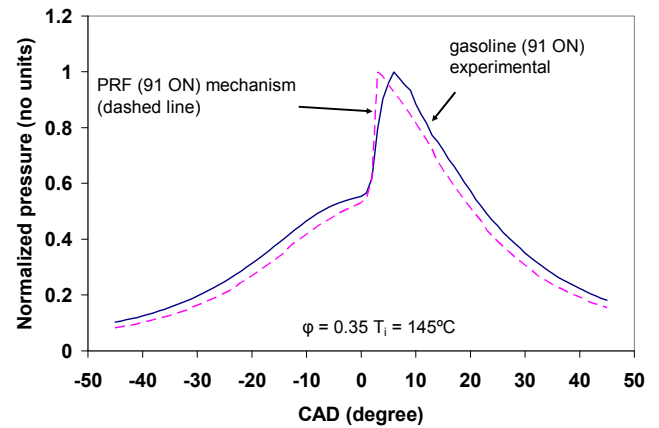


Figure 2. WMR model using the (PRF 91 ON) mechanism predicts an early auto-ignition compared to the experimental auto-ignition of gasoline (91 ON).

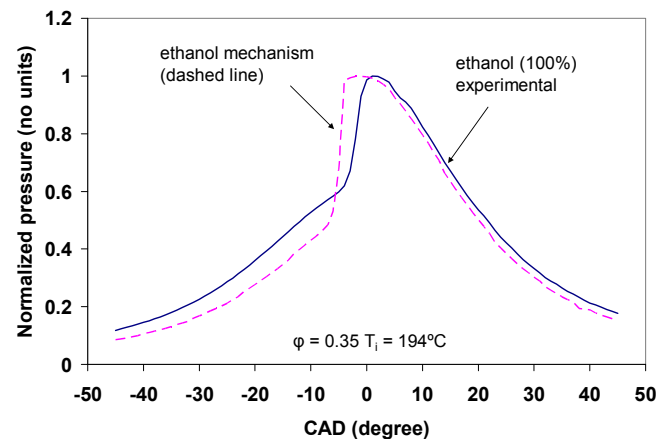


Figure 3. WMR model using the ethanol mechanism predicts an early auto-ignition compared to the experimental auto-ignition for ethanol (100%).

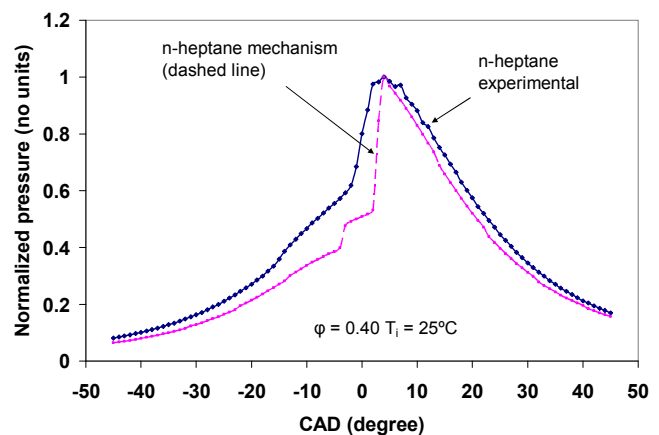


Figure 4. WMR model using n-heptane mechanism predicts a late auto-ignition compared to the experimental auto-ignition for n-heptane (100%).