

Analysis of In-Cylinder Hydrocarbons in a Multi-Cylinder Gasoline HCCI Engine Using Gas Chromatography

Johannes Arning, Tashiv Ramsander and Nick Collings

University of Cambridge

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ABSTRACT

Gasoline Homogeneous Charge Compression Ignition (HCCI) combustion has been studied widely in the past decade. However, in HCCI engines using negative valve overlap (NVO), there is still uncertainty as to whether the effect of pilot injection during NVO on the start of combustion is primarily due to heat release of the pilot fuel during NVO or whether it is due to pilot fuel reformation.

This paper presents data taken on a 4-cylinder gasoline direct injection, spark ignition/HCCI engine with a dual cam system, capable of recompressing residual gas. Engine in-cylinder samples are extracted at various points during the engine cycle through a high-speed sampling system and directly analysed with a gas chromatograph and flame ionisation detector. Engine parameter sweeps are performed for different pilot injection timings and quantities at a medium load point.

Results show that for lean engine running conditions, earlier pilot injection timing leads to partial oxidation of the injected pilot fuel during NVO, while the fraction of light hydrocarbons remains constant for all parameter variations investigated. The same applies for a variation in pilot fuel amount. Thus there is evidence that in lean conditions, pilot injection-related NVO effects are dominated by heat release rather than fuel reformation.

INTRODUCTION

A rising degree of motorisation worldwide, increasing fuel prices and a more sensitive perception in the population towards environmental issues have increased the demand for fuel-efficient vehicles.

HCCI combustion has been seen as a combustion process which combines the advantages of the conventional Compression Ignition (CI) and Spark Ignition (SI) engine, leading to a combustion with high fuel efficiency and low emissions. HCCI combustion is sometimes also referred to as Controlled Auto-Ignition (CAI) combustion [1].

In HCCI combustion, a homogeneous mixture of fuel and air (and in some cases burnt residual gas from the previous engine cycle) is compressed to a stage where the in-cylinder charge reaches conditions that cause the fuel-mixture to auto-ignite. However, excessive rates of pressure rise in gasoline HCCI combustion can only be avoided by diluting the fuel mixture [2]. The engine is therefore running lean, and the maximum load that can be achieved is significantly reduced compared to SI combustion. The consequence is that the HCCI engine also needs to be capable of running in SI mode to cover its entire operating range [3].

Several approaches have been suggested to reach sufficient in-cylinder temperatures at the end of compression, amongst them heated air intake [4], variable compression ratio [5] and recompression of burnt residual gas [6, 7, 8]. The latter has proven to be the most promising technique for a future application in a vehicle.

Unlike conventional CI or SI combustion, HCCI combustion lacks a direct input which initiates combustion. Instead, the start of combustion is determined by the in-cylinder fuel and gas properties at the start of compression. Due to the short time window in which the heat release takes place, the combustion

phasing of HCCI is critical for maintaining a high thermal efficiency.

In HCCI engines using a dual cam system with NVO, the valve timing and thus the amount of trapped residual gas may be altered to change the in-cylinder temperature and therefore combustion phasing of the engine [9]. Further parameters such as altering the timing and amount of a further fuel injection during NVO, often referred to as pilot injection, have proven to influence combustion phasing [10].

This paper is concerned with a study to gain a more detailed understanding of the effects of the pilot fuel injection on HCCI combustion. Standing et al. [11] observed exothermic reactions of the pilot fuel during NVO in the presence of oxygen. Optical analysis of HCCI combustion revealed high concentrations of formaldehyde during NVO [12, 13]. It has been proven that the pilot fuel undergoes both fuel reforming and exothermic reactions during NVO [10, 14, 15, 16]: The reformation of fuel is considered to be resulting in the formation of intermediate species that facilitate HCCI combustion, while exothermic reactions and therefore an increase in in-cylinder temperature due to the heat release during NVO is thought to have a similar effect.

EXPERIMENTAL SETUP

ENGINE - Experiments are carried out on a four-cylinder in-line, four-stroke gasoline direct injection (GDI) engine; for details see Table 1. HCCI combustion is achieved using dual valve timing with NVO.

Type	I4 GDI, 16V
Displacement	1,999 cc
Compression ratio	12.0 : 1
Bore	87.5 mm
Stroke	83.1 mm
Variable Valve Actuation	Dual profile camshaft with switchable tappets Intake VCT 55 CAD Exhaust VCT 30 CAD
Fuel rail pressure	Max. 150 bar
Injector	Bosch 6-hole GDI

Table 1: Engine characteristics

The engine is run on a Shell 95 RON reference fuel with a 4.0 % mass fraction of C4 or lighter species. Intake air temperature and pressure are ambient; the engine coolant water is maintained at a temperature between 85°C and 90°C.

DIRECT SAMPLING - In-cylinder gas is extracted from the combustion chamber and directly injected into a gas chromatograph (GC).

A fast in-cylinder gas sampling system (Combustion Sampling Valve, CSV) is fitted to a sample probe that enters the combustion chamber of engine cylinder 4. The sample probe uses a drilling in the cylinder head parallel to the head face just above the head face and samples gas from the cylinder wall region.

The CSV is connected to the GC via a sampling system which accumulates the engine in-cylinder sample from several engine cycles and then always injects the same volume of sample into the GC.

To control the function of the sampling system, a 6-port 2-way valve for GC applications made by VICI Valco Instruments is used to switch between the two modes 'Load' and 'Inject': During the 'Load' position, the sample gas is pushed through the sample loop, whilst the GC is supplied with the carrier gas, see Figure 1. The sample loop has a volume of 5ml and it contains the gas that will later be injected into the GC. When the valve switches over to the 'Inject' stage, the carrier gas pushes the sample out of the sample loop into the GC, see Figure 2. At the same time the CSV is still extracting in-cylinder gas, but this is now released to the atmosphere without affecting the sample that is injected into the GC.

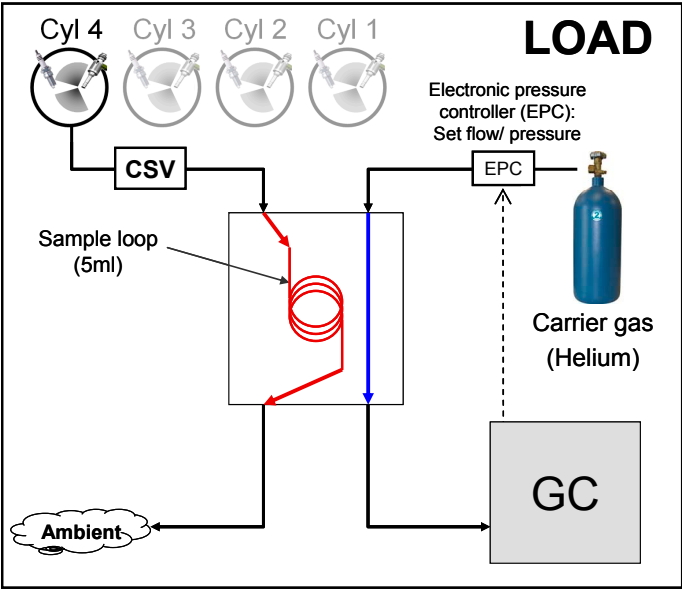


Figure 1: Schematic diagram of the direct sampling system – 'Load' position

In order to avoid condensation of hydrocarbons, major effort has been put into heating all sampling lines and equipment where the gas flows through to a temperature of 190°C. There are no intermittent 'cold spots' between the sample probe upstream of the CSV and the sampling line which leads into the GC.

GAS CHROMATOGRAPH - An Agilent 7890A gas chromatograph is used in combination with an HP-5 column (30m length, 320µm ID, 25µm film thickness).

The hydrocarbons are analysed using a flame ionisation detector (FID). The detailed GC settings for this experiment are listed in Table 2.

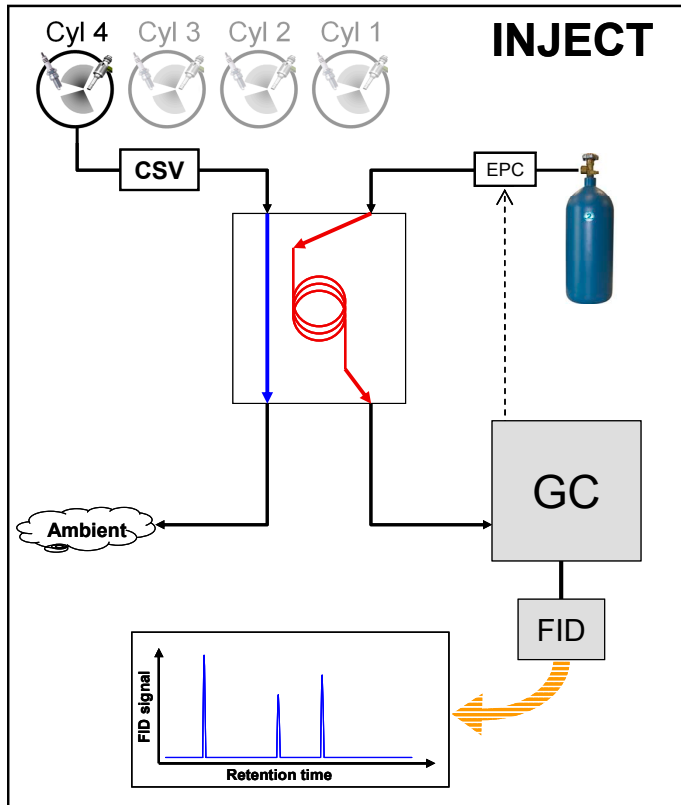


Figure 2: Schematic diagram of the direct sampling system – 'Inject' position

After a run time of 4 min, good separation and retention time of the species is no longer relevant (see 'Experimental Procedure'), therefore the GC is set to a high oven ramp rate that is unattainable in practice and to an increased carrier gas flow in order to reduce the total run time.

Split ratio	150
Carrier gas	Helium
Carrier gas flow	1ml/min (constant flow), increased to 4ml/min after 4 min run time
Oven initial temp.	40°C
Initial hold time	4 min
Ramp rate	108°C/min
Final temp.	300°C
Final hold time	3.5 min
Total run time	9.9 min

Table 2: GC settings

EXPERIMENTAL PROCEDURE

The research presented in this paper focuses on how the pilot fuel changes due to the high temperature and pressure conditions during the NVO event. The in-cylinder gas must be analysed at a stage where it is not affected by the main fuel injection. It is necessary to sample the gas as late in the main compression as possible. This is to ensure that the gas is well-mixed and that the sample extracted from the cylinder is representative of the in-cylinder gas. For this reason the CSV sampling window is at the end of the compression stroke, namely 10-0 CAD BTDC, in all cases. During the intake event the in-cylinder charge is cooled down considerably, leading to the assumption that after the NVO further fuel reforming is negligible.

In order to keep the sampled gas representative exclusively of the pilot fuel reformation, the main injection has to be omitted whenever gas is sampled (see Table 3 for injection timings). However, prerequisite for an investigation on NVO fuel effects in real operating conditions is that the residual gas from the previous engine cycle is typical of normal operation. For this reason the engine is run under normal conditions (i.e. with pilot and main injection) for 14 consecutive cycles before the main injection is omitted in the following cycle and the CSV is actuated to take a sample during that skip-firing cycle. This procedure is repeated continuously to accumulate enough sample for the chemical analysis.

HCCI combustion using NVO is an iterative process due to the internal EGR and therefore does not recover to normal combustion straight away after the main injection has been omitted. Skip-firing every 15th cycle ensures that the combustion has returned to steady-state conditions by the time the main injection is omitted again.

In order to investigate the changes in the fuel from the pilot injection, the hydrocarbons that originate from the pilot injection have to be isolated from the hydrocarbons in the residual gas. This is achieved by taking a sample of the residual gas and subtracting it from the hydrocarbon (HC) concentration of the sample with pilot injection. The procedure for sampling the residual gas is the same as mentioned above, with the only exception that during the skip-firing cycle both the pilot and main injection are omitted. The actual residual gas has in fact been diluted with fresh intake air before it is analysed, however, in this paper the term 'residual' will be used for the diluted residual gas sampled at the end of the compression stroke.

Summarising the above, there are two different sampling cases:

- Pilot + Residual: The engine is omitting the main injection every 15th cycle, in-cylinder gas is extracted during that cycle