

Stabilization of Highly Diluted Gasoline Direct Injection Engine using Innovative Ignition Systems

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ABSTRACT

Dilution is a promising way to improve fuel economy of Spark-Ignited (SI) gasoline engines. In this context, influence of innovative ignition systems on the dilution acceptance of a 400cc optical GDI engine has been studied. Several systems were tested and compared to a conventional coil: a dual-coil system and two nanosecond scaled plasma generators. Two operating points were studied: 2.8bar IMEP (net) at 2000rpm and 9bar IMEP (net) at 1200rpm. Two diluents were evaluated: real EGR and air (lean combustion). High-speed imaging at frequency up to 10kHz was performed to visualize both spark and combustion initiation and propagation. Voltage and current were measured to infer the energy deposited in the spark plug gap.

The dual-coil DCO™ system and the nanosecond multi-pulse plasma generator at their maximum power showed an ability to extend the dilution range of the engine. The flexibility of these devices allowed to conduct studies to evaluate the influence of parameters such as spark duration, spark energy profile deposition. Results show that the dilution limit can be pushed back in certain conditions. Significant gain in the dilution tolerance is obtained by increasing the energy deposition at lower load conditions (2.8bar * 2000rpm), whereas no influence of the ignition system is observed at higher load conditions (9bar * 1200rpm). At low load conditions, it is demonstrated that energy deposition appears to be the key ignition parameter to extend engine stable operation range through higher dilution rate, spark duration showing no significant influence.

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INTRODUCTION

Internal combustion engine research mainly focuses on fuel consumption improvement (targeted CO₂ emission in 2020 in Europe is 95 g/km) and pollutant emissions reduction to comply with future emissions regulations (EU6-7, Tier II-III, CARB LEV III...). A common response to these requirements is downsizing coupled with turbocharging. These strategies offer a significant reduction in pumping losses. However, benefits are mitigated by knock tendency and increased wall losses. A rising approach to limit these phenomena is dilution. At low load conditions, increasing the total intake mass comes along with a lower average gas temperature at the end of combustion [1]. This diminishes wall losses and pumping work. At high load conditions, dilution helps to limit knock tendency [2,3,4] and exhaust gas temperature [5,6]. These respectively allow to

optimize combustion phasing and avoid fuel enrichment. Two gases are commonly used for dilution: EGR (Exhaust Gas Recirculation) and air. Air is reported to be more efficient at low load conditions due to its higher γ (heat release capacity ratio) [7]. Though, the necessary NO_x after-treatment is a significant limitation to lean combustion concepts (except for quasi no-NO_x lean operation like, e.g. HCCI).

Nevertheless the use of diluted combustion in a gasoline engine reveals several disadvantages. First of all, manufacturers can be reluctant to add the cost of an EGR system. The implementation of the system also leads to strong constraints on the engine control due to the induced time response of the air loop. Finally the main flaw is the dilution tolerance of the engine. Diluted combustion goes along with a reduction of the flame speed leading to engine instabilities.

This paper focuses on pushing back dilution limit. Several solutions have been considered in the literature. Adding reactive species can speed up combustion rate [8,9]. Increasing in-cylinder flow motion has also been reported to enhance flame propagation thus helping engine stability for highly diluted operation [7]. Bring a late injection to get stratification at ignition can stabilize the combustion by speeding up combustion initiation [4]. Another mean to enhance combustion initiation is to improve ignition system.

The goal of this work is to evaluate innovative ignition systems potential to improve engine stability in highly diluted conditions, and give insight on key parameters interactions between ignition and combustion. First the experimental apparatus and protocol is presented. Then reference cases are studied, using a conventional coil on a low- and an intermediate-load operating points. Finally, innovative ignition systems are tested. A parametric variation reveals key parameters and a comparison of all the tested systems is presented.

EXPERIMENTAL APPARATUS

Engine Configuration

The single cylinder optical engine used in this program is a prototype designed at IFPEN. It is representative of a modern downsized engine with a high level of turbulence. It has a capacity of 400 cm³, a compression ratio of 10.5:1, and Gasoline Direct Injection (GDI) in central position. This engine is equipped with an extended (bowditch) piston for optical access, though this access was not necessary in these experiments. Dry lubrication is used, meaning no oil film on the liner. The engine was operated with commercial RON95 fuel. The use of a tumble flap allows the level of tumble motion to be varied from 1.1 to 1.5. These tumble motion values correspond to the in-house characterization of the tumble motion. In this study a multihole injector was used. A dedicated external high-pressure, cooled-EGR circuit enables high level of EGR rates to be achieved. Whatever the EGR rate, intake plenum temperature was maintained constant at 35°C. Main characteristics of the engine are summarized in [Table 1](#).

Table 1. Main engine characteristics

	IFPEN Prototype Optical engine
Type	Single cylinder, 4 valves
Capacity	400cc
Bore x Stroke	77 x 85.8 mm
Compression Ratio	10.5 : 1
Injection	GDI central (6 holes) P _{inj} =200bar
Flow motion	Variable tumble (1.1 & 1.5)
Fuel	SP95 (E5)

Quartz windows were mounted in the cylinder head, in the pent-roof axis, to allow optical access in the upper part of the combustion chamber ([Figure 1](#)).

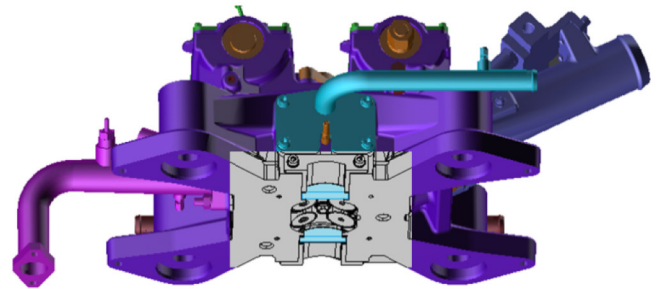


Figure 1. 3D sketch of the cylinder head mounted with quartz windows.

Optical Diagnostic

Spark development at spark plug tip and combustion initiation propagation were monitored using a high-speed camera (Photron SA5) through the optical access presented in [Figure 1](#). Light is collected in the entire visible range. Exposure duration and acquisition rate were set to allow recording spark and combustion simultaneously: 50ms at 20kHz. An example of frame capture is presented in [Figure 2](#). The spark is clearly visible, as well as the burnt gases.

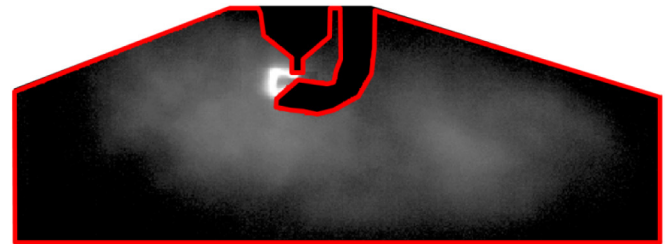


Figure 2. Frame capture of spark and combustion propagation. The ignition system used is the DCO™ system. Exposure time is 50ms.

This diagnostic was used to distinguish misfires due to absence of spark (especially for the nanosecond devices), from misfire due to a non-ignition of the mixture.

Ignition Systems

Four ignition systems were tested:

1. A conventional coil (Eldor-Audi 06H905110E) delivering a capacitive discharge.
2. A Dual Coil system (DCO™) using two automotive-style ignition coils connected by a diode to create a long continuous spark [10]. This system allows to vary spark duration and energy.

3. A Nanosecond Repetitively Pulsed Discharge system (NRPD) delivering high voltage pulses (up to 30kV) lasting 10ns [11]. Repetition frequency is also tunable, from 1kHz to 100kHz. The amplitude and number of pulses is accordable thus allowing duration and energy variation.
4. A Nanosecond High Voltage Single Pulse system (NHVSP) delivering a single 50-ns long high voltage pulse [12].

The first two systems create a conventional arc discharge. This type of discharge leads mainly to gas heating [13]. The two nanosecond systems create a non-equilibrium plasma discharge. Because of the ultra-short duration of the high voltage pulse, the internal energy levels of excited molecules does not have time to reach equilibrium before discharge ends. The time scale of energy deposition and energy transmission to the gas is therefore completely different. Gas heating is less important, and more radicals and excited species are created [14].

For ignition system #1, 2 and 3, a conventional spark plug tip was used. The gap was 0.8mm. For ignition system #4, the spark plug tip was custom made as shown in Figure 3 (cf. [12]).

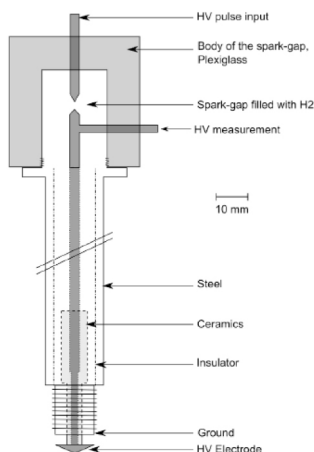


Figure 3. Description of ignition system #4 (NHVSP), reproduced from [12].

Energy Calculation

The energy deposited by an ignition system is usually determined by measuring the voltage before the spark plug (i.e. at the secondary coil) with a high voltage probe, and the current with an ampere clamp on the cable connected on the spark plug. Due the various time scales of the different ignition systems (from nanosecond to millisecond) and their according bandwidth requirements, it would not have been possible to use the same setup for each system. Moreover, with this method energy upstream the spark plug is calculated. To avoid electromagnetic parasites in the ignition electronic system, the spark plug is usually resistive, typically a few kilohms. Thus to

accurately calculate the energy deposited in the spark plug gap, the voltage at the spark tip has to be measured, which is usually impossible since the spark plug is inside the engine. Therefore in this study, a special protocol was implemented. The experimental setup is presented in Figure 4.

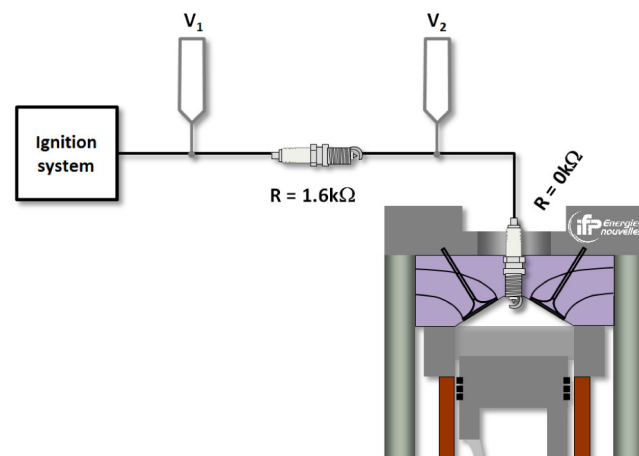


Figure 4. Experimental setup used to measure energy deposited in the spark plug gap.

The novelty of this setup sits in the replacement of the resistive spark plug with a non-resistive spark plug. Thus with the V_2 probes, voltage at the spark plug tip is accessible, even when the engine is running. To keep an electromagnetic protection of the circuit a resistor is connected in serial of the spark plug. To match the usual circuit characteristics, this resistor is a resistive spark plug, of $1.5k\Omega$ which ground electrode has been removed. Using Ohm's law the current can be calculated, adding a second high voltage probe to measure V_1 . Voltage V_1 and V_2 were measured using Lecroy voltage probes (LeCroy PPE20kV). The energy is then inferred from integrating the product $V_2 \times i$ over the spark duration.

All ignition systems were characterized in situ using this protocol, except the NHSVP. Indeed the NHSVP consists in a standard automotive ignition coil connected to a spark gap (cf. [12]). The ignition coil plays the role of both high-voltage generator and loading capacitor. Coupled with an auxiliary spark gap, the ignition coil can then provide nanosecond high-voltage pulses. Therefore the spark plug tip is not directly accessible with a voltage probe, and the energy delivered by the system had to be characterized outside the engine, in standard T,P conditions.

Figure 5 presents measurements obtained for the conventional and the DCO systems. The engine is operated in low load conditions (2.8bar net IMEP * 2000rpm), meaning that at measurement timing temperature and pressure inside the chamber are approximately 8bar, 680K. These results shows that voltage after breakdown is comprised between 300V and