

Experimental and Numerical Investigation in a Turbocharged GDI Engine Under Knock Condition by Means of Conventional and Non-Conventional Methods

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ABSTRACT

The present paper deals with a comprehensive analysis of the knocking phenomenon through experiments and numerical simulations. Conventional and non-conventional measurements are performed on a 4-stroke, 4-cylinder, turbocharged GDI engine. The engine exhibits optical accesses to the combustion chamber. Imaging in the UV-visible range is carried out by means of a high spatial and temporal resolution camera through an endoscopic system and a transparent window in the piston head. This last is modified to allow the view of the whole combustion chamber almost until the cylinder walls, to include the so-called eng-gas zones. Optical data are correlated to in-cylinder pressure-based indicated analyses in a cycle resolved approach.

The numerical investigation is performed through a properly developed 3D CFD model of the engine under study, that employs the Extended Coherent Flamelet Model for the combustion initiated by the spark plug and the Shell model to reproduce the low temperature chemical activity in the mixture not yet reached by the main flame front. The role of the intermediate species of the Shell model in localizing both spatially and temporally the occurrence of undesired self-ignitions is highlighted.

Numerical and experimental data well correlate, in particular regarding the self-ignition location in the combustion chamber on the side where the injector is positioned. The opposite side, in fact, is positively affected by the charge cooling effect deriving from the subtraction of the latent heat of vaporization of the spray droplets.

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INTRODUCTION

The combustion process in a spark ignition engine regularly proceeds starting from the spark plug if the flame front propagates by progressively investing all the mixture within the combustion chamber. Various factors may affect the normal and complete ignition of the charge and determine abnormal combustions. Some operating conditions, or the same geometric configuration, may generate deposits of unburned hydrocarbons or local increase of the wall temperature, which cause spontaneous ignition of the mixture even before it is invested by the flame front triggered by the spark. Among abnormal combustions, the most relevant, without any doubt, is knocking. This consists in the self-ignition of the in-cylinder end-gas zones of the charge, not yet reached by the main flame front [1, 2].

The self-ignition of a fuel-air mixture is the outcome of a series of pre-flame or low temperature reactions, which lead to the start of combustion without the need of an external energy source, but through the formation of not stable products of partial oxidation (peroxides, aldehydes, hydroperoxides, etc.) and the release of thermal energy. When the energy of the exothermic chemical

reactions exceeds the amount of heat transferred from the reacting system to the environment, combustion occurs spontaneously. As a consequence, the temperature of the mixture increases, rapidly accelerating the subsequent oxidation reactions [3].

Knocking limits the performance and the energy efficiency of spark ignition engines, preventing to exceed certain values of the compression ratio and spark advance, and, at the same time, leading to restrictive constraints to the formulation of fuels. It appears as a characteristic metallic noise involving power loss, vibration, and, under particularly severe conditions, damage of mechanical parts [4].

Tendency to knocking is also favorably affected by the direct injection of gasoline within the combustion chamber, due to the decrease of the charge temperature consequent the evaporation process. The complex kind of the pre-flame reactions, of chain type between highly reactive species, produced in an amount superior to the consumed one by different propagation reactions, may be controlled through the introduction of small amount of additives in the base fuel, which hinder or enhance the formation of radicals acting as chain propagators [5, 6].

In the recent past, various measures are being proposed to reduce the knocking tendency as through proper charge stratification [7], by optimal valve control [8], or by cooled exhaust gas recirculation [9].

Nevertheless, and also despite many already performed investigations, the knocking phenomenon remains a crucial topic in the design and development of gasoline direct injection (GDI) engines, with remaining uncertainties and unsolved questions [1, 10]. From the experimental point of view, knock detection is a complicated matter due to the sporadic occurrence the phenomenon may have within the engine cyclic variability. Modeling and previewing the knocking occurrence, on the other hand, is a really complicated matter, since it implies the need to take into account tens of reactions including hundreds of chemical species to reproduce the detailed underlying chemical mechanisms in the mixture not yet reached by the flame front initiated by the spark.

In the present paper, a synergic experimental and numerical study is carried out on a high performance turbocharged GDI engine. Due to the optical accessibility of the engine to the combustion chamber, exhibiting a piston properly modified to allow a large view of the in-cylinder phenomena, cycle resolved images are captured that show the occurrence of self-ignition at some particular locations. A properly developed three dimensional (3D) computational fluid dynamics (CFD) model of the energy conversion process taking place within the cylinder is also developed, able to predict the conditions for which the engine may undergo abnormal combustions.

The Extended Coherent Flamelet Model (ECFM) [11] belongs to the family of the flamelets models and is chosen within the present work to reproduce the propagation of the flame initiated by the spark. This approach is however not able to describe the knocking phenomenon. Therefore an alternative route is followed, just based on what is the underlying mechanism of knocking: while the main flame front propagation follows the ECFM model, the schematization of the incubation phase of combustion in the end-gas zone is made through a reduced number of reactions involving not individual species, but groups of chemical compounds exhibiting a similar behavior. The chosen model, the well known Shell by Halsted et al. [12] assumes, in this zone, the low-temperature activity as occurring through eight steps involving three main fictitious species (indeed group of chemical species), that allow reproducing the major chemical events, as branching, propagation or linear termination. The Shell model has been widely used in engine applications related to both Diesel and spark ignition engines [13, 14]. Although this model was developed more than thirty years ago, it remains of a certain interest for CFD applications, due to its simplicity combined with a generalized description of the kinetic mechanism of ignition, which has been proved as adequate to predict the main phenomena of interest in a variety of situations. Other kinetic mechanisms developed

subsequently to the Shell, on the other hand, have a much higher number of reactions and species involved, which makes for their use being of little interest in complex computational domains [15, 16].

EXPERIMENTAL APPARATUS

The experimental apparatus employed for the collection of data to be used for the validation of the 3D engine model includes the following modules: the spark ignition engine, an electrical dynamometer, the fuel injection line, the data acquisition and control units, the emission measurement system and the optical apparatus. A turbocharged GDI, inline 4-cylinder, 4-stroke, with a displacement of 1750 cm³, is the object of the present study. The engine is equipped with a Bosch 7-hole injector located between the intake valves and oriented at 70° with respect to the cylinder axis.

In the commercial engine configuration, mixture formation is realized in the wall guided mode, being the piston head properly shaped with a nose and an adjacent cavity, to direct the spray and vapor cloud towards the top of the cylinder and the spark plug. In the present study, a flat piston is used, all made of a quartz window to allow the full view in the combustion chamber almost until the cylinder walls. The engine is equipped with a Variable Valve Timing (VVT) system in order to optimize the intake and exhaust valves lift under each specific regime of operation. The engine is not equipped with after-treatment devices. Some details are reported in Table 1, where the crank angle of Exhaust Valve opening (EVO), Exhaust Valve Closing (EVC), Intake Valve Opening (IVO) and Intake Valve Closing (IVC) are all expressed in degrees after (A) or before (B) the relevant dead centre (BDC, Bottom Dead Center; TDC, Top Dead Center). The valve timing angles are referred to a valve lift of 0.15 mm.

Table 1. Characteristics of the engine under study.

Unitary displacement	435,5 cm ³
Stroke	80.5 mm
Bore	83 mm
Compression ratio	9.5:1
Max. boost pressure	2.5 bar
Valve Timing	Int. and Exh. VVT
Exhaust Valve Opening	1° BBDC @ 0.15 mm lift
Exhaust Valve Closing	15° ATDC @ 0.15 mm lift
Inlet Valve Opening	3° BTDC @ 0.15 mm lift
Inlet Valve Closing	20° ATDC @ 0.15 mm lift
Max. power [kW]	147.1 @ 5000 rpm
Max. torque [Nm]	320.4 @ 1400 rpm

An electrical dynamometer allows the operation under both motoring and firing conditions, hence detecting the in-cylinder pressure data and exploring the engine behavior under stationary and simple dynamic

conditions. An optical shaft encoder is used to transmit the crank shaft position to the electronic control unit. The information is in digital pulses, the encoder has two outputs, the first is the Top Dead Center (TDC) index signal with a resolution of 1 pulse/revolution, and the second is the Crank angle Degree Marker (CDM) 1pulse/0.1 degree. Since the engine is 4-stroke, the encoder gives as output two TDC signals per engine cycle. In order to determine the right crank shaft position, one pulse is suppressed via the dedicated software.

A quartz pressure transducer is installed into the spark plug to measure the in-cylinder pressure with a sensitivity of 19 pC/bar and a natural frequency of 130 kHz. Thanks to its characteristics, a good resolution is obtained. The in-cylinder pressure, the rate of heat release and the related parameters are evaluated on an individual cycle basis and/or averaged over 200 consecutives cycles.

Optical Apparatus

The optical accessible engine used in this study is designed in order to maintain as much as possible the thermo-fluid dynamic configuration and the performance and emissions of the commercial engine. The modification needed to realize the optical accesses, in particular the elongated cylinders and elongated transparent piston, are designed in order to limits the alterations of the combustion chamber geometry. A first optical access is achieved through an endoscopic probe inserted in the chamber through the engine head, as in ref. [17], the second is in the piston head as hereafter described.

Pistons and cylinders of the original engine are modified to realize the optical access in the piston head. As shown in [Figure 1](#), the pistons essentially consist of an elongated body that allows the placement of the 45° mirror in axis with the cylinder through a proper opening on the side surface. The piston rings are substituted with Teflon-bronze and Carbon-bronze self-lubricating rings in order to avoid oil fouling of the mirror and of the optical windows. All of these components are designed to be easily assembled and disassembled during maintenance and optical windows cleaning operations [18]. The main optical view to the combustion chamber almost until the cylinder walls is obtained through the piston top by means of the 45° mirror. The piston top is practically replaced by a flat transparent window.

2D-digital high speed imaging is used to follow the flame front propagation in the combustion chamber. Cycle resolved flame visualization is performed by means of a 16-bit grayscale high speed CMOS camera with a resolution of 1024×1024 pixel and a maximum frame rate of 1 million fps. The camera is equipped with a 78 mm UV-Visible Nikkor objective. A region of interest (400 × 400 pixel) and a frame rate of 10000 fps are chosen to obtain a good accuracy in term of spatial and temporal resolution. The exposure time is fixed at 97 μs. A temporal resolution of about 0.9 CAD and a spatial resolution of 0.13 mm/pixel are obtained. An AVL Indimodul records the TTL signal from the camera acquisitions together with the signal measured by the pressure transducer. In this way, it is possible to

determine the crank angles where optical data are detected. The accuracy of the synchronization is controlled recording the camera monitor signal.

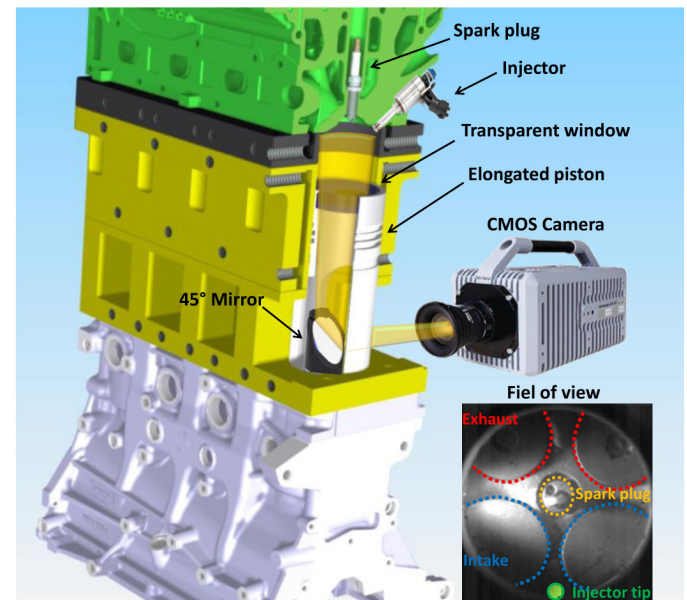


Figure 1. Experimental setup for optical investigation and detail of the combustion chamber field of view.

EXPERIMENTAL RESULTS

Engine Operating Conditions

The forthcoming discussion refers to an engine operation at the speed of 1500 rpm and high load, wide open throttle condition. The absolute intake air pressure is fixed at the mean value of 1300 mbar, the temperature is equal to 323 K. The injection pressure is equal to 10 MPa. Commercial gasoline is delivered through a 7-hole Bosch injector. A summary of the main engine parameters is given in [Table 2](#). Start of injection (SOI) and start of spark (SOS) are expressed in Crank Angles Degrees (CAD) BTDC. Cyclic variability is quantified by the Coefficient of Variation (CoV). [Figure 2](#) reports, in the considered operating condition, the in-cylinder pressure, as resulting from a 1000 Hz low pass filter, and the correspondent Rate of Heat Release (RoHR) for 3 of the collected 200 consecutive cycles. The 3 cycles represent the ones relevant to the slower, the faster and the mean combustion speed between the 73 that exhibit pressure oscillations, hence abnormal combustions. These are indicated in the following as cases c52, c71 and c46, respectively. The mean filtered cycle is used as reference for the assessment of the 3D CFD model described in the following, as it may be considered as representative of the engine operating condition under investigation.

Table 2. Operating conditions considered for study of the knocking occurrence.

Speed [Rpm]	SOI [CAD BTDC]	SOS [CAD BTDC]	DOI [μs]	A/F	Pinj [MPa]	CoV [%]	IMEP [bar]	CO [%]
1500	307	19	3700	14.7	10	2.2	11.9	2.3