

Study of Air Flow Interaction with Pilot Injections in a Diesel Engine by Means of PIV Measurements

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ABSTRACT

With ever-demanding emission legislations in Compression Ignition (CI) engines, new premixed combustion strategies have been developed in recent years seeking both, emissions and performance improvements. Since it has been shown that in-cylinder air flow affects the combustion process, and hence the overall engine performance, the study of swirling structures and its interaction with fuel injection are of great interest. In this regard, possible Turbulent Kinetic Energy (TKE) distribution changes after fuel injection may be a key parameter for achieving performance improvements by reducing in-cylinder heat transfer. Consequently, this paper aims to gain an insight into spray-swirl interaction through the analysis of in-cylinder velocity fields measured by Particle Image Velocimetry (PIV) when PCCI conditions are proposed. Experiments are carried out in a single cylinder optical Diesel engine with bowl-in-piston geometry. A standard 2D PIV system is used for measuring instantaneous velocity fields in a cross section (swirl-plane) inside the combustion chamber. The test matrix is based on an advanced single pilot injection with energizing time and injection pressure sweeps at different crank-angles. Results show that swirl ratio decreases with the increase of injected fuel mass. The decrease in swirl ratio also comes with a homogenization of the flow field. This homogenization along with lower swirl ratios might decrease heat transfer to cylinder walls.

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INTRODUCTION

During the last years the development of new combustion concepts leading towards higher fuel efficiency levels and lower pollutant emissions have been an active research topic in the engine sector. Even though CI engines are known for their high fuel efficiency compared to Spark Ignition engines, levels of NO_x and PM emissions are still a major concern. With the introduction of stricter emissions legislation, reducing exhaust emissions is becoming a more challenging task. As a result, new combustion concepts such as PCCI have been drawing attention. PCCI combustion can be achieved by advancing the injection event. If the injection event is well advanced ignition delay can be long enough so start of combustion takes place after the end of injection. This early injection strategy combined with EGR allows to decouple injection and combustion events providing an extra mixing time after the end of injection and consequently promoting a premixed low temperature combustion that achieves a simultaneous reduction of NO_x and PM emissions [1, 2, 3, 4]. Thus, it is possible to state that mixing process will not only be governed by injection process but also for the in-cylinder flow structures. In this sense, the study of the interaction between an advanced pilot injection and in-cylinder flow structures is of great interest. In light-duty (LD) CI engines with bowl-in-piston geometries the study of spray-swirl interaction is of particular importance since swirl is the flow structure behind large-scale transportation of air [5]. The analysis of swirl interaction with fuel injection may lead to a better understanding of in-cylinder processes such as fuel-air mixture and wall heat transfer under PCCI conditions.

As a part of this analysis, laser-based optical techniques can be used to measure in-cylinder velocities [6]. On this subject, Zha et al. [5] characterized swirl center motion during compression stroke in a LD Diesel engine with a realistic piston geometry using PIV. Results from this study shows that the swirl structure develops asymmetrically leading to an asymmetry mixture preparation. Regarding studies with fuel injection, Zegers et al. [7] used high speed PIV to study flow pattern changes during and after fuel injection in a heavy-duty optical Diesel engine. Velocity maps show that there is a sudden change in flow structure at the beginning of the injection event due to air entrainment into the fuel spray core. Findings in that same direction were made by Valentino et al. [8]. The authors used PIV to evaluate spray structure for different nozzles and injection strategies. From their results it was shown that air entrainment induce changes in the flow structure. This work also evaluated the effect of different nozzles and injection strategies on NO_x and HC emissions. Another optical measurement technique derived from PIV known as Combustion Image Velocimetry (CIV) has been used to analyze the influence of fuel injection parameters on flow structure during the after-oxidation period [9, 10]. Flow structure changes induced by swirl ratio and injection pressure variations seem to have a deep impact on pollutants formation.

As it has been reported, changes in flow structure can affect exhaust emissions. Based on that, improving the understanding of the in-cylinder flow pattern has been the motivation for several research works. Thus, more recently, Tan et al. [11] analyzed changes in

turbulence levels associated with different fuel injection strategies by means of cycle-resolved high speed PIV. Measurements were carried out in a vertical plane in an optical Diesel engine. It was shown that changes in turbulence evolution during compression stroke are highly dependent on the number of injection events. Indeed, combustion is shown as minor contributor to the changes in turbulence and air flow motion compared with the fuel injection impact.

Thus, considering the main impact of injection processes on air flow motion demonstrated in the literature, the objective of this work is to gain an insight into spray-swirl interaction through the analysis of in-cylinder velocity fields measured by PIV under non-reacting conditions using a PCCI injection strategy in a light-duty Diesel engine. Testing under non-reacting conditions offers several advantages such as reduced window fouling with no PM. In reference to injection events, momentum flux was varied by changing injection pressure and fuel injected mass by varying Energizing Time (ET). To experimentally characterize the in-cylinder flow, 2D velocity maps were measured in a horizontal cross-section over the piston top for two crank-angles before firing TDC. Injection strategy was based on a single advanced pilot injection. All PIV measurements were carried out 3 Crank-angle Degrees (CAD) after the End of Injection (aEoI). ET and injection pressure influence on velocity and TKE fields were analyzed. From those results, effect of fuel injection on swirl ratio and heat transfer coefficient has been evaluated.

EXPERIMENTAL APPARATUS AND PROCESSING TOOLS

Test Cell

This section describes the experimental configuration of the test cell and the main subsystems used in this study. As [Figure 1](#) shows, the single cylinder engine is installed in a fully instrumented test cell, with all the auxiliary facilities required for operation and control.

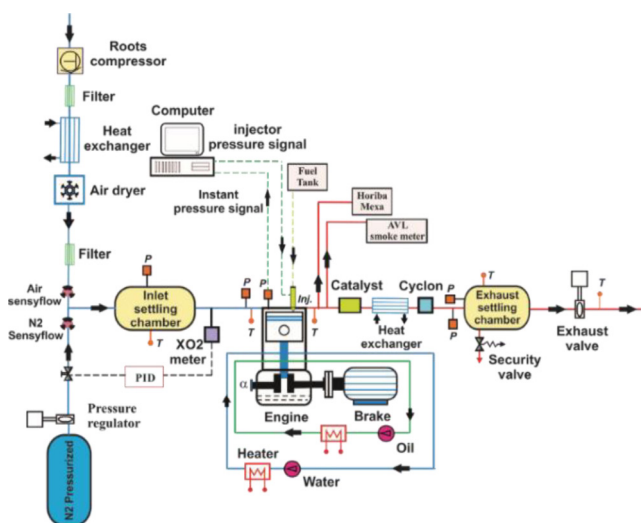


Figure 1. Complete test cell set-up.

The intake air is supplied by a roots compressor with an upper pressure limit of 3 bar. Then, the air flows through a filter to remove possible impurities. Independently on the ambient conditions,

temperature and humidity of intake air are controlled using a heat exchanger and a dryer. Temperature in the inlet settling chamber is maintained constant by using a heater in the intake line.

Oxygen concentration variation is performed introducing N2 into the inlet flow. This approach greatly simplifies the system ensuring a controllable gas composition without an excessive time to adjust the facility. The strategy is based on decreasing the O2 concentration at the inlet manifold by increasing the flow of N2 and keeping the total intake mass flow rate constant. For this purpose a PID controller is equipped to operate an N2 valve governed by the intake O2 meter. In that sense, all tests are conducted with just N2 as intake charge ensuring non-reacting conditions.

In the exhaust line, after the exhaust analyzer sample probe, a cyclone is needed to remove the hydrocarbons. In the same way as in the intake line, a settling chamber is mounted in order to attenuate pressure pulses. Finally, an exhaust backpressure valve is used to maintain a fixed relative pressure to the intake pressure, in order to simulate more realistic conditions.

Single-Cylinder Optical LD Diesel Engine

The study was carried out on a single cylinder optical Direct Injection (DI) Diesel engine. It is derived from a commercial PSA 2.2 L Diesel engine equipped with a Common-Rail fuel injection system. It has four valves per cylinder and a centrally located injector. Swirl flaps allows for swirl ratio variation. The engine is equipped with a Bowditch [12] elongated notched piston with a cylindrical bowl which allows optical access to the combustion chamber through a sapphire window placed at the bottom of the bowl. In addition, quartz windows on the partially extended liner and in the piston upper part allow optical access into the bowl from the side. In addition, a partially extended quartz liner in the upper cylinder part together with the piston side windows allows optical access into the piston bowl from the side. [Figure 2](#) shows a schematic figure of the engine.

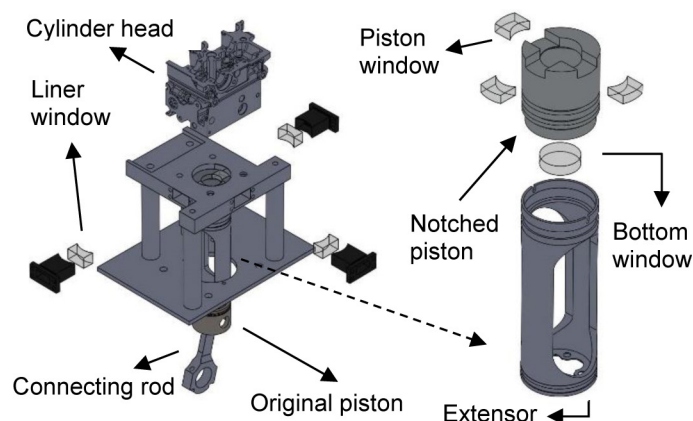


Figure 2. Optical engine.

The fuel injection system is based on an electronically controlled Bosch common rail system. The injector is a Bosch solenoid equipped with a five-hole nozzle. The nozzle orifice diameter is 187 microns. The injection control system makes it possible to modify any injection

event parameter such as the Start of Injection (SoI) timing, injection duration and rail pressure. Both, engine and fuel injection hardware characteristics are summarized in [Table 1](#) and [Table 2](#).

[Table 1. Engine system main characteristics.](#)

Engine	
Type	CI, 4 stroke, DI
Bore [mm]	85
Stroke [mm]	96
Squish height [mm]	1.5
Compression ratio	15.2:1
Bowl diameter [mm]	45
Bowl depth [mm]	12
Inlet valve closing [CAD]	565
Exhaust valve opening [CAD]	162

[Table 2. Injection system main characteristics.](#)

Injection system	
Actuation Type	Solenoid
Included angle	144
Nozzle	Cylindrical with 5 orifices
Orifice diameter [μm]	187

As for the fuel injected, commercially available European Diesel fuel was used for this work. Fuel density and dynamic viscosity at 1 atm and 313 K are 820 kg/m³ and 2.38 cStk, respectively.

Theoretical Tools

0D Thermodynamic Models (CALMEC - SiCiclo)

Two different 0D single-zone thermodynamic models (CALMEC and siCiclo) were used to characterize the engine. Main assumptions for both thermodynamic models are:

- The chamber is considered an open system to account for the fuel injection and blow-by leakage.
- Combustion chamber pressure and temperature are assumed to be spatially uniform.
- Three species (air, fuel vapor and stoichiometric combustion products) are considered [14].
- Ideal gas law is used to calculate gas temperature.
- A filling and emptying model is used to calculate the trapped mass [15].
- The specific heat of the gas depends on both temperature and composition [16].
- Blow-by model is based on the evolution of the gas in an isentropic nozzle [15].

- The chamber volume deformation due to pressure and inertia is calculated by means of a simple deformation model [17].
- The heat transfer coefficient in the chamber walls is calculated with a modified Woschni-like model (1) [18]:

$$h = CD^{-0.2}p^{0.8}T^{-0.53}[C_{w1}c_m + C_{w2}c_u]^{0.8} \quad (1)$$

Where C and C₂ are constants whose values are 0.012 and 0.001, D is the cylinder diameter, p and T are the instant pressure and gas temperature, V_d is the swept volume, c_m is the mean piston speed, c_u is the instantaneous tangential velocity of the gas in the chamber adjusted using CFD calculations [18], and C_{w1} and C_{w2} are constants, whose values are adjusted for each engine by means of a combination of experimental and modeling methodology.

SiCiclo [14] is a predictive tool that provides the in-cylinder pressure evolution. This code was used to model pressure and volume inside the cylinder. On the other hand, CALMEC is a thermodynamic diagnosis tool. It is used to calculate the instantaneous evolution of in-cylinder properties of the gas and to model the internal energy terms [13]. This diagnosis tool uses the in-cylinder pressure as its main input. The in-cylinder pressure was measured with a Kistler 6055B80 pressure transducer. A shaft encoder with 1800 pulses per revolution was used, which allows a 0.2 CAD resolution. Pressure traces for 50 engine cycles were recorded in order to compensate the cycle-to-cycle variations during engine operation. Thus, each individual cycle's pressure data was smoothed using a Fourier series low-pass filter. Once filtered, the collected cycles were ensemble averaged to yield a representative cylinder pressure trace, which was used to perform the analysis.

As previously stated, these 0D tools use a simple model to estimate mechanical deformations. Nonetheless, major mechanical deformations (compared to regular engine configurations) have been reported for Bowditch type optical engines [19]. To evaluate changes due to mechanical deformations a structural analysis was performed using the Finite Element Method (FEM). The analysis was mainly focused on the piston extensor since considerable axial deformation is expected. The simulation was carried out in ANSYS workbench and the results for the axial deformation at TDC are shown [Figure 3](#). Four different meshes with consecutive refinements around the zone with higher deformations were tested to evaluate mesh independence. It was found that a maximum 1.6 mm axial deformation is reached under the critical conditions met at TDC. To account for this behavior the deformation model used by the 0D thermodynamic models was adjusted to simulate mechanical deformation based on the FEM analysis results.

Increase in squish height mainly affects in-cylinder volume around TDC. [Figure 4](#) shows the in-cylinder volume evolution around this crank-angle estimated using SiCiclo. It can be seen that volume at TDC is higher for the case considering mechanical deformations. This bigger volume means a bigger amount of air is kept outside the bowl not contributing to airflow acceleration. This behavior should lead to a lower swirl ratio level around TDC compared to an engine



with similar characteristics without the elongated Bowditch piston. Additionally, in-cylinder volume variations at TDC are relevant for a more accurate estimation of compression ratio.

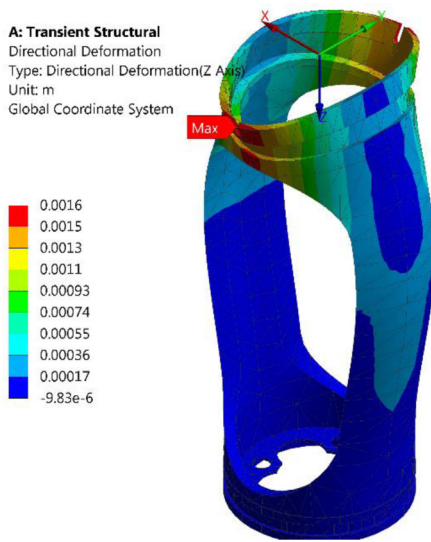


Figure 3. FEM results for extensor axial deformation.

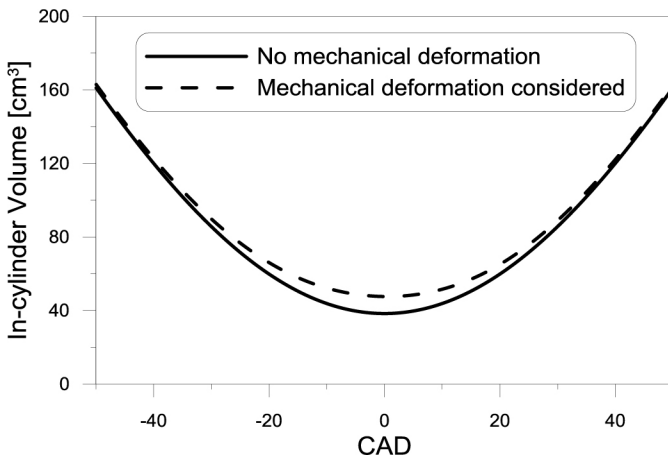


Figure 4. Mechanical deformation impact on in-cylinder volume.

Once the mechanical deformation model has been adjusted to account for larger mechanical deformations, in-cylinder pressure was modeled with SiCiclo and compared to the experimental measurement. Figure 5 shows that SiCiclo is able to model the in-cylinder pressure with a good level of agreement. Pressure at IVC (155 bTDC) and peak pressure are well captured by the model. Some differences are found at EVO (162 aTDC), but within a reasonable range.

Finally, Table 3 summarizes engine characterization results from CALMEC. Effective compression ratio is found to be lower than the geometric compression ratio. This difference is expected due to the in-cylinder volume variation at TDC associated with the increase in squish height. Regarding heat transfer, coefficients for the Woschni-like model are within the typical range for light-duty Diesel engine.

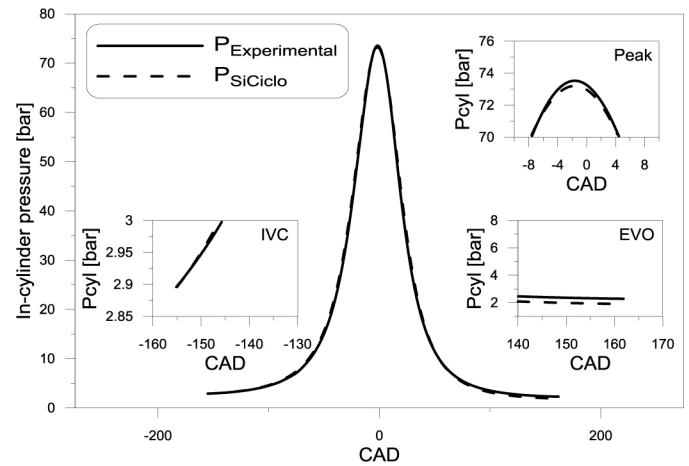


Figure 5. In-cylinder pressure modeled with SiCiclo vs experimental measurement.

Table 3. Engine characterization results from CALMEC.

CR _{eff}	Cw1	Cw2
12.4	1.48	0.869

1D Model for Swirl Ratio Estimation

An extension of the theoretical model described in [20] was used to predict swirl ratio evolution during compression stroke to validate swirl ratio derived from PIV measurements. The model used assumes that the mass of air trapped after IVC is conserved. Additionally, the in-cylinder volume is divided into three volumetric zones as shown in Figure 6. (A green line marks the location of the laser sheet for PIV measurements). Zone 1 considers the volume over the piston bowl. Zone 2 is the annular volume in contact with the liner wall and zone 3 is the bowl volume.

Angular momentum variation over time can be solved in terms of angular momentum transportation by squish flow, angular momentum transportation by viscous shear and angular momentum loss due to wall friction. This model allows for the prediction of the swirl ratio evolution in the three different volumetric zones. The volumetric discretization of the in-cylinder volume also allows for a better comparison of modeling versus experimental results. Accordingly, swirl ratio evolution in volumetric zone 1 is chosen for comparison since the PIV measurements are made over the piston bowl and within a zone contain inside this virtual boundary.

Figure 7 shows modeling results for swirl ratio variation over time. Solid line represents evolution for the reference case considering the measured squish height. Meanwhile the dashed line has been modeled with a bigger squish height to account for the effect of mechanical deformation around TDC.