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CFD Methodology for the evaluation of knock of a PFI Twin Spark engine

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Abstract

A methodology for the evaluation of the effects of twin spark ignition system on CCV (Cycle by Cycle Variability) and knocking combustions is here presented, based on both the use of Computation Fluid Dynamics (CFD) tools and experimental information. The focus of the numerical methodology is the statistical evaluation of the local air-to-fuel distribution at the spark plugs and its correlation with the variability of the initial stages of combustion.

A detailed analysis of knocking events can help improving engine performance and diagnosis strategies. The use of twin spark ignition system can enhance the probability that the initial kernel could come across a zone with the correct air-to-fuel ratio, thus lowering the initial combustion instabilities. Moreover the lower distance swept from the flame fronts can considerably reduce the time for the unburnt mixture to auto-ignite, thus reducing the risk of knocking combustion.

CFD simulations have been used to reproduce knock effect on the in-cylinder pressure trace. The pressure signal holds information about waves propagation and heat losses: it is crucial to relate local pressure oscillations to knock severity. For this purpose, a CFD model has been implemented, able to predict the combustion evolution with respect to Spark Advance, from non-knocking up to heavy knocking conditions. The CFD model validation phase is essential for a correct representation of both regular and knocking combustions: the operation has been carried out by means of an accurate statistical analysis of experimental in-cylinder pressure data.

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Keywords: High Performance Engine; Knock; Twin Spark; Cycle by Cycle Variability;

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Nomenclature

A/F	Air to Fuel Ratio
ADV	Spark Advance
CCV	Cycle by Cycle Variation
CHR_{NET}	Net Cumulative Heat Release
DNS	Direct Numerical Simulation
IMEP	Indicated Mean Effective Pressure
IVO	Intake Valve Opening
IVC	Inlet Valve Closing
LES	Large Eddy Simulation
MAPO	Maximum Amplitude of Pressure Oscillation
MFB10	10% Mass Fraction Burned
MFB50	50% Mass Fraction Burned
MFB90	90% Mass Fraction Burned
MS	Mono Spark
PFI	Port Fuel Injection
RANS	Reynolds Averaged Navier-Stokes equations
SI	Spark Ignition
TS	Twin Spark

1. Introduction

The quest for high performances and low emissions leads engine manufactures to trim the operating range of combustion devices near their stability limit. The capability of accurately simulate the engine in such a critical conditions is indispensable and many steps are made, both in terms of CFD modeling and computational hardware development.

There are above all two limits that restrict engine operation because of CCV: in the lower part-load range one should mention the misfiring limit, which comes into play primarily in the course of high degrees of charge dilution (residual gas, air) and the associated increase in cyclic fluctuations. At full load, on the other hand, the knock limit restricts optimum-efficiency combustion control.

Modeling the CCV (Cycle by Cycle Variation) of spark ignition engine is essentially based on a forced perturbation of the combustion evolution in the chamber: a lot of methodologies today available in literature are based on this mechanism, but the key issue is the way these perturbations are selected. The imposition of a change in the combustion evolution must be based on real engine condition to be predictive.

Even a simple model for cyclic variation based on a Monte Carlo approach [1] can correctly represent the engine behaviour, but no practical information can be used for engine design.

Dai et al. [2] proposed a procedure by which a two-zone thermodynamic model combined with a flame propagation sub-model can be used for predicting the cycle-to-cycle variations of combustion at very lean and high exhaust gas residual conditions. Under such conditions, the variations have been shown to consist of both deterministic and stochastic components. The deterministic component is inherent to the non-linear nature of the combustion efficiency variation with equivalence ratio (or dilution level), while the stochastic component results primarily from noise associated with the parameters that affect combustion. The author considered the deterministic factors as the driving components, and modeled the stochastic ones by adding noise in order to reproduce the total behaviour of the engine, such as turbulence and flow patterns.

Vitek et al. [3] presented a 1D/0D simulation methodology for the evaluation of cycle by cycle variation of a spark ignition engine. The work is based on a perturbation of combustion related parameters. The information on perturbations are extracted from experimental and 3D CFD analysis and imposed to a fractal combustion model for the evaluation of the engine response. The authors found that both turbulence properties and initial flame kernel development are the most critical factors regarding CCV. However Vitek et al. tuned the standard deviation of the perturbing parameters to fit the IMEP (Indicated Mean Effective Pressure) coefficient of variation, without correlating them to any engine initial condition. To overcome this lack, they suggest to ground the methodology on multi-cycle CFD 3D LES simulations.

The actual feasible way to effectively reproduce CCV is by performing full 3D CFD LES (Larg Eddy Simulation) of the engine. Tatschl et al. [4] and Vitek et al. [5] investigated the root causes of CCV by means of a combined 1D-3D simulation: the in-cylinder analysis was based on LES approach. They concluded that the instantaneous flow field of individual cycles in different cross-sections of the cylinder demonstrated a combined small- and large-scale nature of the flow field fluctuation, which interacts closely with the spray droplet distribution and fuel vapor concentration. Other works based on LES methodology [6] [7] showed a good correlation between variability of the velocity fields and the instability of combustion, but the extensive use of these numerical approaches is still limited by the huge request in computational effort.

In the present work the authors propose a RANS (Reynold's Averaged Navier-Stokes equations) methodology for the evaluation of combustion instabilities based on mixture composition at the spark plug. In a previous work [8], the authors investigated the root causes of the cycle-by-cycle variability increase with leaner combustion, by means of a joint numerical and experimental approach: the authors showed that the combustion sensitivity to the initial perturbation of the mixture air index at spark location and to the level of in-cylinder air index homogeneity increases, due to the lower laminar combustion speed of leaner mixtures. The authors concluded that efficient mixing processes are mandatory any time the engine operates with suboptimal air indexes (far from those giving the maximum laminar speed).

The relationship between the variability of IMEP and the fluctuation of local lambda was clearly showed in the work of Ikeda et al. [9] where the chemiluminescence technique was used to analyze the mixture homogeneity and composition at the spark plug for a high performance engine. Unfortunately, Ikeda [9] could not draw conclusions on the cause of such mixture variability.

One effective way to improve combustion stability at low load condition is the use of Twin Spark ignition system: Bozza et al. [10] developed a quasi dimensional three-zone model for the geometrical evaluation of the double kernel formation, and applied it for the simulation of an High-EGR VVT-Engine, in both mono spark and twin spark configuration.

Cavina et al. [11] showed how a multiple discharge is an effective way of improving ignitability of lean and diluted mixtures, shortening ignition delay and combustion duration, and preventing misfire occurrence without any impact on the intake fluid dynamics, and proposed a methodology for real time control purpose.

The aim of this work is the evaluation of combustion behaviour of a Ducati high performance engine, equipped with a twin spark ignition system. The low stroke to bore ratio makes the combustion very critical in the narrow volume of the combustion chamber, especially under part load condition. In this configuration the twin spark ignition greatly improves the stability of the engine, but also in full load condition the fastest initial kernel development reduced the variability of the engine. In this work the full load configuration in analyzed and an analysis of knock is done on a statitsical basis.

Due to confidential agreement with Ducati all the data in the present paper will be referred to a conventional condition.

2. Analysis of experimental data

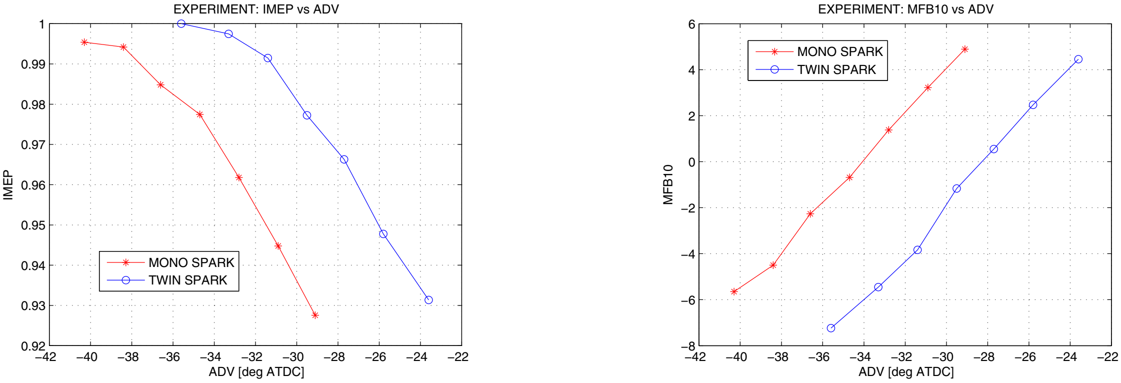
The engine under analysis is a Ducati high performance engine, here evaluated in the configurations of Tab. 1

The engine run on the test bench equipped with a pressure sensor located in the chamber. The pressure traces of 300 engine cycles are recorded for each engine point analyzed for both the Twin Spark and Mono Spark configuration. The spark advance swept is accomplished by advancing the combustion until the maximum brake torque. The indicating parameters are extracted by filtering the pressure signal with a butterworth zero-delay low pass filter at 3kHz for IMEP and CHR_{net}, with a butterworth band-pass filter at between 5kHz and 20kHz for the high frequency parameters.

Fig. 1(a) shows how the twin spark allows more efficient combustions, with higher value of maximum IMEP and faster combustions: the ADV of maximum brake torque is four degrees lower than the single spark configuration.

Table 1. Engine configuration

Bore	106mm
Stroke	67.9mm
Regime	8500 rpm
Load	Full load
Engine ignition system	Mono Spark / Twin Spark
Spark Advance	Sweep until max IMEP
λ	0.83



(a) (b)

Fig. 1. Spark advance sweep: (a) Imep swept - spark advance; (b) 10% Mass Fraction Burned - Spark advance

The increase in combustion rate is focused in the early stages (Fig. 1(b)), with a MFB10 (10% Mass Fraction Burnes) of twin spark configuration four degrees lower. This is the consequence of the double flame fronts initiated in the chamber.

In a previous work the authors [12] showed how the main combustion characteristics can be summarized by means of:

- Combustion initiation (MFB10-ADV)
- Combustion shape (Maximum value of ROHR)
- Combustion duration (MFB90-MFB10)

Corti et al [13] [14] showed that, within a specific engine configuration, all these parameters can be considered dependent on a single combustion information: the MFB50. The 50% of mass fraction burned represents the combustion phasing of the engine and an optimal value for full load condition is between eight and ten degrees after top dead center of combustion. In Fig. 2 the maps of IMEP for both TS and MS configuration are plotted against MFB50. It is clear that the double ignition allows a better indicating efficiency, thanks to lower compression work caused by the faster initial combustion.

The knock tendency of the engine is depicted in Fig. 3(a): MAPO values are evaluated on a crank angle window between 0 and 70 degrees after top dead center, and the mean value over the all 300 cycles is depicted. TS configuration reveals higher knock sensitivity on the whole range of spark advance analyzed. This is true even when considering the oscillations as a function of combustion phasing Fig. 3(b) with the same MFB50 the MAPO values of TS are always higher than MS. The risk of damage can lead to choose lower value of ignition timings, thus canceling the positive effects of better combustion efficiency. A more deep insight in the abnormal combustion is needed and it is accomplished by means of the CFD simulation of the combustion process.

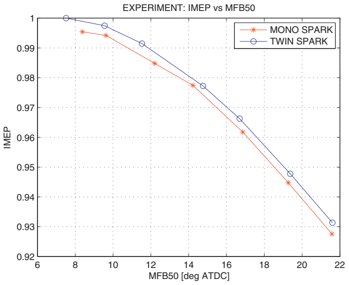
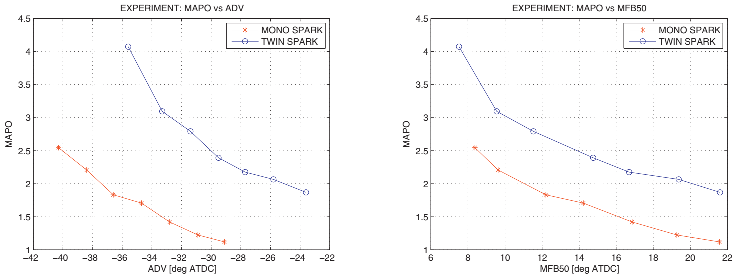


Fig. 2. Indicated Mean Effective Pressure versus MFB50



(a)

(b)

Fig. 3. Maximum Amplitude of Pressure Oscillations with respect to: (a) Spark Advance ; (b) MFB50

3. Description of the CFD RANS Simulation Methodology

The aim of the CFD simulation is the evaluation of combustion of Twin/Mono Spark engine and the understanding of the origin of the higher knocking behaviour of TS configuration. The first step is an accurate reconstruction of the mixture composition in the chamber. A multy-step methodology [15] has been accomplished with FIREv2011 (AVL), a 3D-CFD, where all the physics involved in the injection process are evaluated and validated. The engine is equipped with a multi-hole injector located in the intake duct, downstream the throttle. Ducati made a full characterization of the injector spray (granulometry and patterns) and a semi empirical methodology has been used for the CFD injection setup. In order to better reconstruct the gas-dynamics in the intake duct, the first step is a multicycle simulation without injection. When reached a stationary condition the injection is simulated for the number of engine cycles needed reach the lambda target in the chamber. The engine here analyzed takes three engine cycles to reach an ignitable mixture and six to have lambda target.

Fig. 4 shows the equivalence ratio in the chamber at Inlet Valve Closed and the location of the two spark plugs. The stars in the figures illustrate the spark locations: in the engine analyzed one spark is at the center of the chamber (the only one active in MS configuration), the other between inlet and exhaust valves. The fuel distribution is not homogeneous and the second plug is inside a leaner zone.

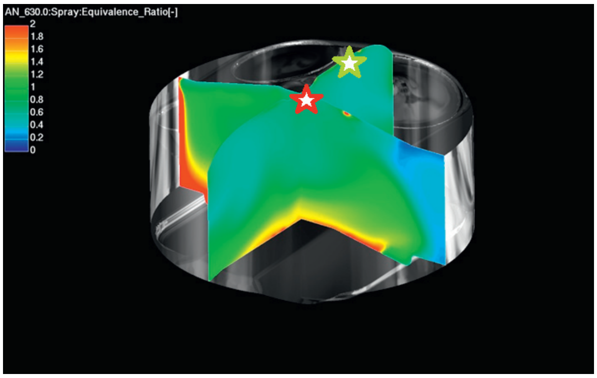


Fig. 4. Distribution of the fuel in the chamber at IVC

The results of injection simulations are then mapped on a modified version of KIVA3D-code, developped at the university of Bologna. The main models implemented in the code are deeply described in [16] and listed in Tab. 2

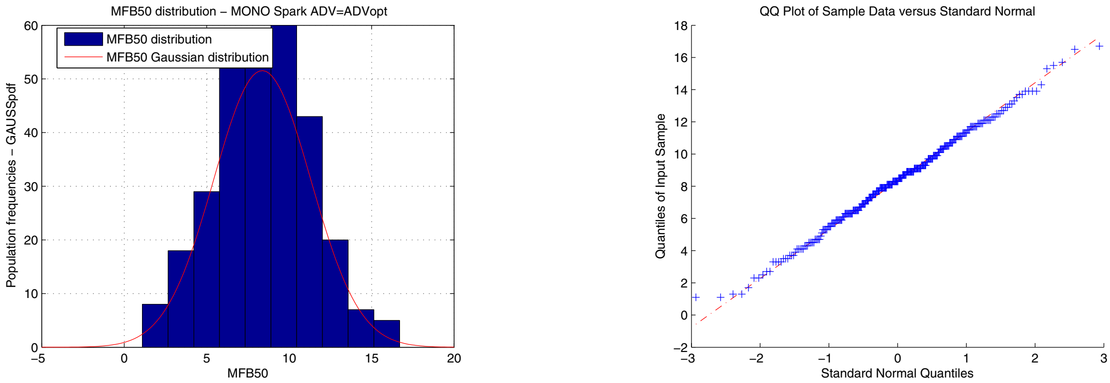
Table 2. KIVA3D CFD MODELS

Turbulence	Standard k-ϵ
Law of the wall	Standard + Han & Reitz
Combustion	Extended Coherent Flamelet
Knock	two step autoignition model based on [17]
Ignition	Lagrangian ignition model [18] [19]

4. Simulation of combustion of Twin and Mono Spark

The flamelet combustion model is tuned in order to correctly represent the real mean behaviour of the monospark configuration. Because of the cycle by cycle variability of the SI engines all the pressure traces of the experimental data are widely scattered, representing very different combustion characteristics. As it was shown in [20], the identification of the representative cycles is a key issue: the standard synchronous pressure average on a crank angle basis can lead to mean engine cycles which do not really exist. The author propose to make a selection of real pressure traces based on the MFB50:

Fig. 5(a) shows the frequency distribution of the 300 cycles considered. The red line is the theoretical Gaussian pdf, plotted for comparison. Fig. 5(b) shows the quantile cumulative distribution of samples with respect to a Gaussian normal ones: samples are almost on the straight line of the graph, thus confirming the effectivness of the hypothesis.



(a) (b)

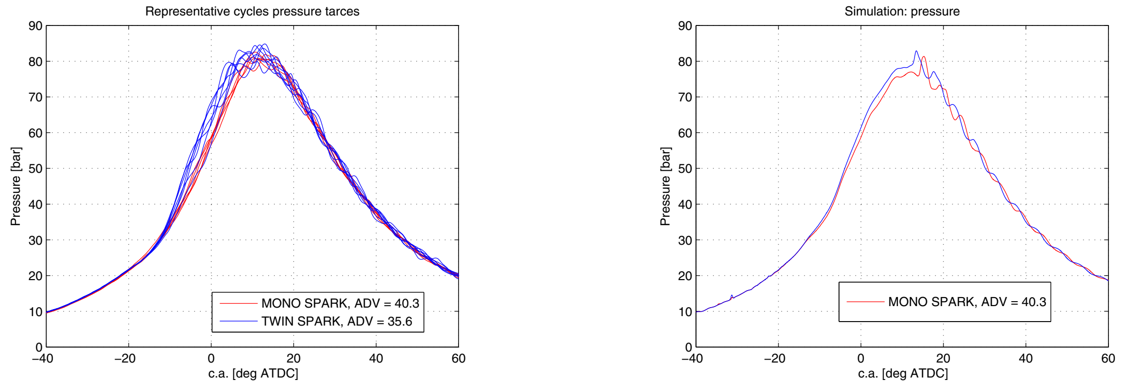
Fig. 5. Selection of representative cycles: (a) Distribution of MFB50 frequencies; (b) QQplot of MFB50 versus normal Gauss distribution

The MFB50 of 8 degrees ATDC is the mean value that best represents the mono spark configuration in the condition of maximum IMEP.

The comparison of the simulated versus experimental pressure tarces is plotted in Fig. 6(a) Fig. 6(b): good is the reconstruction of the evolution of pressure in the chamber in terms of pressure peak and its angular position. As it is clear in the graps, the TS configuration has a faster beginning of combustion, which slowes down when reaching TDC.

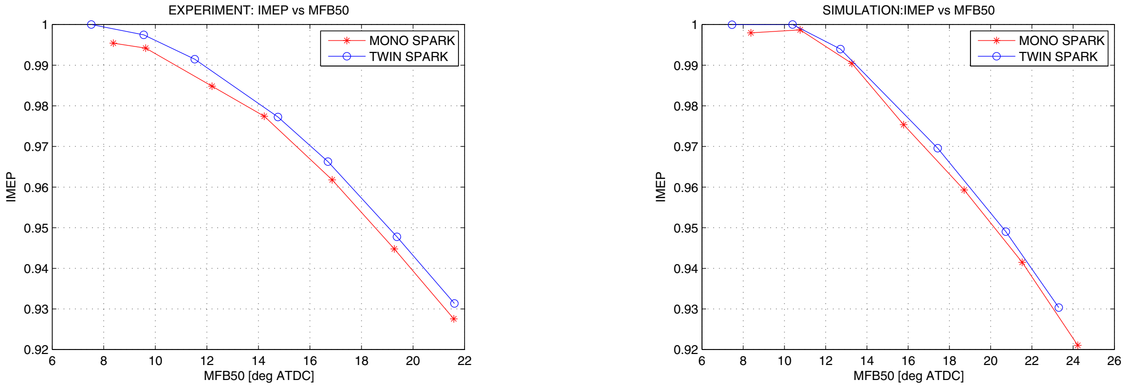
The overall behaviour on the whole spark advance swept is in Fig. 7(a) Fig. 7(b): the simulation is able to represent both the combustion phasing of various spark advance (MFB50 on x-axis) and the higher efficiency of TS solution.

The knocking combustion is a highly stochastic phenomenon and the criteria for the identification of thresholds is often based on statistics. The needs to better identify the overall behaviour of the to spark installations has taken the author to develop a methodology for the evaluation of cycle by cycle variability.



(a) (b)

Fig. 6. Selection of representative cycles: (a) Pressure traces Experimental; (b) Pressure traces Simulated



(a) (b)

Fig. 7. Indicated mean effective pressure: (a) Experimental; (b) Simulated

Table 3. Mixture condition inside a sphere at spark plug at -40degATDC

Parameter	Mono Spark	Twin Spark
Mean Local Lambda	0.98	1.10
Lambda STD at Plug	0.08	0.14
Turbulence intensity/Vmean	0.45	0.5

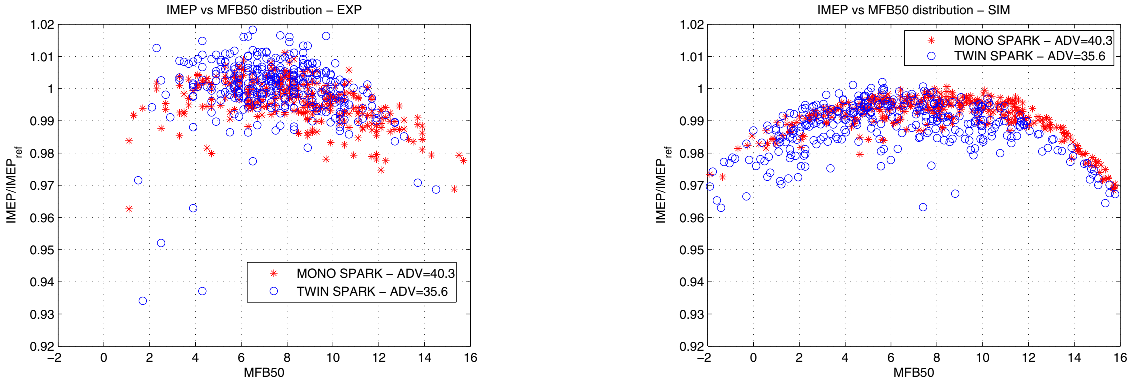
5. Results

An effective way to simulate the cycle by cycle variation of a spark ignition engine is based on a forced perturbation of the combustion evolution, with particular emphasis on the early kernel development. The methodology of perturbation here proposed is focused not only on a simple relationship between the perturbation strength and the amplitude of results, but it is grounded on the spatial characterization of the mixture and turbulence at the spark plug. Tab. 3 describe the local condition of the mixture at the spark plug at -40 deg ATDC.

The perturbation of the combustion is thus imposed on two different physical phenomena:

- The laminar velocity is modified to take into account for the probability that a stochastic value of lambda at the ignition can be interested in combustion, according to the spatial distribution found in a sphere of 12mm of radius
- Turbulent combustion, by modifying the source term of surface density of flamelet, according to the variability of turbulence inside the chamber

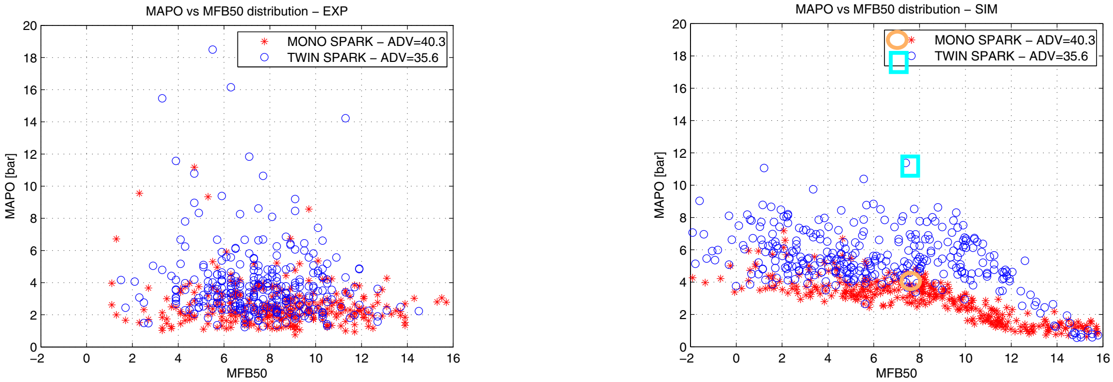
Fig. 8(a) and Fig. 8(b) show the comparison between the TS and MS configuration for both experimental and simulated results. The typical distribution of parabola-like patterns is well gathered, together with the higher tendency of TS configuration to have variability of IMEP.



(a) (b)

Fig. 8. Distribution of IMEP-MFB50: (a) Experimental; (b) Simulated

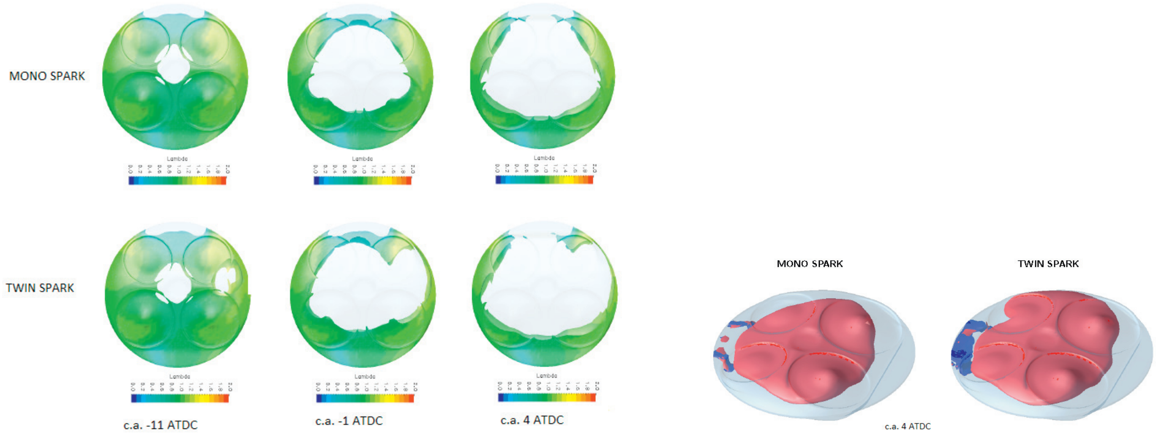
The knock sensitivity can be extracted from Fig. 9(a) and Fig. 9(b): TS configuration has higher value of MAPO all along the MFB50 distribution.



(a) (b)

Fig. 9. Distribution of IMEP-MFB50: (a) Experimental; (b) Simulated

For the analysis of the causes of such behaviour two engine cycles with the same combustion phase have been selected in Fig. 9(b). The evolution of combustion flame front is depicted in Fig. 10(a). The knocking zone is in the exhaust side of the engine: the twin spark configuration allows a faster evolution of the flame front, but the particular installation of the plug does not allow the flame front to fast reach the knocking zone, thus causing an increase in knocking event.



(a) (b)

Fig. 10. Evolution of flame front in the chamber: (a) Flame front evolution; (b) Knocking zones

6. Conclusion

A RANS methodology for the recovery of the information on the influence of mixture composition quality on cycle by cycle variation is presented in this paper.

The methodology is applied to an high performance engine configuration equipped with both Mono Spark and Twin Spark plugs. The methodology is based on the imposition of perturbation based on the quality of mixture at the spark plug and proves to be accurate in the prediction of the main combustion parameter distribution on a cycle by cycle basis.

The higher knocking tendency of the twin spark configuration is well gathered, thus proving to be an useful tools for the identification of best spark plug locations in the chamber

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