

LES Modelling of Spark-Ignition Cycle-to-Cycle Variability on a Highly Downsized DISI Engine

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ABSTRACT

The paper reports an activity aiming at characterizing cycle-to-cycle variability (CCV) of the spark-ignition (SI) process in a high performance engine. The numerical simulation of spark-ignition and of early flame kernel evolution are major challenges, mainly due to the time scales of the spark discharge process and to the reduced spatial scales of flame kernel. Typical mesh resolutions are insufficient to resolve the process and a dedicated treatment has to be provided at a subgrid level if the ignition process is to be properly modelled. The focus of this work is on the recent ISSIM-LES (Imposed Stretch Spark-Ignition Model) ignition model, which is based on an extension of the flame surface density (FSD) transport equation for a dedicated flame kernel treatment at subgrid scales. The FSD equation is solved immediately after spark discharge. The interaction of the flame kernel with the flow field is fully accounted for since spark formation and a transition is provided from ignition to propagation phase. The comparison is carried out with the AKTIM-Euler ignition model in terms of flame interaction with the flow field (e.g. arc convection, flame blow-off, flame holder effect). A multiple cycle LES activity provided a set of cycle-resolved conditions for spark-ignition comparisons, and the flame kernel development is carefully analyzed for the two ignition models on a wide range of thermo-physical conditions. Spark-ignition cyclic variability and combustion traces are compared with experiments. Results confirm that the simulated cycle-to-cycle variability increases through the adoption of the ISSIM-LES ignition model.

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INTRODUCTION

The recent legislation (Euro V, Euro VI and forthcoming) is pushing the engine manufacturers towards renewed design concepts for SI engines. These are driven by the downsizing principle, consisting in more compact yet more efficient engines, in order to preserve the original performance target of old generation units with reduced fuel consumption and pollutant emissions. New generation spark-ignition engines achieve these targets by increasing the volumetric compression ratio, by adopting turbocharging systems and by carefully targeting fuel injection to achieve optimized charge stratification. Limitations to these strategies are due to the poor tolerance of SI engines to these approaches because the first two are responsible for the long-known issue of abnormal combustion onset, also called engine knock, while the third is limited by cyclic variability. Knock is essentially due to the self-ignition of pockets of unburnt mixture in the end-gas region of the combustion chamber before the main propagating flame front consumes it. The sudden heat release and the shock pressure waves that are originated are responsible for serious engine failure: metal erosion [1], lubricant film removal and increased thermo-mechanical loading [2, 3] are just the most relevant damaging mechanisms that are caused by gasoline autoignition. The quest for knock-free higher thermal efficiency is made even harder by the non-repeatability of the highly turbulent combustion in SI engines, which is known as cycle-to-cycle variability (CCV). Extended literature surveys on its main causes are

given by Young [4] and by Ozdor et al. [5]. The main factors causing combustion CCV can be resumed by the random fluctuation of local physical conditions (i.e. flow field, mixture composition and residual concentration) in the spark plug region during early flame kernel formation. Outlier cycles from the theoretical mean one can give rise to both misfiring events (in the low-end portion of the range induced by CCV) or to abnormal combustion/knock (in the high-end part of the same).

As for the knock-free concern, which is the main interest of high-performance engine such as the one analyzed in this paper, this is avoided by reducing the engine spark time with respect to its theoretical optimal condition, in order to keep a safety margin for faster than average cycles. Nevertheless, a small fraction of knocking cycles is tolerated in order not to dramatically limit the engine performance. This threshold is typically based on the manufacturer experience. The same applies to misfiring cycles, for which tolerances are even narrower due to their dramatic impact on engine-out emissions.

This overview highlights the importance of numerical models able to correctly simulate combustion stability in the earliest portion of flame development. Despite attempts to account for flow variability statistics in a RANS framework, such as the work by Hasse et al. [6] regarding knock probability or the Hasse et al. [7] methodology regarding hybrid

RANS/LES turbulence modelling, it is believed that the numerical approach for this kind of simulation must necessarily be some sort of Large-Eddy Simulation (LES). A first support to this argument lies in the intrinsic simulation of the spark-ignition process (i.e. flame interaction with the surrounding flow field) that is carried out by LES, instead of some sort of bulk statistics that is transported with the mean flow. In this way cycle-specific events such as misfire or abnormally fast flame formation can be properly simulated. A second reason comes from the maturity of LES models for both subgrid-scale turbulence closure and for flame propagation, which can exploit the relatively low-cost computational power to give unprecedented insight into the underlying physics of the phenomenon and to suggest new solutions. Extended reviews of the state of art of LES modelling of combustion are given by Rutland [8] and Haworth [9].

The simulation of the spark-ignition process poses several difficulties from a numerical point of view. This is motivated by the extremely short length and time scales of the electric arc and of the initial ionized gas in the surrounding of the spark plug electrodes, as well as their life time, which would make the simulation of these phenomena unaffordable for the commonly adopted grids and time steps. In the illustration of the electric discharge process, Maly [10] points out that the breakdown phase is characterized by time scales in the order of ns and the ionized channel that is formed can reach temperatures up to 60000 K. Therefore, simplifications are usually undertaken in order to represent the spark-ignition phenomenon on commonly adopted CFD codes.

An example of ignition model where the small-scale flame kernel evolution is modelled is the DPIK (Discrete Particle Ignition Kernel) ignition model from Fan et al. [11] and then detailed by Tan and Reitz [12], which is based on a phenomenological transport of discrete Lagrangian particles in order to track the flame kernels evolution. However, the use of discrete kernel trackers is not coherent with the Eulerian concept of flame surface density and the FSD initialization is critical.

A significant modelling complexity is proposed in the SparkCIMM (Spark Channel Ignition Monitoring Model) ignition model by Dahms and co-workers in a series of papers [13, 14, 15]. This includes the creation of multiple local flame kernels along the spark channel and a Lagrangian sub-model accounts for kernels merging in a single larger non-spherical flame front. However, application of this detailed model and not known in the LES context.

From a modelling point of view, the simplest approach to model spark-ignition is to instantaneously impose a small fully burnt volume in order to initialize the combustion model. Examples of such models are the Local Energy Deposit Ignition (LEDI) adopted by Thobois et al. [16] and later by Goryntsev et al. [17] and the AKTIM-Euler ignition model [18, 19], which is illustrated in more detail in the Numerical Setup section and which will be adopted for a part of the presented simulations. An unavoidable drawback of this family of ignition models is in the finite dimension of the initially imposed burnt volume, which must be of the order of the cell size in the spark plug region in order to be filtered and correctly resolved on the grid. This implies the complete lack of the modelling of the phase preceding the flame kernel growth up to that size. This in turn affects not only on the combustion phasing (a portion of flame life time is

not simulated at all) but also the combustion CCV of the early flame kernel: the rigid imposition of a burnt gas profile smears out all the potential deviations in flame evolution up to that point.

An alternative strategy identified by the authors in [20] was to counterbalance the use of the AKTIM-Euler model by adopting a strong mesh refinement (as low as 0.08 mm) in the spark plug region. This strategy effectively limited the size of the filtered flame kernel and the FSD equation handled its propagation since the first stage. Despite the CPU cost due to the grid refinement, a significant improvement of CCV was measured with this technique when compared to experimental measurements.

A relevant attempt to overcome the difficulties of the flame deposition models is the recent ISSIM-LES (Imposed Stretch Spark-Ignition Model) [21] ignition model for early flame kernel propagation. It consists of the use of a modified FSD equation, accounting both for early flame evolution, at subgrid scales for typical engine grids, and for flame propagation, where the standard FSD equation is recovered. Further details of the model will be given in the next section. From a general perspective, a wider set of flame kernel-related phenomena are expected from a simulation with ISSIM-LES ignition model. Given the relevance of flame variability that is originated in the initial combustion stages, it is believed that the adoption of models such as ISSIM-LES could represent a relevant improvement in the simulation of combustion irregularity.

The paper is organized as follows. In the next section the details of the presented numerical simulations are outlined, with emphasis on the fundamentals of AKTIM-Euler and ISSIM-LES ignition models. Later, a first validation of the ISSIM-LES model is carried out against experiments in a homogeneous isotropic turbulent field. Finally, engine cases are presented for a currently produced GDI unit, for which experimental data are available at knock-limited spark-advance and combustion CCV is clearly visible. Statistics on combustion instability are made possible by the large number of consecutive cycles acquired by the experimental campaign. Preliminary results from a Large-Eddy Simulation dataset with ISSIM-LES ignition model are presented and compared to the experiments, both in terms of average combustion development and its CCV. Finally, a comparison between ISSIM-LES and AKTIM-Euler ignition models is carried out regarding flame development and the degree of combustion variability. The analysis is focused on the two most different spark-ignition realizations that are available and the simulation improvement allowed by ISSIM-LES is highlighted.

NUMERICAL SETUP

The numerical analyses presented in this study are carried out by means of a customized version of the commercial CFD code Star-CD v4.20, licensed by CD-adapco. The computational domain for Large-Eddy Simulation on the engine case is composed by approx. 1M cells at TDC and 1.5M at BDC. The numerical grid adopted considers both the intake and the exhaust ports. As for the last, the full geometry up to the turbine inlet section is modelled, since experimental pressure acquisition was measured in this location. The average cell size is about 0.55 mm both in the cylinder and in the ports regions. No symmetry planes are introduced due both to the

inherent randomness of flow realizations when adopting Large-Eddy Simulation and to the asymmetry of the exhaust port configuration. Mesh motion is handled by an Arbitrary Lagrangian-Eulerian (ALE) approach by the *es-ice* plug-in. The adopted time-step is approx. $1e-6$ s, although this is further reduced in the proximity of valve opening or closure events. The complete mesh and a close-up on the cylinder domain are represented in Figure 1. Subgrid-scale turbulence is modelled by the algebraic Smagorinsky model [22], with C_s constant equal to 0.202. Despite the limitations inherent with the model simplicity, above all the excessive subgrid energy dissipation and the lack of a subgrid kinetic energy budget, its stability still constitutes a valuable point for such CPU-intensive analyses. The combustion model adopted for all the presented simulations is ECFM-LES [18, 19], which maintains the flame surface density (FSD) formalism of the ECFM-family combustion models widely adopted in RANS analyses with dedicated subgrid-scale terms for transport, stretch and curvature. A set of hybrid boundary conditions for pressure and temperature is adopted: pressure is experimentally measured by mean of fast-response pressure transducers located in the intake/exhaust ports, while for temperature a 1-D time-varying profile is derived from a tuned model in use by the engine manufacturer.

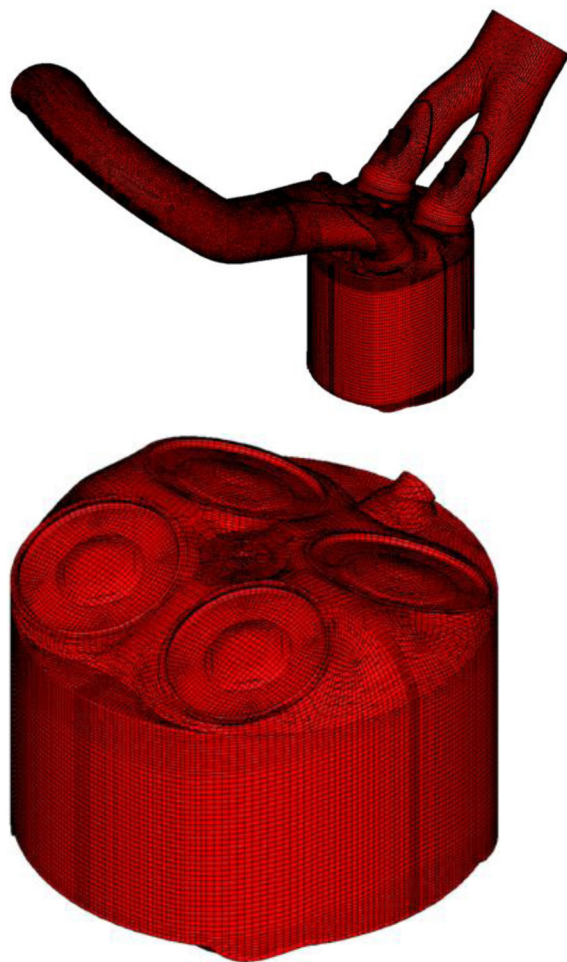


Figure 1. Numerical grid used for LES simulations. Top: complete domain; bottom: close-up on the cylinder domain.

Uniform wall temperatures are imposed for each metal component, while wall heat transfer is modelled through the Angelberger et al. [23] approach. Two-phase flow is accounted for by a pre-atomized

population of droplets imposed at each nozzle exit, whose validation is reported in [24], while the Reitz and Diwakar model [25] is used for secondary break-up. It is important to underline that the simulation of fuel injection is performed without any external imposed perturbation, i.e. the mixture stratification and the resulting degree of CCV are the result of the interaction with the turbulent cycle-dependent flow field. Second-order TVD-based numerical schemes are used for momentum discretization, while density is calculated with a central differencing scheme; first order time-integration is adopted. The CPU time for a single full-cycle simulation requires approx. 36 hours on a 48-core Linux cluster.

Finally, the validity of the adopted numerical framework is verified by means of the Energy Resolution (ER) criterion as proposed by Pope [26]. The ensemble average results from the calculated dataset at approx. 600 CA and 670 CA during the compression stroke are reported in Figure 2.

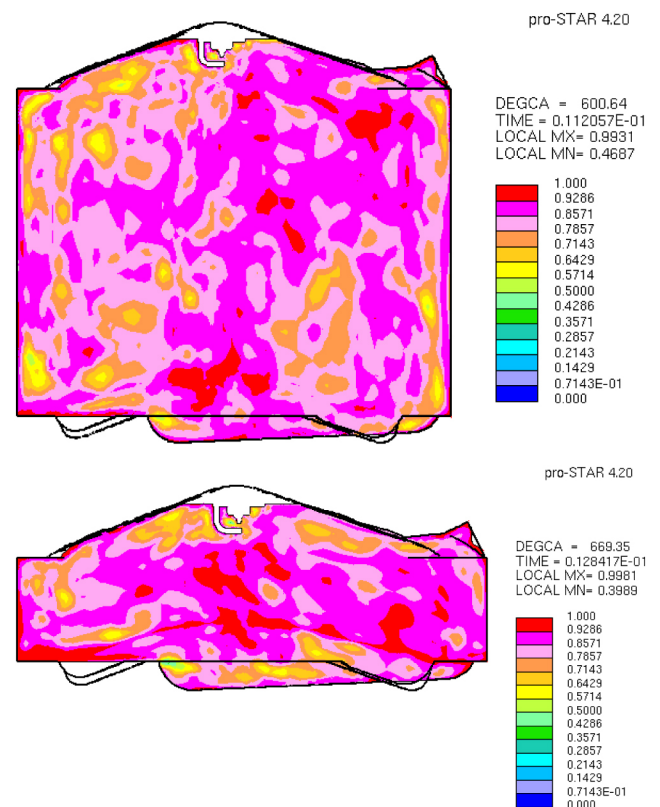


Figure 2. Energy Resolution (ER) field on an axial section for different CA positions. Top: 600 CA; bottom: 670 CA.

A fraction of approx. 80% of the flow turbulent kinetic energy is simulated by the filtered momentum equation, instead of being modelled by the subgrid-scale closure model. This is in line with the recommendations by Pope. Therefore, the present grid is judged as adequate for the modelling of the presented flow realizations. Finally, it is worthwhile to mention that several other mesh quality validation indices in the context of LES are proposed in literature in addition to the widespread ER criterion, and a detailed survey of these can be found in [27].

ISSIM-LES Ignition Model

The ISSIM-LES ignition model was first proposed by Colin and Truffin [21], who exploited the theoretical ability of the FSD equation to model flame propagation since the early stages. A modified FSD transport equation was proposed (Eq. 1) for the temporal variation of the filtered FSD $\bar{\Sigma}_c$. This is able to handle both the ignition phase, during which the volume burnt by the spark energy is excessively small to be resolved on common engine grids and for which a dedicated subgrid-scale treatment is proposed, and the resolved flame front during propagation.

$$\frac{\partial \bar{\Sigma}_c}{\partial t} = T_{res} + T_{sgs} + S_{sgs} + \alpha C_{sgs} - \nabla \cdot (\alpha S_d N \bar{\Sigma}_c) + \alpha (C_{res} + S_{res}) + (1 - \alpha) \frac{2}{r_b} (1 + \tau) \Xi S_L \bar{\Sigma}_c + \dot{\omega}_\Sigma^{ign} \quad (1)$$

In Eq. 1 T_{res} , T_{sgs} , C_{res} , C_{sgs} , S_{res} , S_{sgs} are terms related to the standard FSD transport equation for LES proposed in [18, 19]. They account for resolved and subgrid FSD transport (T_{res} and T_{sgs}), curvature (C_{res} and C_{sgs}) and stretch (S_{res} and S_{sgs}), respectively. As stated earlier, the focus of this work is on the ISSIM-LES model implementation, which requires the addition of new contributions and/or the modification of existing terms.

An additional term $\frac{2}{r_b} (1 + \tau) \Xi S_L$ is introduced with respect to the standard FSD equation proposed in [18, 19]. It considers the subgrid curvature contribution to FSD creation given by $2/r_b$, the expansion ratio $\tau = \rho_u/\rho_b - 1$, the turbulent wrinkling factor Ξ and the laminar flame speed S_L . In particular, the wrinkling factor is imposed equal to 1 for this preliminary implementation: this implies that the FSD production due to subgrid turbulence is underestimated and it is the object of current analyses aiming at model improvement. The laminar flame speed S_L is calculated following the relationship proposed by Metghalchi and Keck [28] for isoctane. Finally, the source term $\dot{\omega}_\Sigma^{ign}$ accounts for the FSD creation at spark time following a spherical shape assumption for the flame kernel as proposed in [21]. This expression guarantees a correct representation of the subgrid-scale FSD generation during the ignition when the flame can be approximated by an expanding sphere modelled at subgrid level.

The transition between the subgrid-scale and the resolved level is governed by a continuous ad-hoc α -function, varying from 0 to 1 for ignition and propagation phase, respectively. The α -function is dependent on the equivalent flame radius r_b , which is calculated assuming a spherical shape for the flame following Eq. 2:

$$r_b = \sqrt[3]{\frac{3}{4\pi} \cdot V_{flame}} \quad (2)$$

During spark discharge, the initial kernel radius $r_{b,ign}$ is initialized following the same spherical kernel assumption and it is derived from an initial distribution of filtered progress variable $\tilde{c}_{ign}$ respecting the condition in Eq. 3.

$$\frac{4}{3} \pi r_{b,ign}^3 = \int \tilde{c}_{ign} dV \quad (3)$$

The α -function is deputed to the suppression of erroneous terms during the subgrid/ignition phase while activating a dedicated FSD term for subgrid stretch during ignition. As the flame radius increases, a smooth transition is carried out to recover the standard FSD equation. The same α -function definition as the one proposed in [21] is adopted in this study. It follows Eq. 4 and it is represented in Figure 3.

$$\alpha(r_b^+) = 0.5 \cdot \left[1 + \tanh\left(\frac{r_b^+ - 0.75}{0.15}\right) \right] \quad (4)$$

$$r_b^+ = r_b / \hat{\Delta} \quad (5)$$

In Eq. 5 r_b^+ is the flame radius resolved at the combustion filter size $\hat{\Delta}$, which is typically higher than the cell size Δ . In this study $\hat{\Delta} = 5 \cdot \Delta$. However, it is important to underline that this function is not based on physical arguments, its only requirements being:

1. $\lim_{r_b^+ \rightarrow 0} \alpha(r_b^+) = 0$;
2. $\lim_{r_b^+ \rightarrow +\infty} \alpha(r_b^+) = 1$;
3. Continuous and derivable algebraic function;
4. Asymptote to unity for $r_b^+ \approx 1$.

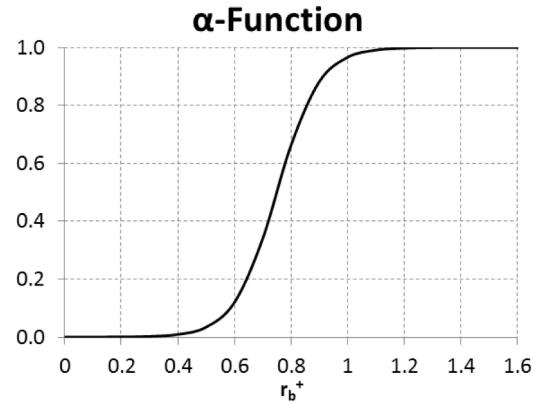


Figure 3. α -function as a function of r_b^+ .

Since this function is deputed to switch between subgrid and resolved scales, it should be somehow linked to the filter length, i.e. the local cell size in the flame kernel region. A dynamic version of the α -function, being able to locally adjust the modelling transition based on the filter length, would be an interesting step forward and it is currently under development. The proposed ISSIM-LES model is implemented in Star-CD in a joint cooperation between University of Modena and CD-adapco.

AKTIM-Euler Ignition Model

The AKTIM-Euler (Arc and Kernel Tracking Ignition Model) ignition model is investigated as representative of several spark-ignition models based on the concept of a flame deposition over the resolved flow field in the spark plug region. It was adopted in several publications by the authors on the same engine and operating point as that of this study [20, 29, 30, 31]. The model fundamentals are here briefly resumed for the sake of completeness.