

Optical and Numerical Diagnostics for SI Engine Combustion Studies

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ABSTRACT

Representative achievements that can be expected from optical diagnostics and newer direct numerical simulations, in the framework of their applications to spark-ignition engines are presented. An example of diagnostics is given with planar laser induced fluorescence and its applications to the air-gasoline-residuals mixture and combustion visualizations. It shows the variety of information that can be obtained for basing understanding, model development and design support. DNS are now applicable as exact experiments providing detailed information on combustion processes that would be difficult to infer from measurements, and are relevant to support engine code development. These new research tools appear now as essential to develop the low emission and high efficiency engines of the future.

INTRODUCTION

The development of new low emission and high efficiency engines under the pressure of the market and more stringent regulations is now a very complex and challenging task for automotive engineers. More technologies are used to reach balanced trade-offs: complex multi-valve head, direct injection, variable valve-timing, flexible digital engine management, ... For the engineers, this implies an increasing number of parameters to optimize making the best choice very costly to determine by try an error traditional experimental procedures. However, the optical diagnostic and multi-dimensional modeling tools which development for engine applications began in the seventies are now emerging as valuable supports for engine designers, if not essential.

The goal of this paper is to show how basic research tools that first gave insights to engine internal combustion are now usable in many various ways. Instead of making an extensive presentation of available techniques, the applications of two recent diagnostic tools to spark-ignition engine problems are presented. The first one deals with the use of experimental *Laser Induced Fluorescence (LIF) visualizations* to characterize mixture and combustion. The second is a new numerical technique called *Direct Numerical Simulations (DNS)* which can be considered as a very precise numerical experiment.

LIF is an optical diagnostic which has now been implemented in various way in engines. For certain applications, it can provide quantitative data in 2D, and this information is relevant to give basic information on in-cylinder phenomena, to validate 3D modeling codes, or to support directly engine development.

DNS is a modern numerical tool that has been shown recently to be very useful to describe engine-like specific combustion situations. This technique must not be mistaken with multi-dimensional modeling, but is a support for this design tool, as well as an understanding technique.

None of these new tools offer a complete solution to the engine designer. However, it is hoped that this paper will enable the reader to feel that their continuous use is slowly changing and improving the common picture of engine reacting flows. In some cases, they may even lead to significant changes in engine design, directly by the information they provide, or indirectly through the integration of new knowledge in 3D engine codes.

LASER INDUCED FLUORESCENCE APPLICATIONS TO SI ENGINE

At a first stage of applications to engine, the power of laser based measurements was mainly related to the basic understanding of the nature of engine flows. Much was learned qualitatively related to flow velocities and flame propagation. These measurements provided a good basis to identify the relevant engine controlling parameters. Many poorly known processes still need to be studied that way, such as pollutant formation and reduction, injection. But optical diagnostics have now reached a second stage with two supplementary directions. One is related to the building of "optical data base" that can be used to validate multi-dimensional models. The codes, once validated in a certain range of operating parameters (they are not fully predictive yet), are run to compute industrial cases. Another new proven use of optical diagnostics has been to directly guide engine development, when they were applied to answer well formulated questions.

Laser induced fluorescence and its recent application for visualizations in engines is a good example of these various uses of optical diagnostics.

Applications to mixture characterization

The knowledge of distribution of major species, such as gasoline, air or residual gases is important to characterize the conditions that the engine propagating flame will encounter. Scalar measurements in engines were very unsuccessful up to recent days. The use of laser induced fluorescence has brought the possibility to visualize concentration fields, although getting quantitative data remains a complex task.

Gasoline distribution

The observation of the gasoline field in SI engine was made first possible with Rayleigh scattering [1], essentially with point measurements, and often replacing the gasoline by gases with a high index of refraction. Latter on, laser induced fluorescence techniques have been used. Direct observation of the gasoline fluorescence is difficult since commercial fuels vary very much in composition, and that it is mostly impurities that cause a fluorescent signal. Pure fuels with properties close to commercial gasoline usually do not fluoresce. Seeding the gasoline with a relevant fluorescent dopant as shown to be more successful. In that case, the problem is to find a dopant following as closely as possible gasoline during its vaporization. Various dopant have been tried recently, leading to interesting results [2], [3]. The use of biacetyl as a fluorescent tracer of iso-octane as the fuel is presented here.

The experimental set-up necessary to perform PLIF measurements in engine is shown on Figure 1. It is necessary to modify the engine for large optical access. The most common solution to enable the use of standard heads is to have an elongated piston with a fused silica top, and to install some side windows. A laser sheet, formed from a pulsed Yag laser beam at 352 nm to get both sufficient energy and time resolution, is sent into the engine. The images are collected with gated intensified camera, and then computer processed for image correction and enhancements. Devoted data acquisition and engine-apparatus control systems are necessary to phase data taking and engine. For the gasoline concentration visualization, 3-5% biacetyl has been diluted in iso-octane.

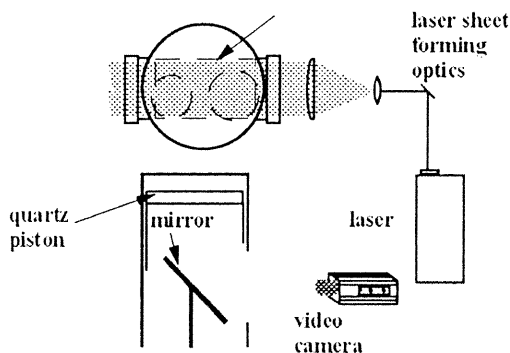


Figure 1: Planar laser induced fluorescence in engine

In a flat chamber engine with conventional port-injection, typical images such as those of Figure 2 were obtained. The quantitative aspect of the technique was assessed in [4]. The PLIF technique is able to distinguish the local homogeneity levels of two different intake

configurations creating swirl or tumble flow. The tumble flows with a higher turbulence level creates a rather uniform air-gasoline mixture, while the swirl mixture is much more uneven in this chamber.

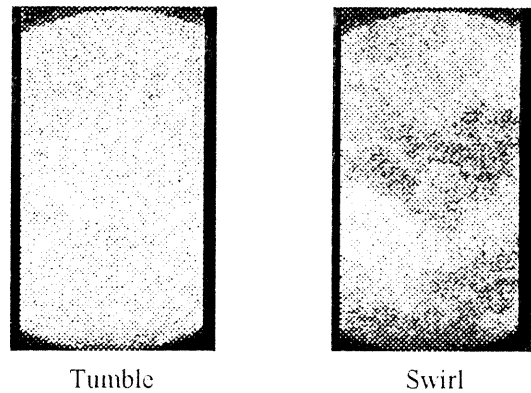


Figure 2: Typical PLIF images in the flat-head engine

Using various image operators, quantities characterizing the mixture evolution during compression were determined. On Figure 3, the evolution of the overall homogeneity was measured for various flow and injection timing. The very heterogeneous mixture formed at BDC (with large differences between the various operating conditions) tends to homogenize during compression. However, at TDC, there is still a 10-15% variance in fuel vapor distribution, which may cause significant combustion variations, especially during the initiation phase for lean mixtures. The results show also that there is a complex interaction between flow and injection, and that no rigid rules regarding injection phasing can insure the best level of mixing.

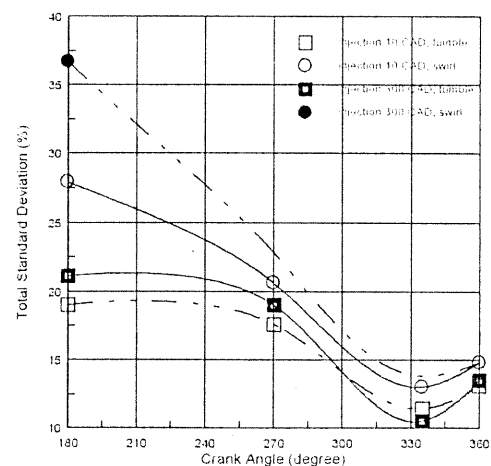


Figure 3: Evolution of gasoline-air mixture homogeneity during compression

After this successful application of the biacetyl-PLIF technique in a simple research engine, it was applied on a commercial 4-valve engine in [5]. The optical access for this engine was quite similar to the flat-head one, except for a narrower laser sheet of light. The engine was normally fired, and various mean flows were produced by mean of shrouds installed or not on the intake valves. This produces flows ranging from slow to fast tumble, and low to high swirl, with

one or two active intake valves. Also, the injection could be activated in one or two of the intake ducts.

Mean mixture fields at TDC are presented on Figure 4. The images are in a plan parallel to the piston, and lined-up with the roof edge, 5 mm below the spark gap. At 25 degree before TDC, the gasoline fields are on a large scale quite uniform for all the configurations, except for the two tumble flows with injection in one intake duct. The observation of the gasoline fields shows that within 60 mm in a 83.5 mm bore engine, the ratio of maximum to minimum equivalence ratio can reach a factor of 2. For both tumble single injection cases, the very uneven fuel distribution of the intake stroke is never homogenized, and for each cycle, a very stratified mixture is observed at TDC. The higher the tumble, the most stable the frontier between rich and lean mixture. Complementary LDV measurements have shown that the high tumble case exhibits both higher mean velocity levels during intake, and higher turbulence levels around TDC.

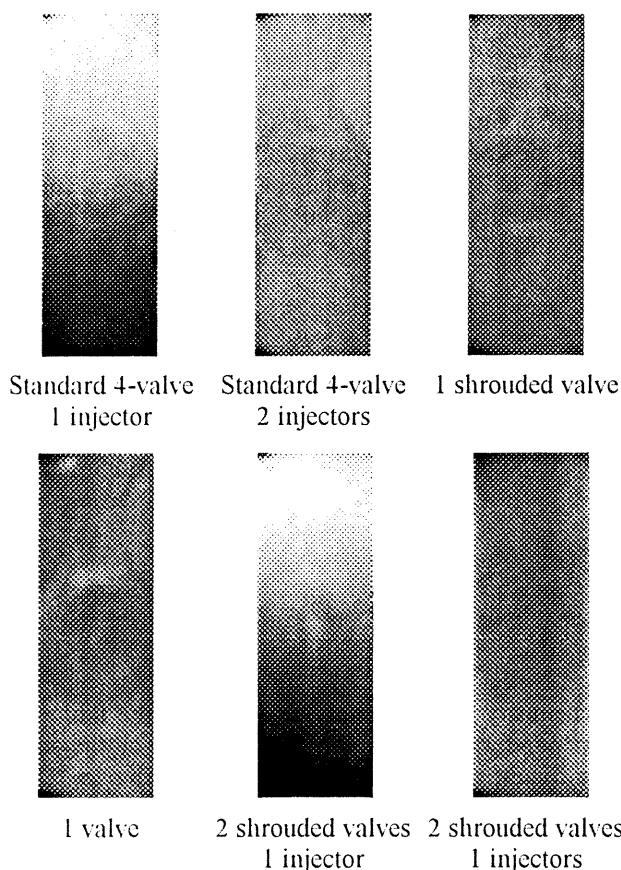


Figure 4: Mean gasoline fields for various flow and injection patterns.

This gasoline distribution control has been exploited to run the engine very lean with a stratified charge, and it confirmed previous work of [6] with a quantification of the concentration gradient. Putting the spark plug 3 cm off-center, in the richer region of the chamber, it was possible to run the engine very lean with extremely reduced cyclic variations. On Figure 5, plots of the pressure signals for the base engine with low tumble, homogeneous mixture, and central ignition are compared to the stratified, high tumble, off-center ignition. The clear advantage of the

stratified charge and high turbulence case is evidenced, despite the fact that an off-center spark plug offers geometrical disadvantages.

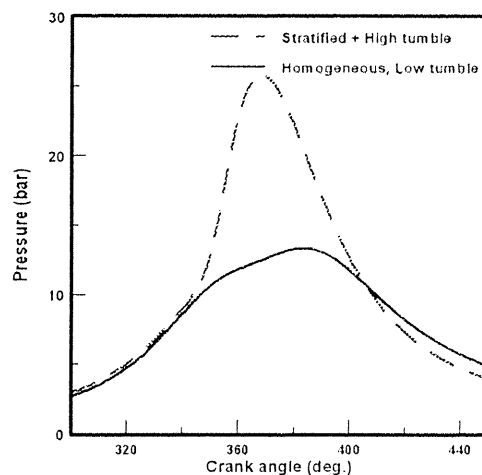


Figure 5: Pressure signals comparing the homogeneous low tumble with the stratified high tumble 4-valve engines at equivalence ratio 0.7

Residual gases visualization

The biacetyl-PLIF has been used in the same 4-valve engine, but to show the distribution of residual gases. In that case, the engine was run on a propane-air mixture, and biacetyl was added far upstream the intake valves, insuring a perfect mixing with the unburned gases. When the seeded mixture burns, the biacetyl as well as the propane burn. Hence, in the residual gases remaining in the chamber at the end of the exhaust phase, there is no biacetyl. When the unburned mixture penetrates into the chamber, the mixing with the residual is visualized by imaging it with PLIF. What is obtained is the 'negative' image of the residuals.

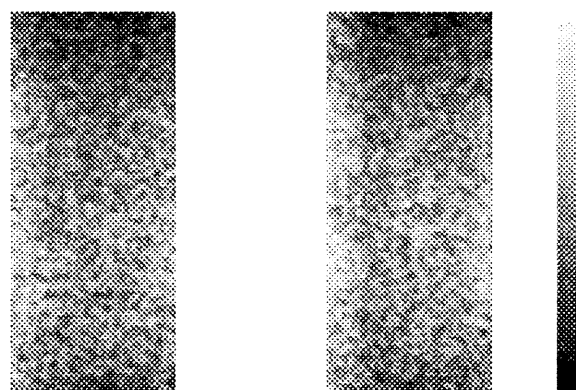


Figure 6: Residual gases fields in a 4-valve engine with a counter-pressure of 110 mbar. Gray scale from 16 to 26 % residual concentration.

With the same field of view than for Figure 4, an image of the ensemble averaged residual distribution is shown in Figure 6. With the presented engine configuration, the residuals are obviously not well mixed, and located in the middle of the chamber. The residual concentration was estimated quantitatively by normalization procedures, and the sensitivity of the methods was checked by varying the

exhaust throttling. Mean residual concentration across the imaging zone between 15% (no throttling) and 20% (110 mb counter-pressure) were found with a 8 to 1 compression ratio. This negative PLIF method is then shown to be usable in engines to provide mean residual fields. However, due to the limited dynamic of intensified camera, and the fact that the residual concentration is rather low, the method is not yet reliable for cycle resolved measurements. A method showing directly the residual would be preferable, but is not available yet.

Origin of the cyclic variations

The use of various optical diagnostics described in the previous section has shown to provide many types of information. Since these diagnostics are now well mastered, a good attempt can be to use an array of them on well defined engine and/or operating conditions to analyze the relative influence of independent parameters. This has been performed in [7], to study the origin of cyclic variations.

Cyclic variations have multiple causes including cycle to cycle variations of the bulk flow, turbulence, gasoline and residuals distributions, and spark discharge (this last parameter is very linked to the mean flow at the spark gap). To estimate the relative importance of all these local parameters on the fluctuation on combustion, a multiple-variable correlation technique has been applied on a set operating conditions in a flat-chamber engine with varying swirl level. On these operating points, the heat release was computed from the pressure traces using a two-zone thermodynamic model. The velocity was measured in the spark gap with LDV, and the velocity fluctuations decomposed in high and low frequency contributions characterizing the turbulence and mean bulk flow. Planar LIF such as described in a previous section gave the local fluctuations of gasoline and residual concentrations.

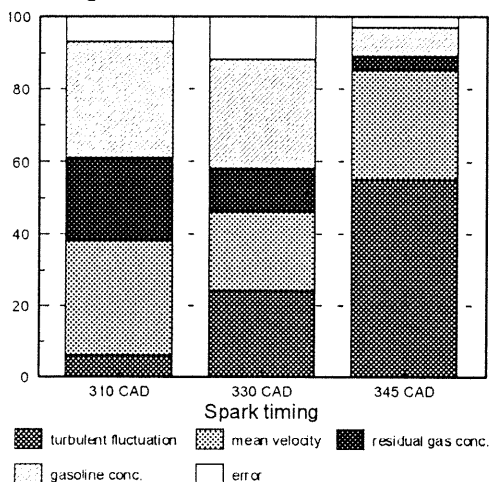


Figure 7: Statistical analysis of the origin of the various contributions (%) to the fluctuation of the 5% burnt fraction angle. Engine fed with iso-octane, and fired every cycle.

All these measured parameters fluctuations and the corresponding fluctuations of 5% burnt fraction angle for the various operating conditions form a matrix that can be statistically analyzed with correlation techniques. A typical result is presented in Figure 7. The bar chart shows the

relative influence of each of the studied parameters on the 5% heat release crank angle fluctuations for various spark timing. It can be seen that the major parameters influencing the initiation were measured since the unexplained variance (error) is rather small. An interesting feature is the change of relative influence of each parameter. For large spark advance, the laminar flame speed is low due to the low temperature. In that case, the contribution of the mixture composition is dominant, along with bulk convection effects. For higher flame speed, with ignition closer to TDC, the turbulent flame speed becomes dominated by the turbulence level, while the effect of mixture composition becomes very reduced.

Combustion diagnostics

The development of the large optical access engines have allowed the utilization of many combustion diagnostics. The visualization of burnt gas luminous emission was the first and is still commonly used. The combustion process is followed using high speed and short exposure time film or video camera. Easy to implement, this diagnostics is now used by most of the engine laboratories as a simple way to characterize early flame propagation or flame convection. Shadow or Schlieren visualization provides a better description of the flame zone, but with a more complex optical apparatus. These techniques have the characteristic that they integrate along a line of sight.

To resolve the inner structure of the flame brush, planar imaging is done using sheets of laser light. First planar measurements of flame were done with Mie scattering [8]. The light diffused by particles seeding the mixture, with a much higher particle volumic concentration in the unburned gases, permits to distinguish the interface between unburned and burnt gases. However, due to window fouling and uneven seeding, the accuracy of this technique is limited, although very interesting results have been obtained [9].

More recently, planar Laser Induced Fluorescence has been used to provide 2D images of the flame front. Two main techniques give different kind of results. For the first one, a chemical radical is imaged, such as OH [10]. However, intermediate species are in low concentrations, or their chemistry is not directly an image of the flame front location, and this makes the interpretation of the images quite difficult. The second one is very similar to 2D Mie visualization: the unburned mixture is seeded with a fluorescent dopant excited by the laser wavelength. The advantage on the Mie scattering is that the dopant completely burns at the flame front, and that there is no pollution of the windows. This allows a much better determination of the flame front location.

An example of doped fuel PLIF flame imaging is presented in Figure 8. The experimental apparatus is essentially the same than in Figure 1. A typical flame image was obtained by uniformly seeding a propane-air mixture with biacetyl (as it was described in a previous section to visualize indirectly the residual gases). The spatial resolution is limited by laser sheet of light thickness, while the time resolution (15 ns of the laser pulse) is good enough. The laser sheet is just below the spark gap in a flat-head engine. Two engine speeds are compared (600 and 1200 rpm), at an equivalence ratio of 0.7 and a volumetric

efficiency of 0.6. The image crank angle is 10 (600 rpm) or 20 cad (1200 rpm) after spark beginning. At 600 rpm, the flame is smoothly wrinkled. At 1200 rpm, the structure of the propagating flame appears clearly as being made of very wrinkled flamelets. At the difference of Mie scattering techniques, it is possible to observe an extremely convoluted flame front due to the very low noise level of the technique. This is the case when the laminar flame speed is low while the turbulence level is very high, so essentially for very lean mixture. This good definition of the flame interface allows to perform quantitative analysis of the flame images on large sampling sets. For instance, statistical flame densities, such as computed by flamelet models described latter in the paper are obtained. In Figure 8, such a flame probability of presence is shown. One can see that if for one cycle, the flame front is made of a thin interface, the statistical analysis of its location gives a rather continuous distribution due to both small scale turbulence, and cycle to cycle variation of the bulk convection. Other information, such as mean flame position, flame brush thickness can also be compared to combustion modeling prediction such as presented at this COMODIA [11]. This type of information is crucial to validate in detail combustion models, since the simple heat release analysis is too global.

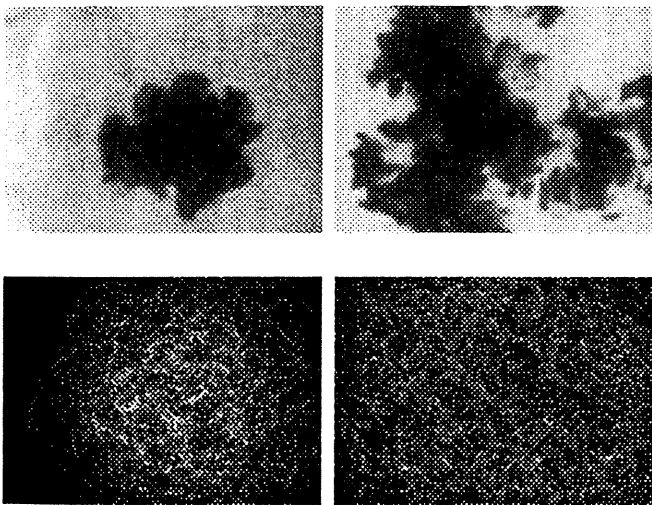


Figure 8: Flame contours (top) at 600 (left) and 1200 (right) rpm, and probability of flame front presence (bottom) for a lean air-propane mixture ($\phi = 0.7$), 10(600 rpm) and 20 (1200 rpm) cad after beginning of ignition at 335 cad.

DIRECT NUMERICAL SIMULATIONS FOR SI ENGINE COMBUSTION

What are Direct Numerical Simulations ?

Numerical techniques have become essential tools to study engine turbulent reacting flows. Multidimensional numerical techniques in which the reacting flow is solved for using a space-resolved numerical technique may be classified in different categories: - Reynolds- or Favre-averaged approaches based on Turbulent Combustion Models (TCM) in which one looks for average quantities (averaged over realizations (cycles) for flows like those found in piston

engines). - Large Eddy Simulation (LES) techniques in which only small- scale perturbations are averaged but large-scale variations are explicitly computed. - Direct Numerical Simulations (DNS) in which all scales are explicitly computed. In DNS methods, no modeling is required at all since one only needs to solve the full Navier-Stokes equations without any other assumption. In that sense, *DNS appear as exact numerical experiments*.

However, due to excessive computer requirements, DNS methods are very limited in terms of parameter range. For the foreseeable future, numerical simulation of the full three-dimensional governing partial differential equations with variable density and transport properties and complex chemistry will remain intractable; thus various levels of simplification will remain necessary. Therefore DNS has to be performed in connection with theories and experiments.

In the present paper, DNS results relevant to SI engine turbulent combustion are presented. Most of the outputs are relevant in the framework of flamelet models. This classical theory assumes that the turbulent premixed flame is an ensemble of small laminar flames ('flamelets') stretched and curved by turbulence.

A typical DNS code: NTMIX

Many choices can be made relative to the code used for DNS. The results presented here are obtained with a very comprehensive code, NTMIX, performing a fully compressible computation. It has the advantage of offering an easier treatment of boundary conditions, while taking into account heat release and pressure waves. A sixth-order Pade scheme on all directions and a third-order Runge Kutta method for time advancement are used.

The choice of the chemical scheme is essentially dependent on the question to address: considering pollution problems with DNS will require a reasonably complete chemical scheme, while the effect of turbulence on flame wrinkling may be addressed with simple chemistry. Because of cost considerations, the possibility of performing two-dimensional computations is often used. For premixed flames, DNS [12] show that the probability of finding a locally cylindrical (2D) flame sheet is much higher than the probability of finding a really 3D spherical flame shape, and this justifies the preliminary 2D approach.

Computing time for DNS is the limiting factor. Three-dimensional computations performed with simple chemistry (Arrhenius law, variable density, variable viscosity) represent more than a hundred Cray hours for each run, while two-dimensional requires on the order of ten hours. Complex chemistry computations are out of reach of most research centers at the present time but this status is changing rapidly [13].

The main problem of DNS methods is to be able to compute flow in boxes of sufficiently large size. For reacting flows, this is even more true, since the computation has to resolve all flow scales but also all chemical scales inside the flame front. At top dead center in engines, integral scales of a few millimeters have been measured, while a typical engine flame thickness is about 0.1 mm. This domain of practical interest for piston engines applications has a significant overlap with the present domain of application of DNS

using modern super computers and typical grids (600^2 in two dimensions and 128^3 in three dimensions).

Application to SI engine combustion

There are three important aspects of premixed turbulent combustion where DNS has proved to be a valuable tools for modelers: - turbulent flame propagation as modeled in flamelet models - flame ignition in turbulent flows - flame-wall interactions. We will present at the end the impact this DNS results analysis had on the accuracy of the modeling of SI engine combustion such as implemented in the KIVA code at IFP.

Turbulent flame propagation

Flame-vortex studies using DNS tools [14] or experimental methods [15] suggest that the effect of turbulence was probably too simplified in classical turbulent combustion models where the Kolmogorov strain rate is often taken as the characteristic flame strain. How can this result be incorporated in models ? This may be done in the framework of models using a conservation equation to predict the flame surface density Σ (defined as the flame surface per unit volume). For example, the formulation of the Coherent Flame model [16] provides a conservation equation for S in a Lagrangian frame moving with the turbulent flame.

$$\frac{d\Sigma}{dt} = \bar{\kappa}\Sigma - Q_c \quad (1)$$

where $\bar{\kappa}$ is the mean stretch rate averaged along the flame surface. The second term Q_c on the RHS of Eq. 1 corresponds to flame surface annihilation by mutual interaction of flame fronts (for example, the merging of two flame fronts together). The average stretch $\bar{\kappa}$ is of utmost importance in Eq. 1 because it imposes the source term for the flame surface and therefore the mean turbulent reaction rate \bar{w} given by

$$\bar{w} = w_L \Sigma \quad (2)$$

where w_L is the mean consumption rate per unit surface along the flame front (if one assumes that the flamelet has a laminar structure, w_L will be the laminar consumption rate for the same chemical parameters and the same stretch). In Eq. 1, the flame stretch $\bar{\kappa}$ measures how fast flame surface is created by the turbulent flow. If this stretch is supposed to be equal to the Kolmogorov stretch $\sqrt{\langle \varepsilon \rangle / \nu}$, then one assumes that these Kolmogorov scales are the most efficient in flame stretching (which is wrong). If this time is $\langle \varepsilon \rangle / \kappa$ supposed to be equal to the large scales stretch, then one neglects intermediate scales and tests in flamelet models show that such models do not follow effects of changes in turbulence scales or in laminar flame speeds. The ITNFS model was introduced to predict what $\bar{\kappa}$ should be, taking into account the progressive effect of viscosity on the stretching capacities of turbulent vortices as their size diminishes. A complete derivation of this model is given in [17]. It is based on measurements of flame stretch from flame-vortex DNS which were extended to turbulent situations using multi-fractal analysis. The main result is that a correlation for $\bar{\kappa}$ is obtained in the following form:

$$\bar{\kappa} = \gamma_K \sqrt{\langle \varepsilon \rangle / \nu} \quad \text{with } \gamma_K = f(u'/s_L, L/\delta_l)$$

γ_K is the ratio of the flame stretch to the small scale stretch $\sqrt{\langle \varepsilon \rangle / \nu}$. For infinitely thin flames ($L/\delta_l \approx \infty$), γ_K

was constructed to go to a limit value of the order of 0.28 as obtained in simulations of material surfaces by [18]. For 'usual' flames placed in 'usual' turbulence, flames can not be considered as infinitely thin and generally, γ_K is of the order of 0.001 to 0.01. This expression of stretch also plays an important role near walls: in these regions, the characteristic turbulence scale decreases drastically and so does γ_K . This leads to a limitation of flame surface density near walls in contrast to expressions using for example $\bar{\kappa} = \langle \varepsilon \rangle / \kappa$ which create large values of stretch rates and a non-physical explosion of flame surface density near walls. Note however that using the ITNFS model near walls is not enough and that more efforts must be devoted to the wall effects as will be shown latter. ITNFS was coded into KIVA and KIVA predictions compared with measurements performed at IFP [25]. Results showed that ITNFS would allow a correct prediction of the effects of volumetric efficiency, equivalence ratio and spark timing while models based on $\bar{\kappa} = \langle \varepsilon \rangle / \kappa$ would fail to do so. Later the ITNFS model has been used in many other engine codes in the framework of the tests of the Joule program [19] as well as in other research centers [20].

Flame ignition

Flame ignition in piston engines takes place in a turbulent situation [21]. Although much is known about ignition processes in laminar flows, the application of these studies to practical cases is limited by the unknown effects of turbulence on these processes. Only a few results on ignition in turbulent flows are available. Research scientists working in the field of reciprocating engines have been quite active ([22], [23]) but the complexity of flow fields and the difficulty of performing measurements inside piston engines makes some of the relevant information difficult to extract from these studies (the turbulence characteristics, for example, are complex and difficult to estimate). Fundamental information on these phenomena is lacking.

DNS of ignition in turbulent premixed flows have been performed in the last years [24] to gain some understanding of the processes controlling ignition. A typical example of results given by DNS for an ignition of premixed gases by a spark in two-dimensional turbulence is displayed on Fig. 9. The calculations are initialized with reactants everywhere in the square domain. The initial velocity field is specified at $t=0$. This field has a zero divergence and corresponds to a 'synthetic' turbulence: its spectrum can be specified and its initial RMS velocity u' and integral length scale L are imposed. The system is then allowed to evolve in time. After a certain delay t_{delay} , combustion is initiated in the middle of the computation box. This is done by adding a localized source term of size R and power Q during a time $t_{ignition}$.

Typical superimposed contours of reaction rate and vorticity are shown in Figure 9. The initial u'/S_f is 5, and the ratio of the integral scale to the flame thickness is 6. Three times after beginning of spark discharge are shown in adimensional flame time unit defined as the ratio of flame thickness to flame speed (3, 6, and 9).

The spark creates a flame which grows first in a laminar-like fashion and later transitions to a turbulent flame which has an aspect very similar to the PLIF visualization at low engine speed shown in a previous

section. This result confirms experimental findings which describe the initial growth of the flame as an essentially laminar process, and this because it is controlled first by the large energy deposited by the spark which feeds the temperature field and helps it grow beyond the critical size needed for self-sustaining reaction.

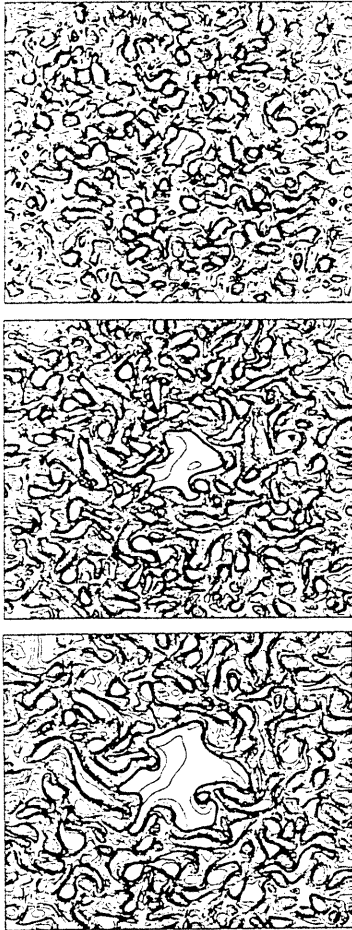


Figure 9: DNS of ignition in premixed turbulent flows

These DNS have led to models which have been incorporated into KIVA at IFP [25]. This was done in separate steps: (1) DNS and experiments show that the first instants after ignition are similar to a laminar ignition since they are controlled by the energy deposition (and only marginally by the turbulence). This result suggests that the first instants of ignition may be computed using a separate one-dimensional spherical solver. (2) In a second phase turbulent stretching begins to influence the growth of the kernel (of mean radius R). A 'simplified' model of kernel growth taking into account laminar growth and turbulent stretching may be derived and run in KIVA. (3) The transition from this second phase to fully turbulent flame (where kernel growth is not important any more) is then achieved when turbulent stretch is larger than the stretch rate due to the growth of the laminar flame kernel $(1/R)(dR/dt)$. Turbulent stretch is computed using the ITNFS model. Transition criteria were tested versus DNS results. (4) The distribution of flame surface density at the transition time (from kernel-type flame to freely propagating turbulent flame) was modeled and compared to DNS results. This distribution was then used as 'initial condition' for the

flamelet model in KIVA. (5) Coupling of this model with KIVA was achieved as described in [25].

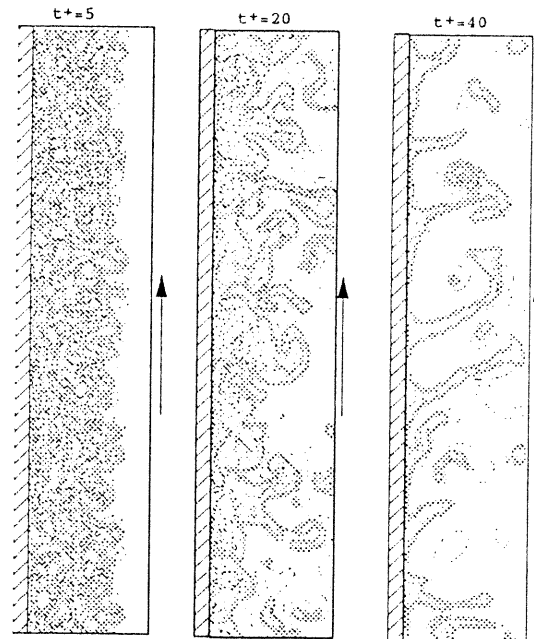


Figure 10: DNS of flame-wall interaction in a shear boundary layer

Flame wall interaction

Even in the absence of chemical reaction, understanding and modeling of turbulent phenomena that occur near walls is a formidable task. Building 'law-of-the-wall' models or low-Reynolds-number models is an ongoing research subject and no satisfactory practical solution is yet available for general use in engineering codes. The situation is even more difficult when a flame is present. Combustion is strongly influenced by the presence of walls which may cause flame fronts to quench, for example. Moreover, the flame has a significant effect on the flow in the vicinity of the wall as well as on the heat flux to the wall. For these reasons, modeling of flame-wall interactions in turbulent situations is an important issue. Still, few experimental or modeling results have been reported and most present models for turbulent premixed combustion do not use any specific corrections for near-wall effects. At best this may result in errors in the prediction of the reaction rate and of the wall heat fluxes and temperatures. In some cases the absence of any reasonable approximation of the wall effects leads to numerical difficulties and to the use of ad-hoc numerical corrections to obtain solutions.

DNS of flame-wall interaction mechanisms were first performed in 1992 and led to the formulation of a flame-wall interaction model called FIST [26]. The flame-wall model was derived in the framework of flamelet models and may be used with any model using flame surface density as the representative flame variable. Fig. 10 shows a typical DNS of flame-wall interaction. Vorticity fields and reaction rates are superimposed while the flame approaches the wall. Fresh gases are trapped between the wall and the flame (as in a real piston engine) and turbulence is generated at the initial

time in the whole domain. The flame is initially planar. There is a mean flow parallel to the wall with a velocity gradient. The initial temperature of the fresh gases is equal to the wall temperature. The turbulence intensity is $u'/s_L = 6.5$ and the integral scale L is given by $L/\delta_l = 2.5$. The flame propagates towards the wall and gets eventually quenched when it comes close to it. During this process, post-processing of DNS results may be used to track flame front characteristics, flame curvature and strain, heat flux distribution on the wall. Simulations reveal that the turbulent flamelets behave in different ways when they reach the wall depending on their history but that the quenching distance δ_Q (the minimum length between wall and non extinguished flame elements) is of the same order than in a purely laminar case. In the same way, the maximum heat flux to the wall in the turbulent case never exceeds the flux obtained in laminar Head On Quenching situations.

These DNS results may be used to build a model for combustion near walls (a model similar to law-of-the-wall models for non-reacting turbulent flows). Such a model was derived in [26]. A term is simply added to the flame surface density conservation equation in the first cell near the wall and represents the destruction of flame surface density by wall effects on flame wrinkling and quenching. This term may be added to any flamelet model for premixed turbulent combustion.

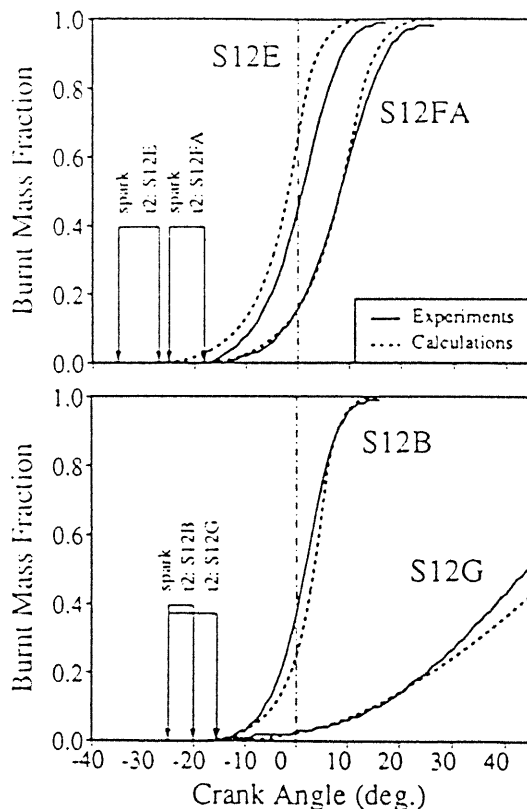


Figure 11: Evolution of the burnt fraction as computed by the ITNFS-CFM combustion model implemented in KIVA for a flat-chamber engine. Base line S12FA (1200 rpm, $\phi = 0.9$, vol. eff.=0.5). Variations of equivalence ratio (S12G, $\phi = 0.7$), volumetric efficiency (S12B, vol. eff.=0.9), and spark timing (S12E, -10 cad)

Implementation in a 3D modeling engine code

The CFM-ITNFS model and the ignition model, and latter on the flame-wall FIST model described above have been incorporated into KIVA and benchmarked using the data base of IFP obtained in a two-dimensional engine [27]. Results of these tests are given in [25] or [26]. The evolution of the computed heat release for various operating conditions are shown on Figure 10. The results were obtained after a fit of the CFM-ITNFS model on a reference case. Then, the code was run without any change to study the effect of equivalence ration, volumetric efficiency and spark timing. The obtained agreement is very satisfactory, with a good quantitative response of the engine code.

An important aspect of ignition mechanisms which was not treated in the work of [25] and [26] is the effect of a large convective velocity near the spark at the time of the discharge. This effect was studied using DNS in 1993 [28] and incorporated later in KIVA. It is used for the three-dimensional cases of a 4-valve engine as described in a paper presented at this COMODIA conference [29].

CONCLUSION

Examples of state-of-the-art experimental and numerical diagnostics related to SI engine research and development have been presented. The complexity and diversity of the mechanisms by which these tools can bring new information and support design are evident.

The now very successful optical diagnostics, most often planar and laser based, can bring basic understanding on the interaction between flow, gasoline distribution and combustion. They are unique to validate multi-dimensional engine codes. They are also new tools supporting directly engine development. Application of Laser Induced Fluorescence applied to the visualization of the air-gasoline-residual mixture and combustion is a spectacular demonstration of all these aspects.

If the use of computer code to support engine development is increasing, a new use of the computer power has emerged: solving without modeling the exact reacting flow equations with Direct Numerical Simulation. These new numerical experiments, although quite fundamental, have shown already their amazing relevance to SI engine combustion. They have already supported the development of more predictive models, and their use should increase in the near future, especially when complex chemistry computation will be used to understand pollutant formation in engine.

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