FINAL TECHNICAL REPORT
PART 1 - PUBLISHABLE FINAL REPORT

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LESSCO2

Large Eddy Simulation techniques to Simulate and COntrol by design Cyclic variability in Otto cycle engines

PROJECT CO-ORDINATOR : IFP

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LESSCO2

Final Technical Report
Part 1 - Publishable Final Report

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1 - EXECUTIVE PUBLISHABLE SUMMARY

Objectives

The major objective of the work in LESSCO2 was to demonstrate the feasibility of industrial LES (Large Eddy Simulation) engine simulations, and their potential for addressing phenomena not accessible to today's RANS simulation tools, and in particular the occurrence of cycle to cycle variations. The realised research was limited to spark ignited premixed combustion engines.

Methodology

In a first project phase, the necessary theoretical basis was to be laid by the R&D partners, to yield research tools and models adapted to LES in piston engines. Phenomena that were to be addressed were liquid fuel injection, premixed combustion and knock, as well as adapted boundary conditions and mesh management techniques. Experimental work was to furnish data for validating these developments. In a second project phase, the originality of LESSCO2 was that while further improving the theoretical basis, an important effort was dedicated to an efficient transfer to the industrial partners in order to allow them to perform LES simulations of flow and combustion in real engine geometries. As a major outcome, the participating industrial partners aimed at being able to perform multi-cycle LES engine simulations at the project end, which had never been realised prior to LESSCO2.

Results and exploitation

The main outcome from the project is the availability to the project partners IFP, RWTH-ITV, BMW and Renault of 2 research and 2 industrial CFD piston engine codes able to realise LES simulations. Their potential in this sense has been evaluated by a number of simple test cases furnished by IFP and computed with all project CFD codes. The CFD codes were in particular updated with two LES turbulence models – one based on a sub grid scale kinetic energy, the second on a DES (detached eddy simulation) approach – as well as with two LES models for premixed truculent combustion in spark ignited piston engines – one based on a CFM (coherent flame model), the second on a level set approach. Extensive validations on basic test cases were performed.

These developments allowed a number of project partners to realise multi-cycle LES studies of cold flow and combustion in real piston engine configurations. In particular, IFP used its AVBP code, co-developed and co-owned with CERFACS, to realise the first ever multi-cycle LES simulation of 9 consecutive engine cycles in a PSA XU10 spark ignited, port fuel injection, 4 valve single cylinder engine. These simulations demonstrated the unprecedented potential LES has to reproduce and predict cyclic variability in real configurations, at a competitive CPU cost. A comparable simulation was also realised by the industrial partner Renault.

In addition, a number of developments were achieved within the project, that laid a good basis for future further exploitation after the project end: automatic mesh management technique for piston engine simulations tested successfully on mesh only simulations of a real geometry by Queen's U. Belfast, a purely Eulerian formulation of a LES model for liquid spray by Institut de Mécanique des Fluides de Toulouse, a fast tabulation technique for including complex chemistry effects n CFD by Lund TH, and inflow boundary conditions for turbulent compressible LES simulations allowing to have a specific turbulence enter the computational domain whilst generating minor levels of perturbations by LITEC-CSIC.

Concluded with an expected minimum of 6 scientific articles, a project workshop named "LES for piston engine flows" organised in March 2006 at IFP in Rueil-Malmaison (France) and a dedicated mini-symposium at the 2006 ICNC conference organised by SIAM in Granada (Spain) in April 2006, the work in LESSCO2 set a reference in the domain of LES and piston engine simulations in Europe and worldwide, and is expected being followed by a number of follow-up R&D actions with a strong dedication to industrial application.

2 - PUBLISHABLE SYNTHESIS REPORT

The major objective of the work in LESSCO2 was to demonstrate the feasibility of industrial LES (Large Eddy Simulation) engine simulations, and their potential for addressing phenomena not accessible to today's RANS simulation tools, and in particular the occurrence of cycle to cycle variations.

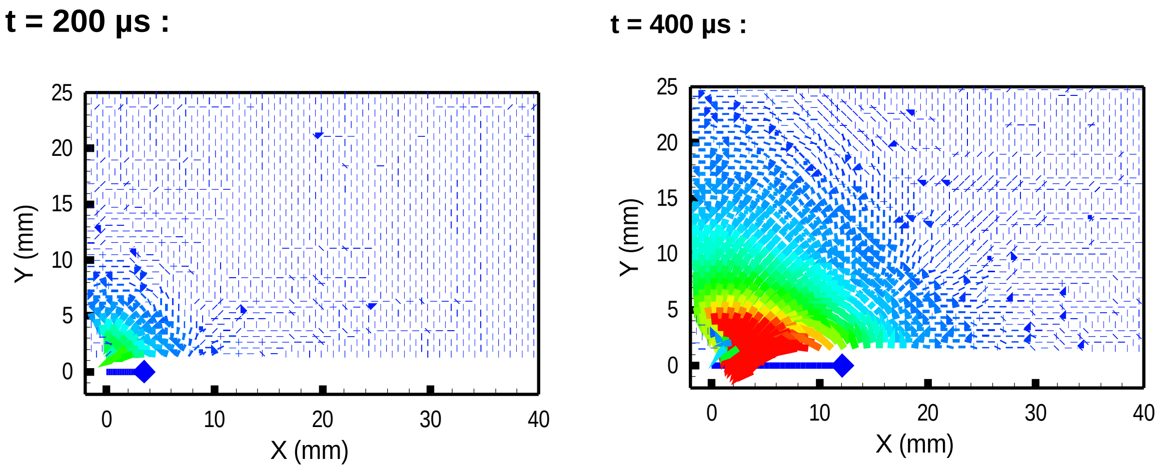
2.1 Databases for LES

In order to furnish validation data for the simulation activities, the partner *Peugeot-Citroën (PSA)* acquired, using optical diagnostics, two experimental databases:

- **Visualization of liquid injection in a cold constant volume vessel**

The aim of this activity was the experimental characterisation, using different techniques, of a liquid gasoline jet injected into a cold, quiescent constant volume bomb:

ü Shadowgraphy to get a direct visualization of the liquid spray development;
ü Malvern technique to measure distributions of droplet sizes in order to characterize the breakup process.
ü PIV (Particle Image Velocimetry) technique to get information on air entrainment by the liquid spray. Figure 2-1 shows a typical time sequence acquired on the studied injector at a given bomb pressure.



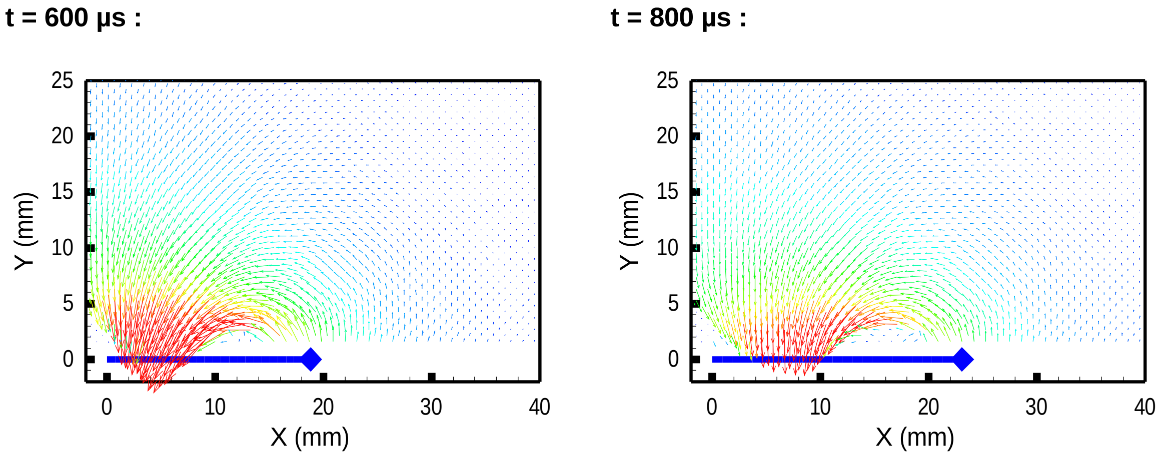


Figure 2-1: Typical evolution of velocity filed induced by the studied swirl injector.

Data was acquired for different injection duration, injection pressure and counter pressures and concatenated on a CD-ROM. It is readily available to serve as a validation base for the development of LES spray models.

- **Visualization of flow, mixing and combustion in a spark ignited gasoline engine**

Three different techniques have been applied to characterise flow, mixing and combustion in a PSA 4 valves - GDI optical engine:

ü PIV (Particle Image Velocimetry) to study aerodynamics inside the engine;

ü FARLIF (Fuel Air Ratio Laser Induced Fluorescence) was used to characterize the mixture formation for homogeneous conditions;

ü Direct visualization of the combustion progress, as shown in Figure 2-2 depicting the visualization of flame front as function of crank angle, correlated with mean cylinder pressure.

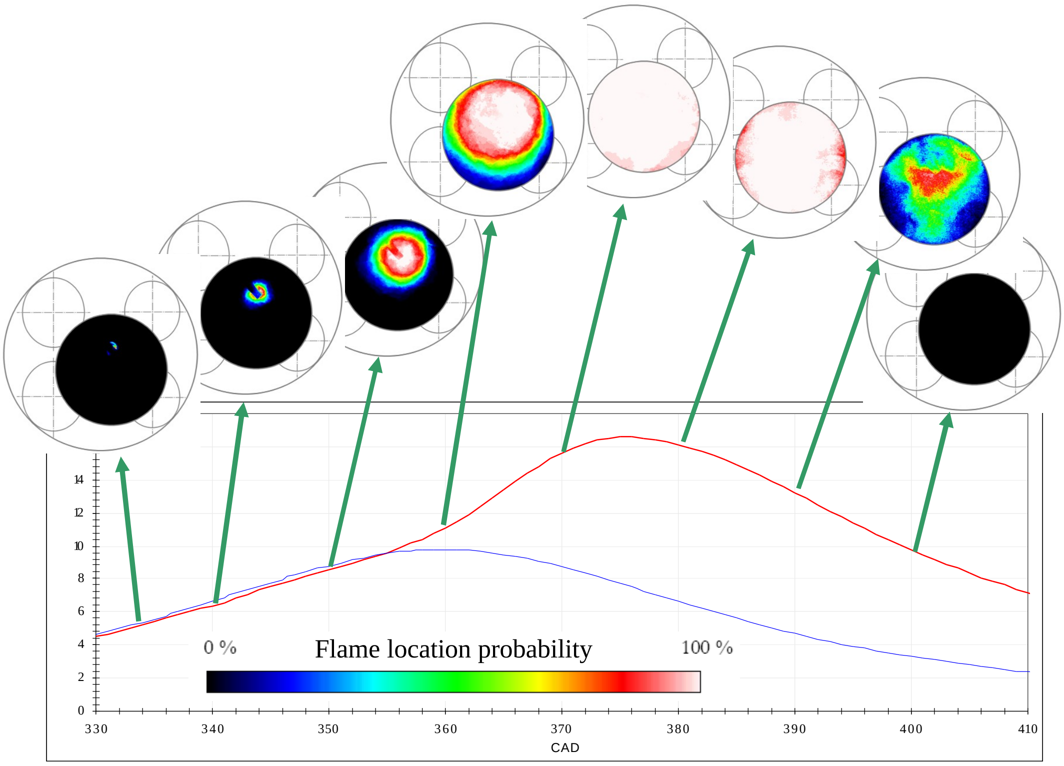


Figure 2-2/ Flame location probability related to in-cylinder pressure (SOI = 28 CAD).

Furthermore *Institut de Mécanique des Fluides de Toulouse (IMFT)* built a DNS (for Direct Numerical Simulation – a technique allowing to resolve exactly all flow scales and thus comparable to a numerical experiment) database concerning the turbulent dispersion of solid non evaporating droplets. This was realised through a Lagrangian simulation of the evolution of an initial slab of solid particles, submitted to a homogeneous isotropic turbulence. The influence of different parameters, as in particular Stokes and Reynolds numbers, have been investigated. Figure 2-3 shows typical results concerning the local particle concentrations for a given case of the database.

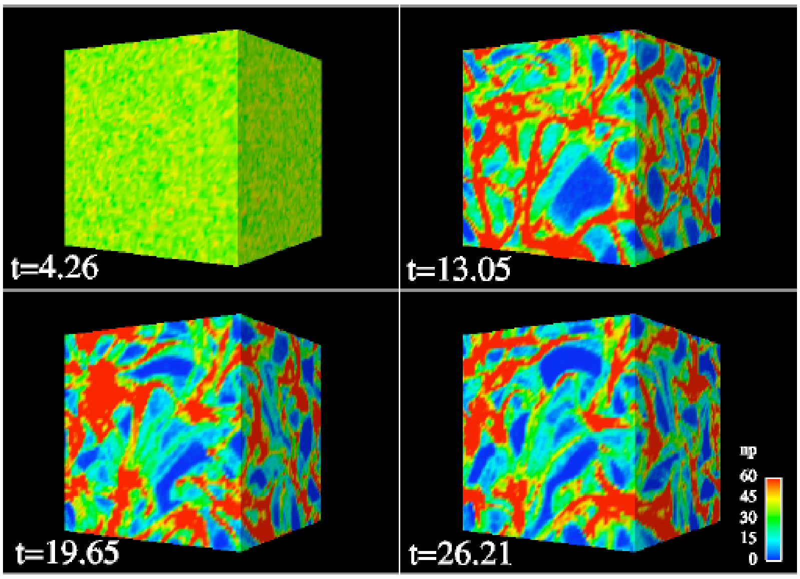


Figure 2-3: Snapshots of particle density number for one simulated case of the DNS database.

The results served then for a priori testing of the developed Eulerian formulation and allowed to validate in detail elements of the model proposed by IMFT.

2.2 Numerics and LES

The originality of LESSCO2 was to bring together the research partners RWTH-ITV and IFP, working on the development of their respective research LES codes for piston engine applications, with the industrial partners BMW and Renault, taking profit from these developments to have their commercial CFD codes for piston engines be adapted to realise LES.
The basic question that these partners attempted to address was to check the adaptation of the four concerned CFD codes for realising LES simulations. The major requirement in this sense was fund to be the numerical precision of the convective schemes used in these codes. In industrial codes, these schemes prefer stability over numerical accuracy, to ensure robust behaviour even on very complex geometries that cause problems of numerical stability. This possible lack of precision might be detrimental to the capacity of resolving the large scales, which is the basic principle of LES.
IFP proposed a set of simple tests that were run by all partners in their codes and helped to assess the differences between the codes, and to select especially for the industrial codes the numerical schemes and their parameters most adapted to LES. The principle of these tests is to have a vortex be convected on an initially regular periodic mesh, with no molecular or turbulent viscosity added. The exact solution is just a time translation of the initial vortex. Computing this simple Eulerian case thus allows measuring the order of convergence after a certain characteristic time, i.e. the

precision of the available schemes. As meshes are deforming in engines, these test were also performed with different mesh deformations imposed during the simulations.

Figure 2-4 shows a typical result obtained with IFP's AVBP code. The Lax-Wendroff (LW) scheme shows an order of convergence of two, independent of the mesh movement. This was also found to be true with most other second order schemes used in the 3 other codes.

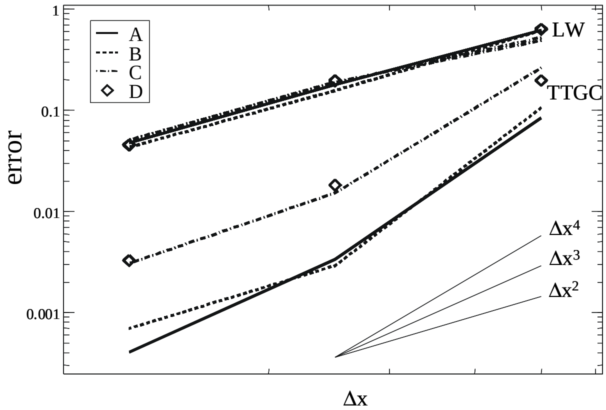


Figure 2-4: Order of convergence for the schemes of the IFP/CERFACS code AVBP. Case A is a fixed mesh cases, cases B, C and D correspond to different mesh deformations.

The definite advantage of AVBP is to dispose of the TTGC scheme of 3rd order, that clearly is more precise than the 2nd order schemes of the other codes, even if the level of error somewhat depends on the type of mesh movement (and thus induced cell anisotropy).

A second case corresponds to the simulation of a periodic 3D box, initialised with a homogeneous isotropic turbulence, and with no added viscosity. Theory says that enstrophy should blow up exponentially. Depending on the level of numerical dissipation introduced by different schemes, one can observe typical results as shown in

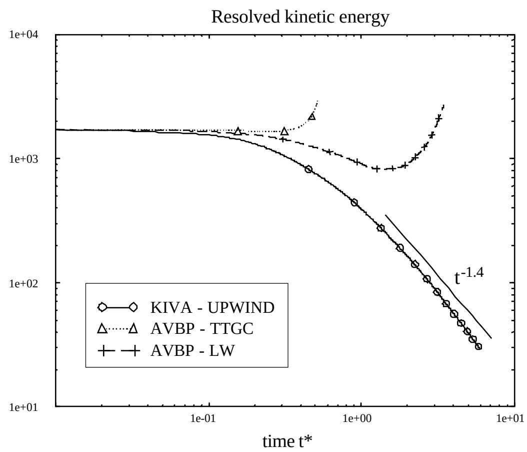


Figure 2-5; Decay of the mean resolved kinetic energy with time for different numerical schemes.

With a scheme of the precision (and thus low dissipation) of TTGC, one clearly can see the expected blow-up. With less precise schemes like Lax-Wendroff (LW), this happens also, but at later times, indicating higher levels of dissipation. Other 2nd order schemes proved to be even more dissipative than LW, questioning their usage in LES. The shown curve for an upwind scheme may differ from code to code, but typically this type of schemes is found to be too dissipative, no blowing-up taking place. Another factor of importance identified and which influences strongly the codes' precision is the time stepping (not shown here).

2.3 Managing mesh movements

The movement of valves and pistons in the combustion chamber of piston engines imposes the necessity to dispose of efficient and yet easy to use techniques to adapt the mesh at each time step to cope with the induced deformations. The difficulty is to realise this, whilst ensuring that the resulting mesh verifies certain quality criteria which it is necessary to respect to ensure a good level of numerical resolution. This is all the more true in LES, were the quality of resolution has to reach a certain level to allow using this technique with some confidence.

Queen's University Belfast (QUB) has developed during the project an automatic mesh management technique to address this question. First, a set of elementary tools to locally refine and coarsen tetrahedral meshes was developed and tested on simple cases. These were then combined in an overall tool which allows, based on the data structure of IFP's AVBP code and with the definition of certain quality criteria by the user (like maximum and minimum cell volume, skewness) to handle automatically the mesh modifications rendered necessary for simulating a whole engine cycle. Figure 2-6 shows an example of the resulting mesh at two different crank angles for a simple test case.

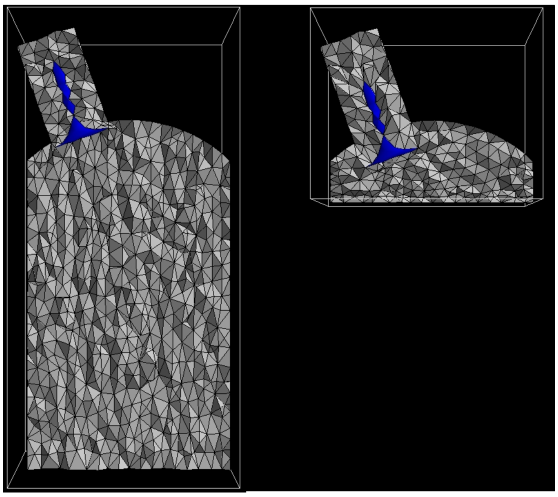


Figure 2-6: Crinkle cut through the preliminary test case mesh at BDC (left) and TDC (right)

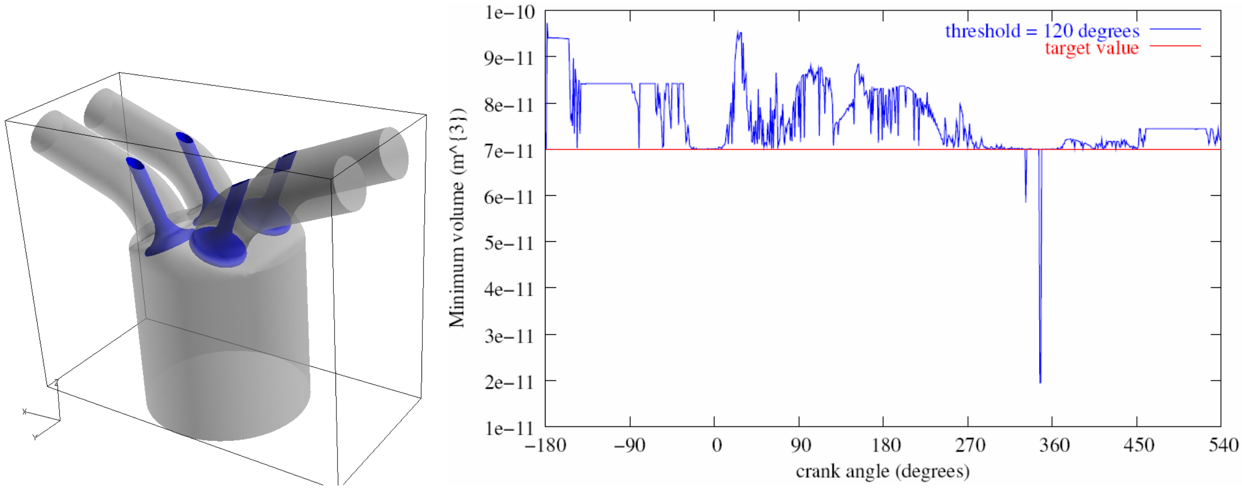


Figure 2-7: The PSA XU10 geometry and resulting Evolution of the minimum element volume with QUB's mesh management technique.

Figure 2-7 illustrates, for the realistic case of a PSA XU10 mesh, the evolution of the minimal cell volume obtained by using the technique developed by QUB. In a follow-up research action with

IFP, this technique shall be integrated into the AVBP code and be tested on LES simulations of the XU10 engine.

2.4 Acoustic boundary conditions for turbulent subsonic inflows

In the long term perspective, LES of piston engine flows should be able to take into account not only the combustion chamber and parts of the inlet and outlet ducts, but the effect of the whole engine set-up. This is necessary as cyclic variability is not only triggered by phenomena local to the combustion chamber, but also e.g. by the acoustic waves propagating in the induction and exhaust systems. As it is not possible, especially for real engine set-ups, to simulate the whole engine with LES, a possible approach would be to combine LES in the combustion chamber and parts of the intake and exhaust ducts neighbouring it, with 1D simulations of flow and acoustics in the rest of the system. One element to achieve this is to dispose of adapted boundary conditions for the 3D LES able to couple the 3D simulation with the 1D part, especially in terms of type of turbulence entering the 3D domain and acoustic waves.

In this sense, the LITEC laboratory of the Spanish *Conseja Superior de Investigaciones Cientificas (CSIC-LITEC)* in Zaragoza developed a novel inflow boundary condition which allows to have a subsonic flow of given turbulent characteristics enter a 3D computational domain, with a minimum level of acoustic perturbation. This was based on a NSCBC type of approach, which decomposes the inflow into 1D waves and allows imposing given characteristics with sufficient flexibility to avoid reflexion of outgoing acoustic waves.

The resulting boundary condition was implemented into IFP's AVBP code and tested using three different approaches for imposing turbulence on a test case corresponding to a turbulent channel flow. Figure 2-8 shows an example of results obtained, indicating a quite good reproduction of all major channel flow characteristics.

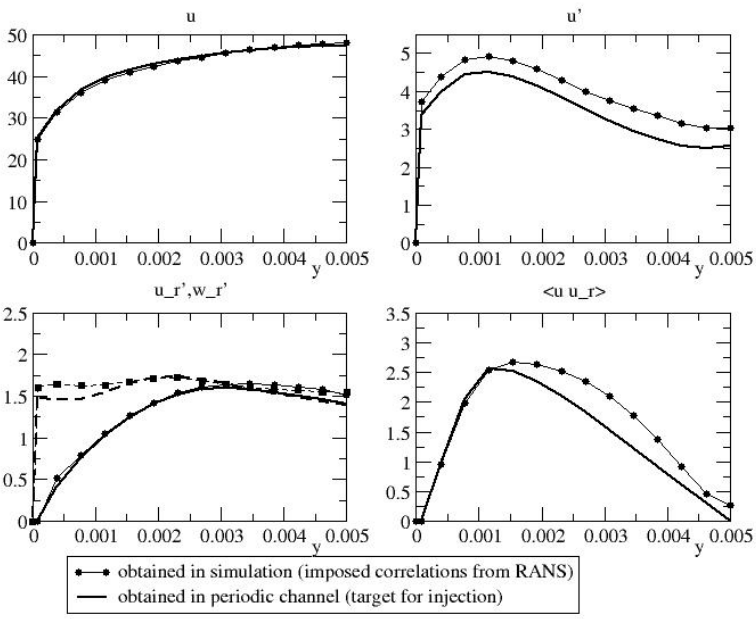


Figure 2-8: Statistical wall-normal profiles in the LES of a turbulent pipe flow with a turbulent inlet condition reproducing the mean u, fluctuations and correlations corresponding to RANS calculations, as given by experiments and theory.

These developments will be used by IFP as a future key element for coupling 1D simulation with 3D LES in piston engines.

2.5 Modelling turbulence in piston engines

One of the basic questions the research partners had to address was whether LES was feasible in a piston engine environment, and what turbulence models are most adapted. Reynolds numbers of typical piston engine flows are quite low (<100 000), with integral length scales between 1 and 10 mm, and the smallest Kolmogorov scales around 0.01 mm. Given typical scales of piston engine combustion chambers, and assuming that 10Mcells is a maximum allowable today, one can expect typical mesh sizes of at best 0.1 mm in the near future. Although this indicates a potential sufficiently high resolution of the largest turbulence scales, it also indicates that near solid walls, or at top dead centre, the mesh resolution may not be high enough to locally realise LES.
RWTH-ITV and IFP thus proposed approaches consisting of combining LES in regions where the flow resolution is sufficient, with a RANS type approach near solid walls or in regions with less resolution.

RWTH-ITV developed new hybrid RANS-LES model. Starting from a one-equation sub-grid k model as proposed by Yoshizawa and Horiuti, a model equation for the sub-grid rate of dissipation e_r has been added. The turbulent viscosity is determined based on the sub-grid kinetic energy and a length scale l, which represents the integral length scale in RANS regions while being equal to the filter width in LES regions. The new model allows for an automatic switch between the standard RANS model in regions of low grid resolution and the one-equation LES model in areas of finer meshes. The new model has been implemented into the research code and validated via simulations of a transient turbulent mixing layer and a backward facing step.

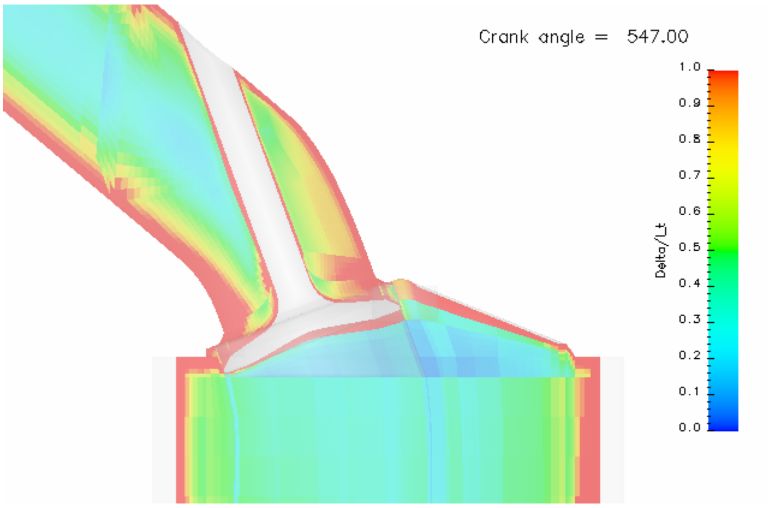


Figure 2-9: Estimation of the current mesh resolution for a typical engine using the ration of the filter width (grid size) and the integral length scale.

Figure 2-9 presents the ratio the filter width, here taken to be the cubic root of the cell volume, to the integral length scale as determined by a two equation RANS model (standard k-e model of Launders and Spalding) in atypical engine geometry; values smaller than 1 indicate that the filter width is smaller that the integral length scale, which implies that the integral length has been fully resolved. The figure shows that in large areas of the computational domain the mesh resolution is sufficient to employ a LES model as the integral length scale is well resolved, while in the near wall regions the grid is not able to resolve the integral structures. This fact motivates the usage of a hybrid LES-RANS model with the LES model being used in regions of fine meshes, while the RANS model is employed in areas where the integral length scale is not fully resolved.

IFP made the choice of using LES models like Smagorinsky or the LES model for the subgrid scale kinetic energy developed in the project in the whole domain, in combination with standard laws of the wall taken from RANS to bridge the near wall region. This approach was tested on basic test cases, and on the compressed tumble geometry experimentally studied in the LES-Engines EC project by IMFT (this case was also simulated by the other partners for validation purposes, as it is close to realistic engine geometry and is experimentally well documented).

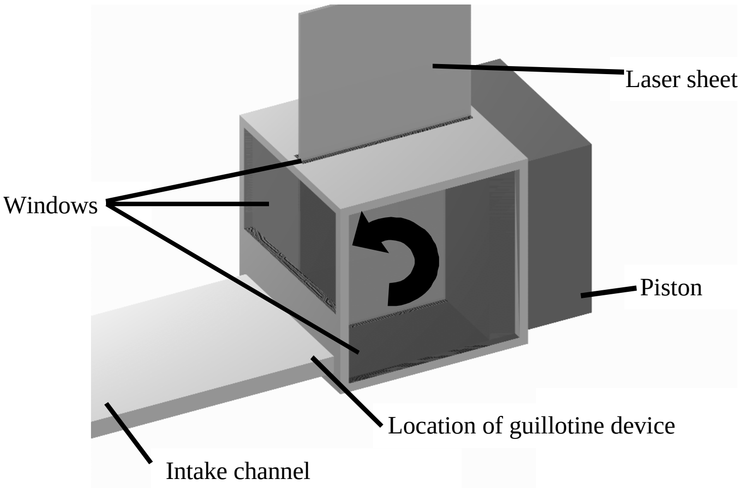


Figure 2-10: Sketch of the compressed tumble, square piston engine

Figure 2-11 shows typical results obtained with IFP's AVBP code and the developed models.

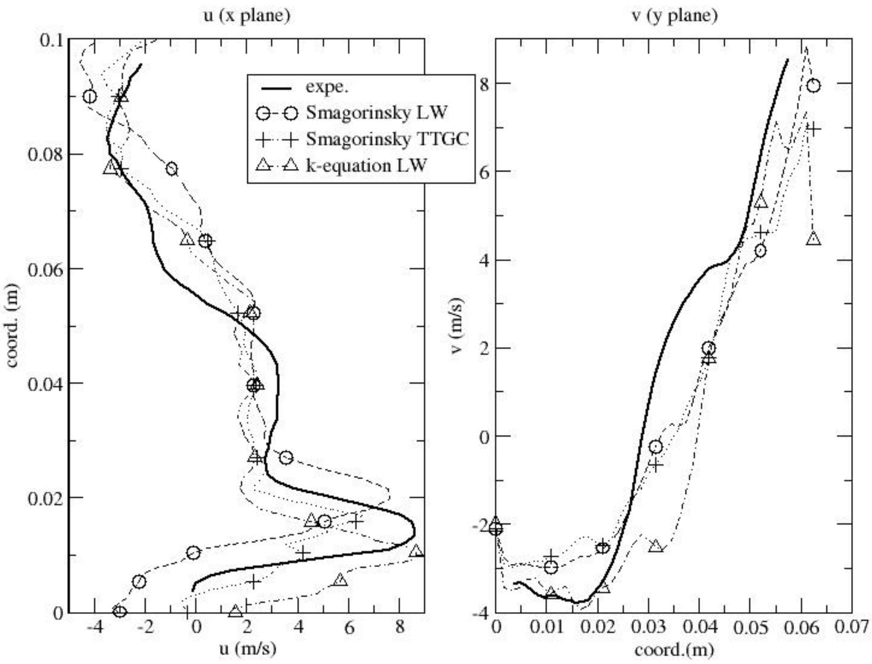


Figure 2-11: Mean velocity profiles at 270°CA BTDC (intake).

2.6 Modelling premixed combustion in spark ignited engines

The major element towards realising the project's objectives was to dispose of adapted LES combustion models for premixed, spark ignited engines. The typical width of a premixed flame in such engines if of the order of 0.1 mm, and can thus not be resolved on LES meshes (see estimate above). This indicates the need for adequate models able to address the resolved and unresolved part of the combustion.

RWTH-ITV chose to develop a LES formulation of the G-equation approach, in which the flame is viewed as infinitely thin, and propagating at a turbulent flame speed taken from experimental correlations. This model was coupled with the hybrid LES/RANS turbulence model and implemented in the ACflux research engine code. Different validations were performed, as illustrated below.

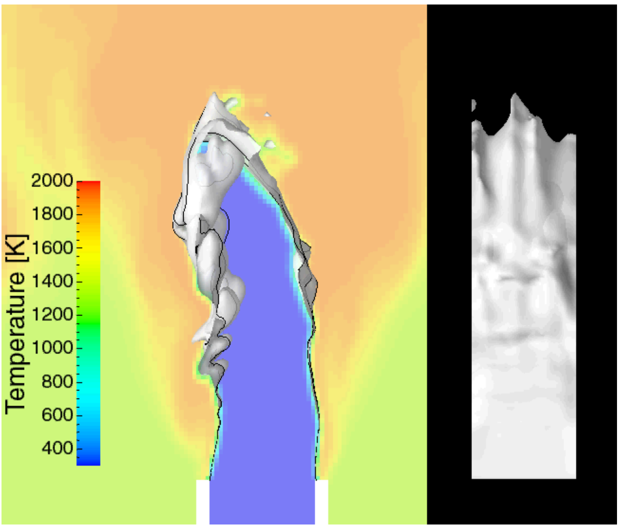


Figure 2-12: VLES simulation of a turbulent Bunsen flame (right) using the G-equation model (left).

This model was also transferred to the commercial CFD code of BMW, integrated and further validated and began to be applied to engine combustion at the project closure. Further work on this approach will take place after the project end.

IFP decided to formulate a LES version of the ECFM model, which consists of separating turbulence effects, taken into account via a transport equation for the filtered flame surface density, from chemistry effects, taken into account via laminar flame speed correlations. The model was implemented into AVBP and carefully validated on a number of basic test cases. A spark ignition model was also developed and validated.
This model was applied to simulate combustion in the PSA XU10 engine and proved to yield a very satisfactory reproduction of experimental findings. In particular Figure 2-13 shows that CFM-LES correctly yields a total – i.e. the sum of resolved and subgrid scale – flame surface that is nearly independent of the flame resolution, which is a necessary requisite for all LES models. This model was also used in the multi-cycle LES engine simulations of IFP (see below).

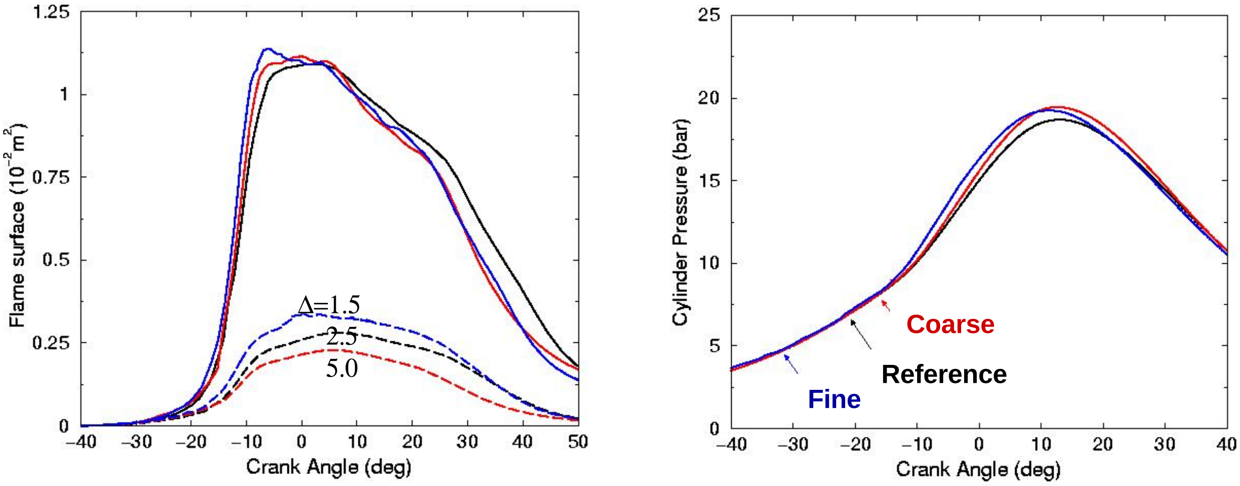


Figure 2-13: CFM-LES model applied to the PSA XU10 engine: Evolution of total (resolved + sgs) and resolved flame surface (left) and cylinder pressure (left) for three flame resolutions.

The model was finally transferred into the commercial CFD code of Renault, who used it with quite some success in its own LES engine simulations.

2.7 Towards LES models for liquid injection in piston engines

Two complementary approaches were taken for developing elements for LES models of liquid sprays: one based on a mixed Eulerian (in the vicinity of the injector) and Lagrangian (far from the injector) approach, the second being a purely Eulerian approach.

IMFT developed, based on the DNS database it had generated an Eulerian formulation for the dispersion of solid non evaporating droplets in a turbulent filed.
Figure 2-14shows the principle of an experimental case that was simulated to compare model findings with experimental ones as shown in Figure 2-15. The model behaviour can be considered as satisfactory.

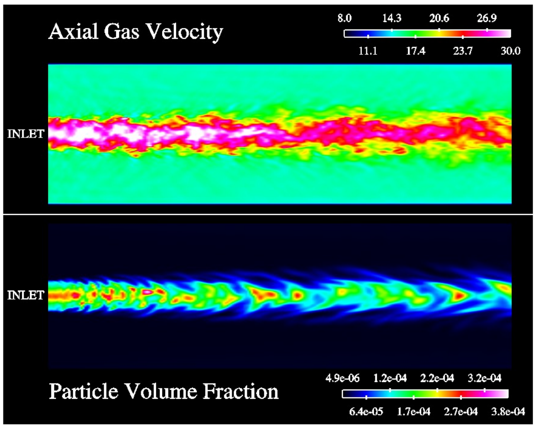


Figure 2-14: Snapshot of the axial gas velocity and particle volume fraction.

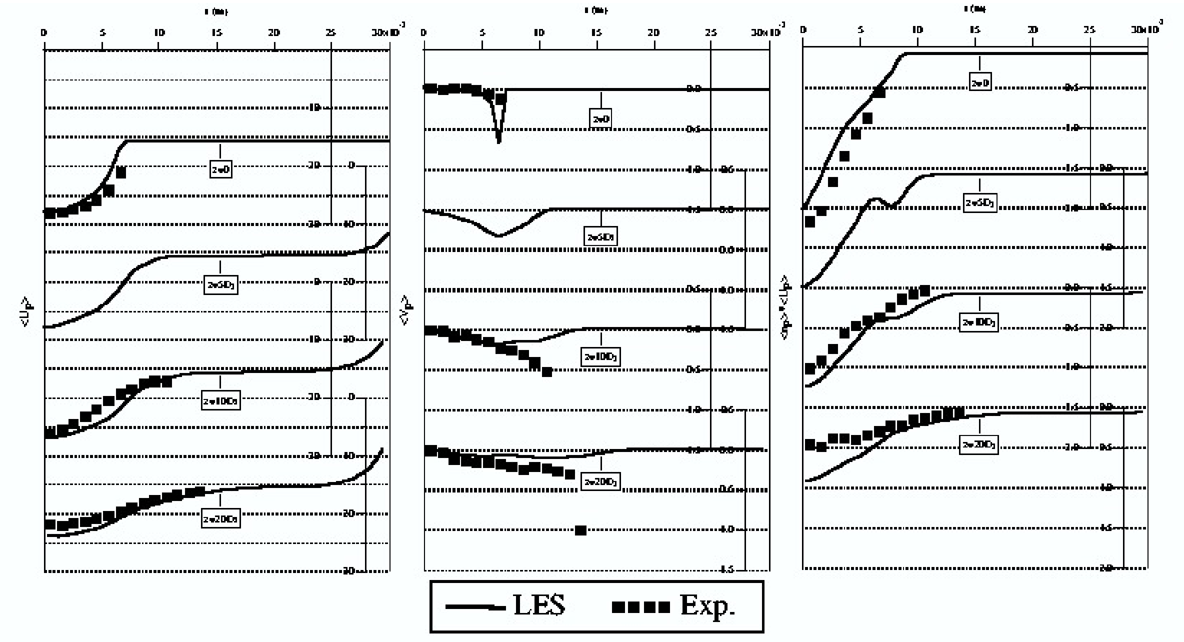


Figure 2-15: Particle comparison LES-Experiments
Left: Mean axial velocity, Middle: Mean radial velocity, Right: Axial Mass flux.

Although a solid basis has been laid by this work towards the formulation of an Eulerian LES model for liquid injection in engines, it will have to be completed in future work by taking into consideration e.g. evaporation, two-way coupling, break up, droplet collisions and wall films. Improvements to the subgrid scale closures will also have to be considered.

RWTH-ITV worked on a mixed Eulerian-Lagrangian model for liquid injection. Sample spray simulations have been performed using a Discrete Droplet Model (DDM) for analysing and testing the performance, accuracy, stability and characteristics of the model as currently implemented in the code. Model improvements and extensions both from a physical and numerical point-of-view have been performed as well as a number new types of injectors have been added.

Besides the Lagrangian approach of the DDM mode, an Eulerian spray model has been considered. Starting from full spray equations, which are three-dimensional in space, we could reduce the dimensionality of the model to one by using mean values of the spray variables, averaged over the cross-section; this leads to the CAS (Cross section Averaged Spray) model. This approach is applicable for processes where only small influences from off-side directions occur. This assumption is valid for spray injection due to the high injection velocities of modern injectors. The following the spray processes are considered in the CAS model:

- two-phase flow ,
- droplet evaporation ,
- droplet heat-up by surrounding gas,
- break-up of large droplets,
- entrainment of gas from outside of the spray, and
- spray deflection by e.g. swirl.

The CAS model equations, which originally were derived in a RANS context, have been analyzed with special regard to the models application in an LES environment. The newly revised model has been implemented in a stand-alone version with advanced numerical schemes. The new implementation is characterized by improved stability and accuracy as well as an enhance interface. The Eulerian equations form a system of hyperbolic equations, therefore a hyperbolic equation solver was implemented; this standalone package without any connection to a CFD code is called Cross-Section Averaged Spray Model (CAS), which is used for one-dimensional test cases.

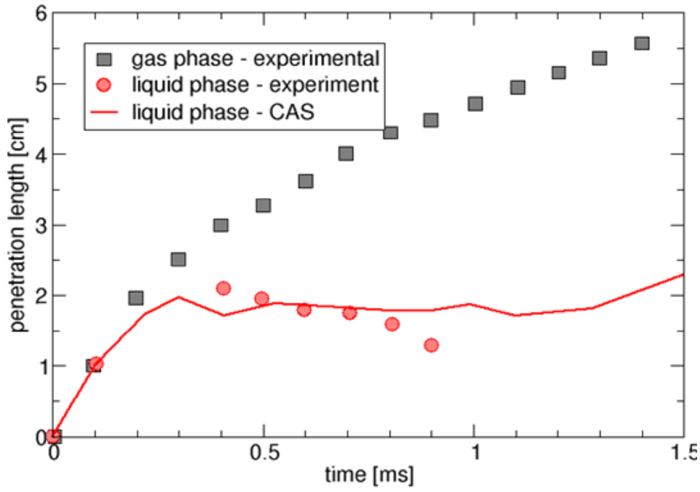


Figure 2-16: Spray penetration length for the liquid and gas phase, experimental data taken from Koss [3].

To validate the implementation we compared the calculated penetration depth of the liquid phase as calculated by CAS with the experiments done by Koss et al., see Figure 2-16.

2.8 Including complex chemistry in 3D CFD

Including chemistry into LES engine simulations is of great importance to be able to address phenomena like auto-ignition or pollutant formation. It nevertheless causes a numerical problem, as the schemes describing realistic fuels are too large to be integrated into parallel CFD simulations in a straightforward manner. Furthermore the resolution of the related system can also be extremely time consuming.

For this reason *Lund University of Technology (Sweden)* developed a new method, Adaptive Polynomial Tabulation (*APTab*) that provides fast chemistry in reactive flow calculations. It uses two existing local polynomial tabulation methods, *ISAT* (first degree polynomial) and *PRISM* (second degree polynomial). *APTab* is based on a modification of *PRISM* which, instead of using factorial design to produce points for calculating the local polynomial approximations, accumulates local points until an approximation can be calculated. During this accumulation, local first degree approximations around the accumulated points, as in *ISAT* are used. This enhances not only reuse (avoidance of solving the associated set of differential equations), but also accuracy of the second degree polynomial through broader spread of points. This tool is versatile and adaptive and can be applied to any reactive flow application. The code was tested with a stochastic reactor model (*SRM*) simulating hydrogen /air fuel in a spark ignition engine. The tests predicted auto-ignition in the unburned gas region of the reacting mixture. The results further showed a speed of factor of 3 in using *APTab* compared to control runs with the chemical ordinary equation (*ODE)* solver. The temperature, pressure and radical species profiles of *APTab* were in very good agreement with those from *SRM* calculations using the chemical *ODE* solver.
Figure 2-17 shows the typical reuse factor distribution achieved by the method.

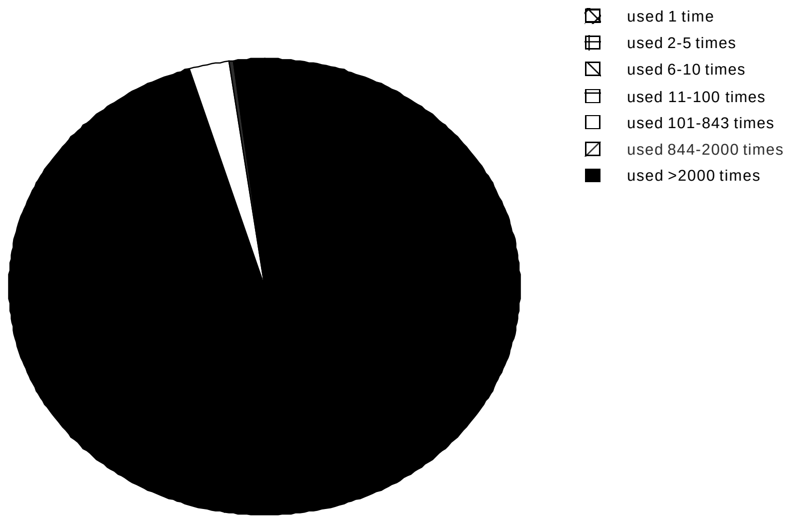


Figure 2-17: The frequency distribution of ISAT reuse of accumulated points. The number of computational particles in this SRM simulation with APTab was 9000.

It was not possible within the framework of LESSCO2 to start implementing APTab into a CFD flows solver, which could be the subject of future research.

2.9 Exploring cyclic variability with LES

The main objective of LESSSCO2 was the exploration of cyclic variability using the developed LES techniques. The basic principle was to realise LES simulations of non-fired and fired piston engines that cover not only one but several consecutive 4 stroke cycles of 720°CA. The term used for such simulations is multi-cycle LES simulations. The idea is that if LES is able to capture realistic engine behaviour, it should be able to yield a cyclic variability in multi-cycle LES that should be comparable to experimental findings.

A priori there are a number of causes for cyclic variability in engines, amongst which:

- aerodynamic effects: turbulence generated in the intake pipes, by the flow detachment around the valves or created by compression by the piston of the large scale motions generated by the intake; large scale coherent motions that vary from cycle to cycle (e.g. precessing tumble);
- acoustic waves travelling through the intake and exhaust system can generate variations of mass of air induced during intake or expelled at exhaust, and can also affect the aerodynamics. These waves are rarely in phase with the opening and closing of the valves, and may thus lead to cyclic variability;
- turbulence and flow generated by injectors (essentially in direct injection engines) that may not be repeatable or generate turbulent flow with a level of variability.

All these phenomena can affect the trapped mass (and thus chemical energy available for combustion), slightly change the way combustion is initiated at the spark (and even lead to misfires), affect the increase of flame propagation speed caused by turbulence, and change the flow conditions at the end of a cycle, which in turn affects the way the following cycles starts.

In LESSCO2 the partners essentially concentrated on the first effect. Taking into account acoustic waves needs specific techniques to be able to couple the LES in the combustion chamber with 1D simulations of the flow in the rest of the engine, which was not addressed in this first attempt. Although work on liquid injection was part of LESSCO2, it was not possible to use the developed models for exploring the effect of liquid injection. Both these not explored phenomena will certainly have to be studied in follow-up research projects, as they can not be neglected in general.

A number of first simulations concerned the exploration of the variability of engine aerodynamics on absence of combustion. As an example, RWTH-ITV realised 10 complete cold cycles using their mixed LES/RANS model.
Figure 2-18 shows the history of the turbulent kinetic energy and the axial velocity respectively at a monitoring location in the cylinder head for ten cycles; a crank angle of 0° denotes TDC. The profiles of the turbulent kinetic energy show that after three cycles a tuning process has been completed; therefore the first three cycles have been omitted in the velocity plots. The differences between the individual cycles are rather small at the beginning, i.e. when the intake valves open at -220° CA, for both the kinetic energy as well as for the axial velocity. During the intake phase the differences between the profiles become more apparent. The largest deviation between the profiles can be found at around -60° CA bTDC, i.e. during a phase which is essential for the air-fuel mixing process. After TDC the differences become small, i.e. the cyclic variations are widely compensated.

The different flow fields in the different cycles during the compression phase lead to a variation in the fuel-mixture generation as well as in the transport of the air-fuel mixture. Although the chosen operating point of the model engine (part load, constant operation conditions) is not *per se* in a critical region for misfires, the different flow pattern during the compression phase present an indication for the cause of cyclic variability.

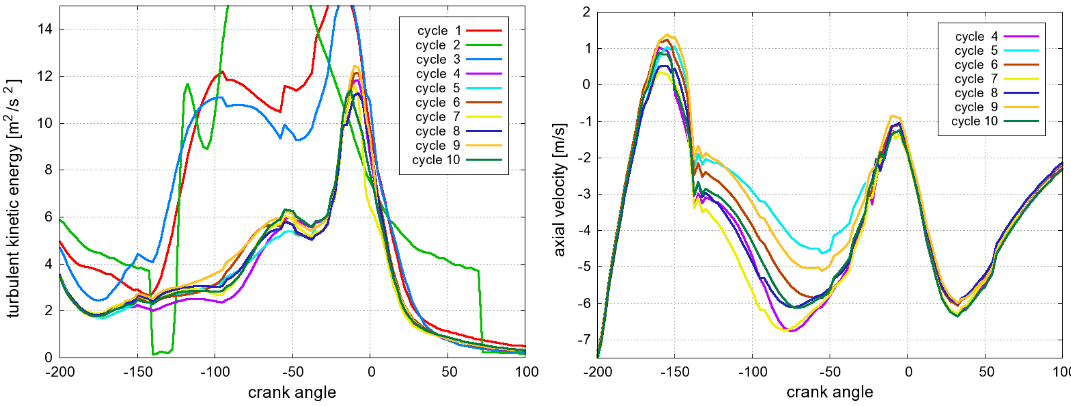


Figure 2-18:.History of the turbulent kinetic energy (left) and the axial velocity (right) versus crank angle over multiple cycles at a monitoring location in the cylinder head for the cold flow VLES simulation.

Comparisons with RANS results obtained in the same conditions indicated that they do not exhibit the variability of aerodynamics found in LES. Similar findings were reported by BMW and Renault.

The LES study of cyclic variability was then further advanced by including combustion into the multi-cycle simulations. IFP, RWTH-ITV and Renault wee able to realise such simulations within the project. The most advanced study reported was the one by IFP, which for the first time ever was able to simulate 9 consecutive fired cycles of a PSA XU10 4 valve engine, as illustrated in Figure 2-19, which compares cylinder pressures and work of the combustion phase with experimental findings. The simulated cylinder pressure evolutions are within the experimentally observed envelope for all cycles. The sequence of cylinder pressure shows no convergence of the simulations, a level of cyclic variability is clearly observed. This is more clearly apparent in the scatter plot of combustion phase work, where one can observe that the simulated cycles follow a certain sequence with the number of cycles, which is qualitatively and quantitatively comparable to the shown experimental findings.

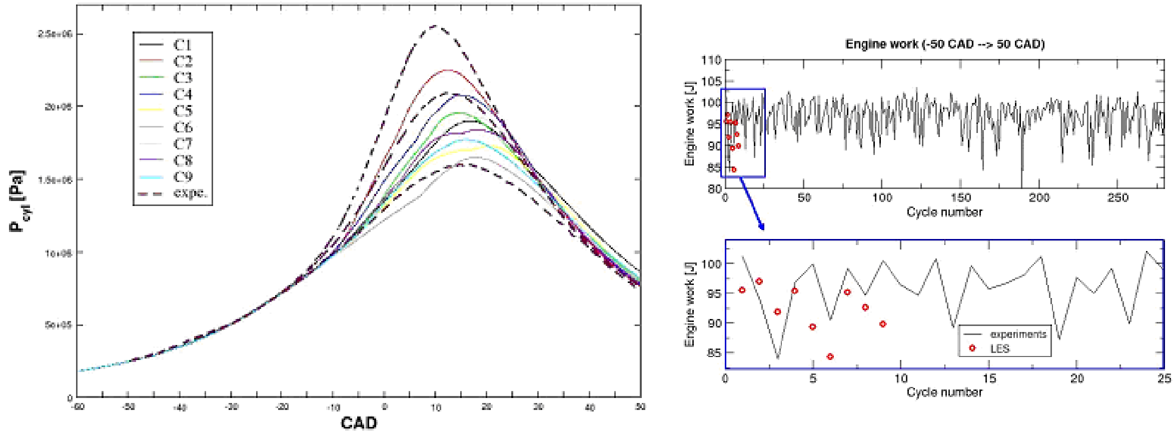


Figure 2-19: Multi-cycle results – Left: cylinder pressures of the individual simulated cycles, superimposed to the maximum, minimum and mean pressure from the experiment – Right: Experimental and simulated variation of combustion phase work per cycle.

Figure 2-20 shows the trapped, fresh gases and residual mass during the combustion phase for the simulated cycles. After cycle 2, all three quantities show only minor variations, which can not explain the observed variability.

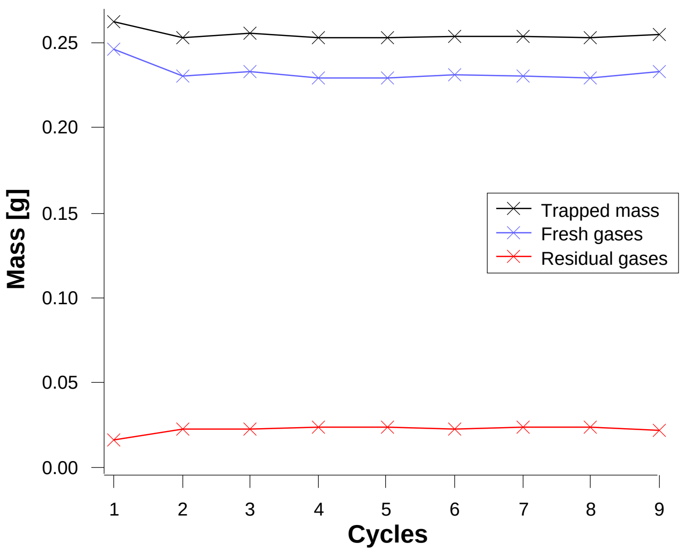


Figure 2-20: Trapped, fresh gases and residual mass in the cylinder during the combustion phase for the 9 cycles simulated with LES.

Figure 2-21 shows the development of the resolved flame front for three selected cycles and three crank angles. Clearly, combustion in all cycles is not equivalent, cycle 2 starts earlier than cycle 9 and even more 5. Further analysis showed that small variations in the intake aerodynamics (related to small cycle to cycle variations of the in-cylinder conditions and intake pressure upon intake valve opening) induce varying levels of turbulence, which in turn are responsible for the observed variations in flame propagation and thus heat release and cylinder pressure.

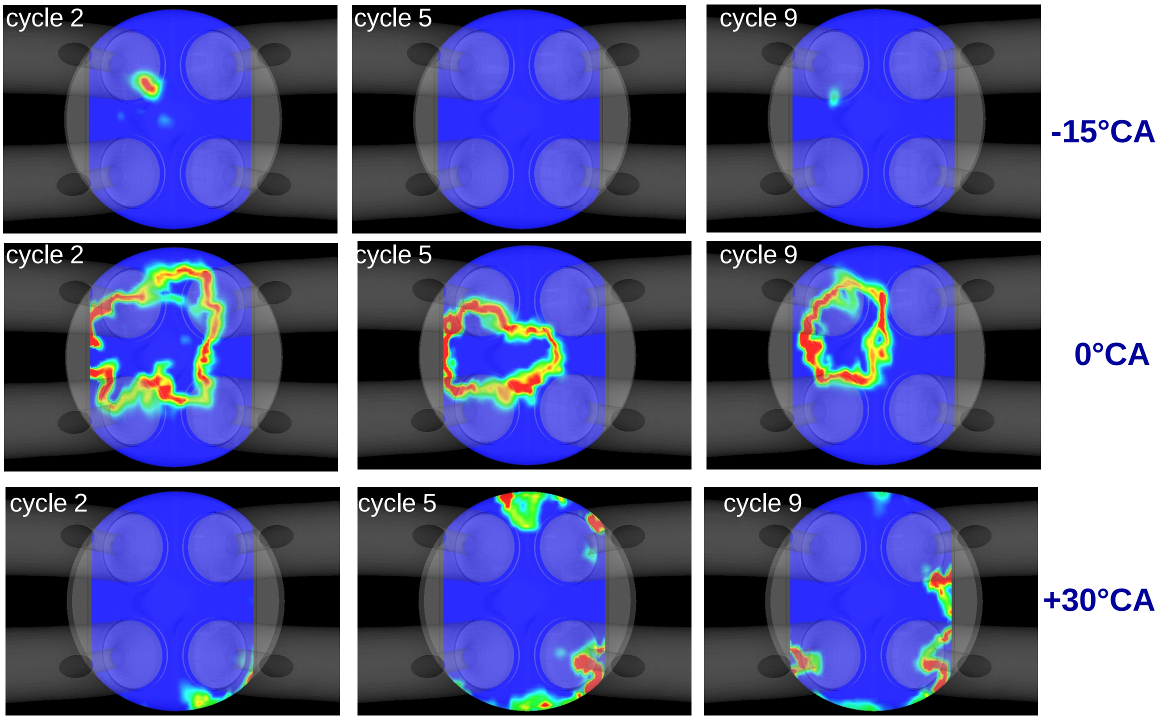


Figure 2-21: Snapshots of the resolved flame front for 3 individual cycles and 3 crank angles.

These results showed that although all phenomena, and especially acoustic waves, were not accounted for, the approach developed within LESSCO2 allows reproducing at least qualitatively, cyclic variability in gasoline engines.

Furthermore, the IFP simulations were realised using 32 processors of a Xeon Linux cluster, which yielded CPU times of ~120hours per cycle, which could be reduced to about 24h per cycle using 200 processors (even if the parallel speed-up in this case would not be linear anymore due to the too small mesh size). This also showed, confirmed by results by Renault, that multi-cycle LES for engines is very close to become compatible with industrial requests on return times.

2.10 Conclusions and perspectives

In summary, LESSCO2 was able to demonstrate the feasibility of LES simulations of piston engine flows, and their unprecedented ability to reproduce cyclic variability. In this sense it set a reference in the domain of engine simulation in Europe and world-wide and is expected to potentially lead to the emergence of a new type of simulation tool to support advanced engine design. From the experience gained within LESSSO2, LES could be used in the very near future as a type of numerical experiment, able to explore in all details, and without a priori knowledge, the functioning of a piston engine operating under stable but also unstable operation. In this sense it could complement RANS codes, which are very useful for providing a fast comparison of different options, but which can hardly address phenomena like cyclic variability, transients or cold start, which can effectively be studied by LES.
Furthermore, and most importantly, the partners of LESSCO2 also demonstrated that LES can be realised with return times that are already close to that of RANS simulations, and will become more and more competitive as the computational power of parallel machines increases. Of course, LES will always be more expensive than RANS, as it necessitates the realisation of multi-cycle simulations to be able to yield reliable predictions. But even single cycle LES can help gain a view

at engine combustion that may be much more realistic than RANS, even if of no use in terms of mean behaviour or variability, which could readily complement this standard method of today.

Although many highly innovative research paths were opened and first applications realised, there still remains important issues that will have to be addressed in future research. Among these, one can cite:

- further validation of turbulence models in the engine context, and especially the aspects related to solid wall resolution which can dominate certain phases of the engine cycle;
- further development of LES models for combustion, with models for diffusion combustion, ways of integrating chemistry to address auto-ignition and pollutant formation;
- further development and validation of LES models for liquid injection in an engine, with special emphasis on high parallel efficiency;
- further development of mesh management techniques able to handle efficiently and accurately the important mesh deformations and the constraint they impose on LES in piston engines;
- definition and validation using dedicated experiments of methodologies for using LES in the design process of piston engines. In particular the coupling of LES in the combustion chamber with 1D simulations of flow and acoustics in the rest of the engine will have to be addressed, as well as effects of liquid injection;
- the continuous adaptation of the CFD codes to be able to exploit the full potential of the fast developing parallel machines.

2.11 The LESSCO2 team

March 31st 2006, IFP, Rueil-Malmaison (France)

Back row, from left to right:

Christian Angelberger (IFP), Vincent Dugué (Renault), Gaële Valet (IFP), Neil Forsythe (QUB), Edward Blurock (LTH), Frank Freikamp (RWTH-ITV), Betrand Naud (LITEC-CSIC), Jens Ewald (RWTH-ITV), Benoit Bédat (IMFT), Jean-François Pech (IFP), Jens-Dominik Müller (QUB)

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Adlène Benkenida (IFP), Olivier Colin (IFP), Stéphane Richard (IFP), Volker Sohm (BMW), Philippe Schild (EC), Laurent Duchamp de Lageneste (PSA), Carmen Jimenez (LITEC-CSIC), Bodo Durst (BMW)