Modulation du taux d’introduction avec le système d’injection TwinCR: couplage des approches expérimentale et numérique

Injection Rate shaping with the TwinCR System: A coupled Experimental and Modelling Investigation

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Abstract: Nowadays in the race of Diesel engine emission reduction, many efforts are carried out on the improvement of Diesel injection system performance. This paper focuses on the injection rate shaping effects on Diesel combustion, emissions, fuel consumption and generated noise. The R&D Twin Common Rail (TwinCR) system is used on a single cylinder engine in order to explore the effects of injection rate shaping on combustion, emissions, fuel consumption and generated noise on a mid-load operating point. Moreover a 3D CFD code is validated on these investigated injection strategies. The combination of experimental observations and 3D outputs is exploited to explain the behaviour of the in-cylinder combustion processes.

Keywords: Diesel engines, Diesel injection, injection rate-shaping, emissions, fuel consumption, combustion noise

1. Introduction

In principle the Diesel combustion intends to realize the combustion process by controlling the heat release rate by the injection rate profile. This strategy faces two problems: the presence of an ignition delay, producing also the combustion noise, and the delay between injected and burned fuel. In order to improve the emissions and fuel consumption of current Diesel engines, many researchers have proposed to better control the injection system. The Diesel injection market is shared between unit injectors and common rail systems. Unit injectors are designed to control the injection rate by the modification of the injection pressure, while common rail systems make wide use of the flexibility of the needle actuation: multiple injections up to 9 injections/cycle are now possible, and the upcoming of piezo actuated systems opens the way for direct needle control.

2. R&D Injection System TwinCR

Based on the assumption that at certain operating points shaping the injection profile provides a significant potential for the pollutant emission reduction, a flexible CR research FIS (Fig. 1) was developed at IAV with assistance of the ITV, University of Hanover [1;2;3]. Important degrees of freedom are a controllable opening time being independent from the injection pressure and a freely selectable injector needle lift. In conjunction with a pressure modulation unit, the research injector overcomes the dividing line between the so-called pressure controlled (PC) injection of the unit injectors and the so-called needle lift controlled (NC) injection of CR systems as we know it from modern production injection systems. The system was enhanced to meet the requirements of passenger car engines. The system allows for direct control using an especially developed version of IAV’s test control unit Piezo-FI^{2RE} [5].

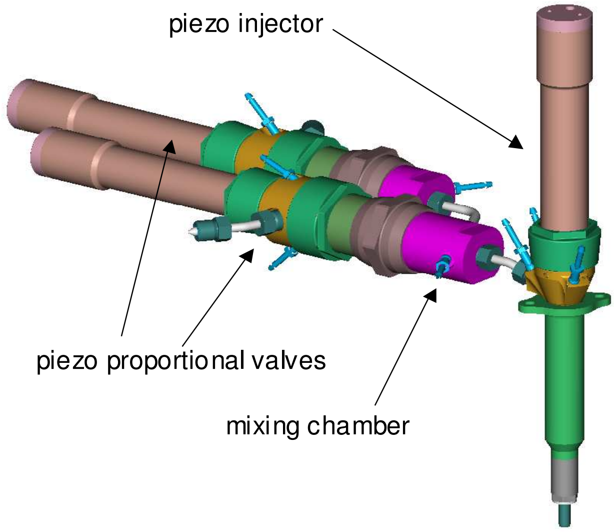


Fig. 1: *TwinCR research FIS [2]*

The TwinCR pressure modulation unit varies the injection pressure during the injection process by applying two separately supplied fuel pressure levels to the HP line feeding the piezoelectric injector with the help of two piezoelectric proportional valves (PPV). Electrically powered CR pumps feed separate rails in which the requested pressure is adjusted with the help of pressure regulating valves. The PCV used in this project limit the maximum rail pressure to 1800 bar. From the rail, the fuel is transported to a PPV and then into a common line towards the piezoelectric injector. The PPVs are mounted in the vicinity of the injector and their actuation process is derived from the above-mentioned piezoelectric injector. The actual valves are modified injection nozzles with a large sac hole diameter for reasons of pressure and wear resistance. The technical data of the pressure modulation unit can be summarised as follows:

- Max. pressure increase:1800 bar/ms.
- Pressure range: 0–2000 bar.

Both system parts, injector and pressure modulation unit are based on the direct mechanical piezo-actuated valves. In order to enable the demanded lift of the needle at the injection nozzle or proportional valve of 200 µm in combination with the demanded maximum needle speed representing actual injection systems a special control unit and innovative piezo-technologies are needed and provided by Noliac, Denmark. The unique and innovative multilayer technology reduces driving voltage, and their ring shaped actuators secure a better implementation. Further, Noliac has the expertise of stacking and thereby building actuators in any length, which in this case results in the World's longest multilayer ring actuator (OD: 18mm, ID: 5mm, H: 180mm) for IAV's TwinCR application. Needle lifts of up to 200 µm are possible; the injection nozzle is fully closed or opened in a minimum time of about 200 µs. The maximum injection pressure of the injector is 2000 bar as designed up to now. It has the capability to shape the injection profile and meter out extra-small quantities.

The NC rate limitation is realized by partial lifts of the injector needle at a constant injection pressure. The annular gap between the injector needle and the needle seat acts as a throttle cross section. However, cavitations are generated and are carried into the combustion chamber with the injection spray, having a major impact on the spray pattern and spray break-up [1]. The throttling effect of the needle seat generates an increased spray break-up especially detectable close to the nozzle which can be explained by intensified turbulence due to increased cavitation phenomena inside the nozzle.

In addition to the NC injection system, a pressure modulation unit was developed that allows the injection profile to be shaped via an injection pressure that is variable during the injection. That means that two separate mechanisms are available to influence the temporal and spatial distribution of fuel in the combustion chamber: it is possible to produce identical injection profiles both

- at full injection pressure and partial lifts of the injector needle: NC injection rate as well as
- at full needle lift and variably modulated injection pressure: PC injection rate.

When compared with previous publications on approaches to pressure modulation, the TwinCR system offers some advantages when used in conjunction with the direct piezoelectric injector. The two rail pressure levels, e.g., only define the lowest or highest injection pressure respectively. Between these two values, fully flexible variation of the pressure gradient is possible. Several partial injections can be generated at different injection pressures and the injection profile can either be "boot" or "ramp" shaped. Due to the very high opening speed of the piezoelectric injector which does not depend on injection pressure, it is possible to examine the effects of PC injection without major influences caused by transient throttle effects at the needle seat of the injector nozzle.

The calibration control unit Piezo-FI^{2RE} from IAV allows several piezoelectric actuators to be operated independently with variable (dis-)charging curves. Fig. 2 shows the ability of the TwinCR system to generate comparable ramp shaped injection rates by using the effects of throttling at the needle seat and pressure modulation separately.

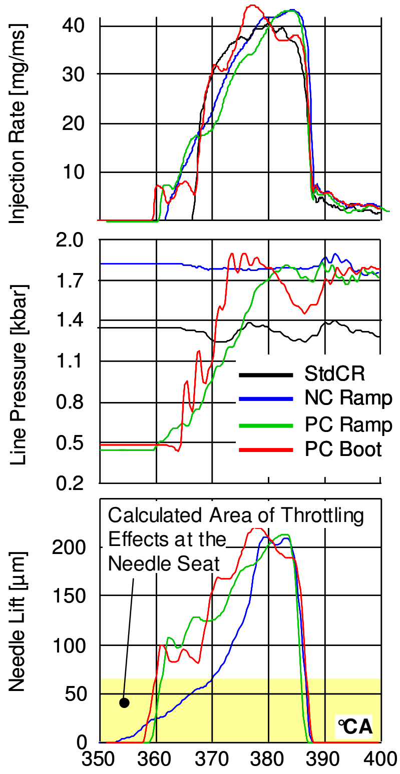


Fig. 2: *flexible rate shaping of the MI*

3. Description of Tools

Single Cylinder Research Engine:

A Diesel small-bore single-cylinder engine was used for the different measurements of this study. It is a Euro IV derivate from the PSA DW10B engine, with the main following characteristics:

Stroke (mm)	88
Bore (mm)	85
Displaced Volume (cm^3)	499
Compression Ratio	18

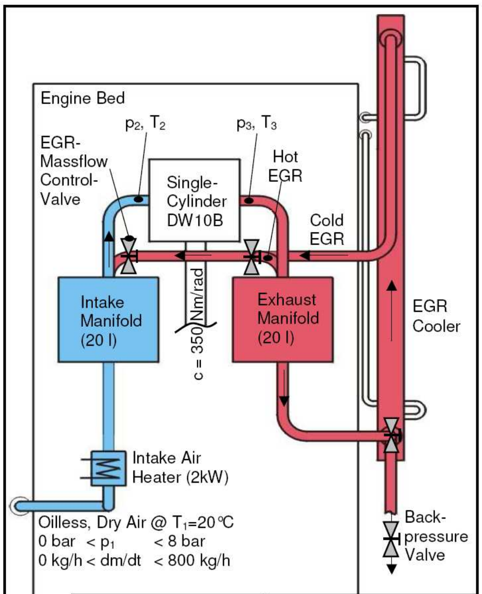
Table 1: *single cylinder engine characteristics*

The FIS used as a reference is a Bosch Cri2.2 solenoid injector, to ensure the nozzle compatibility with the TwinCR system. In order to keep a good spray to spray reproducibility, a sac hole technology was chosen instead of a VCO one. Table 2 gives the main characteristics of the nozzle:

Hyd. Flow (cm^3/100bar/30s)	360
Hole diameter (µm)	139
k-factor	2
HE-rounded (%)	10.5
Number of holes	6
Spray position angle (°)	153

Table 2: *nozzle configuration*

All the tests were conducted on a dedicated test bench with the configuration and measurement tools as shown in Fig. 3.



Air Massflow Meter	ABB Sensyflow P
Fuel-Balance	AVL 733S
Fuel Conditioner	AVL 753C
Noisemeter	AVL 4050 A01
Smokemeter	AVL 415S
Exhaustgas-Analyzer	Horiba EXSA 1500L
Indication-Measurement	SMETEC Combi Executive
Dynamometer	Siemens (DC, Θ=1,4kgm²)
Torque-Measurement	HBM Flange T10F
Data Aqcuisition	AVL PUMA 5.6

Fig. 3: *setup of the test bench*

Injection Analyzer (IA):

The IA is used for investigating hydraulic parameters in the course of development work on HP FIS [4]. The measuring principle employed generates a basic signal containing information of such high quality as to permit highly detailed analyses of injection processes. The IA works on the principle of measuring the dynamic rising pressure in a fuel-filled measurement tube. Brought about by an injection cycle, this pressure increase is proportionate to the injection rate. Unlike other measuring systems, the IA can be used for simultaneously measuring injection rates as well as injected fuel quantities as individual events with maximum accuracy and reproducibility. The data recording unit plots the course of injection from stroke to stroke and, on the basis of these readings, calculates the injected fuel quantity in real time. The IA provides the capability of recording and plotting up to 7 partial injection events within 720 °CA. Statistical analysis of measurement readings provides immediate insight into key injection cycle parameters.

Pressure indication and heat-release analysis

As a complement to the fuel introduction rate, the information gathered from the heat-release analysis is key for the comprehension of the mixture preparation and fuel conversion phenomena [7].

For this study the single-cylinder engine was equipped with two water-cooled cylinder-pressure sensors (Kistler 6041A and 6043A60), one of which was replaced by an optical probe in the case of the ILM measurements. For the detection of detailed combustion effects (like the premixed combustion phase) the indication was performed with a resolution of 0,2°CA. All tests were conducted at constant $IMEP_{HP}$ and a distinct set of CA50% points to allow a good comparison of the individual ROI and ROHR signals.

For the in-depth analysis of the 0D-thermodynamic phenomena an IAV code called OPEN TDA was used. This code is written as an open source tool on MATLAB with special attention paid to the modelling of the calorific charge properties, its adaptability to different data formats and it its computational performance (complete analysis of consecutive engine cycles).

Integral Light-Conducting Measurement Technique

As an optical measurement technique that requires no or only small modifications to the test-engine, the ILM is a unique tool for the cycle resolved acquisition of characteristic electromagnetic spectra from the combustion process (Fig. 4). Compared to the heat-release analysis, the ILM-data conveys more information about the reaction intermediates relevant for the emission formation and oxidation.

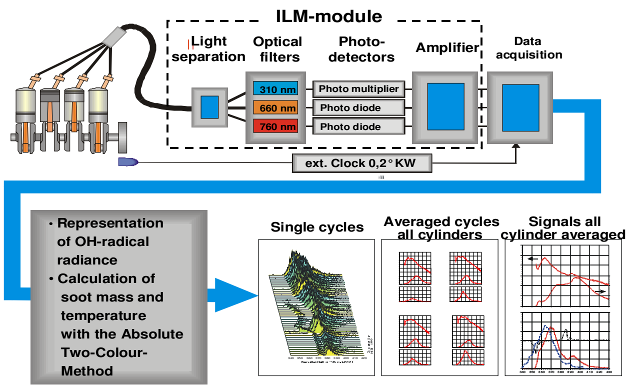


Fig. 4: *setup of the ILM*

The Diesel engine ILM detects two wavelengths (660 nm and 760 nm). The radiation intensity is caused by the soot particles solid body radiation. The discrete intensities evaluated by the “Two-Colour-Method” allow to calculate the temperature and soot mass curves. Additionally, the OH radiation intensity is detected at 310 nm (ultraviolet range) as an indicator for the energy conversion process and as a key reaction intermediate in the soot reaction mechanism. The temperature of the soot particles in/near the flame zone and the in-cylinder soot mass are additional output values that are calculated in the post-processing. The information about the soot build-up and oxidation particularly helps for a better understanding of the combustion process. Under consideration of the temperature curve and the OH radical emission, indications can be extracted, when and why pollutants are generated.In Fig. 5 the optical access to the combustion chamber is shown.

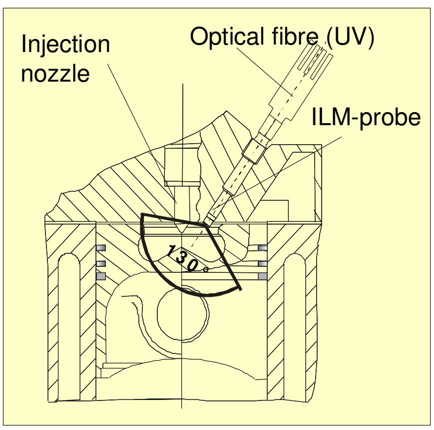


Fig. 5: *optical access to the combustion chamber*

The chosen design is optimised for the minimal probe fouling even under EGR conditions. This attribute of an ILM probe allows quantitative statements about the particle temperature and the soot mass over the whole engine map. With the 130° aperture angle almost all of the important regions of the combustion chamber can be detected. The miniaturized probe is easy to install and is adaptable to the engine conditions (package). On Diesel engines normally the glow plug bore is used.

Fig. 6 shows ILM results for the mid-load point chosen for this study. The high temperature level at this operating point causes a short ignition delay for all EGR rates which can be seen by a comparison of the ROI and ROHR signals. The fuel conversion rate and the combustion duration is not altered noticeably with the use of EGR. Consequently, the thermodynamic analysis shows comparable ROHR traces for this variation. The ILM data can help to understand, why with respect of the pollutant formation the combustion processes differ considerably.

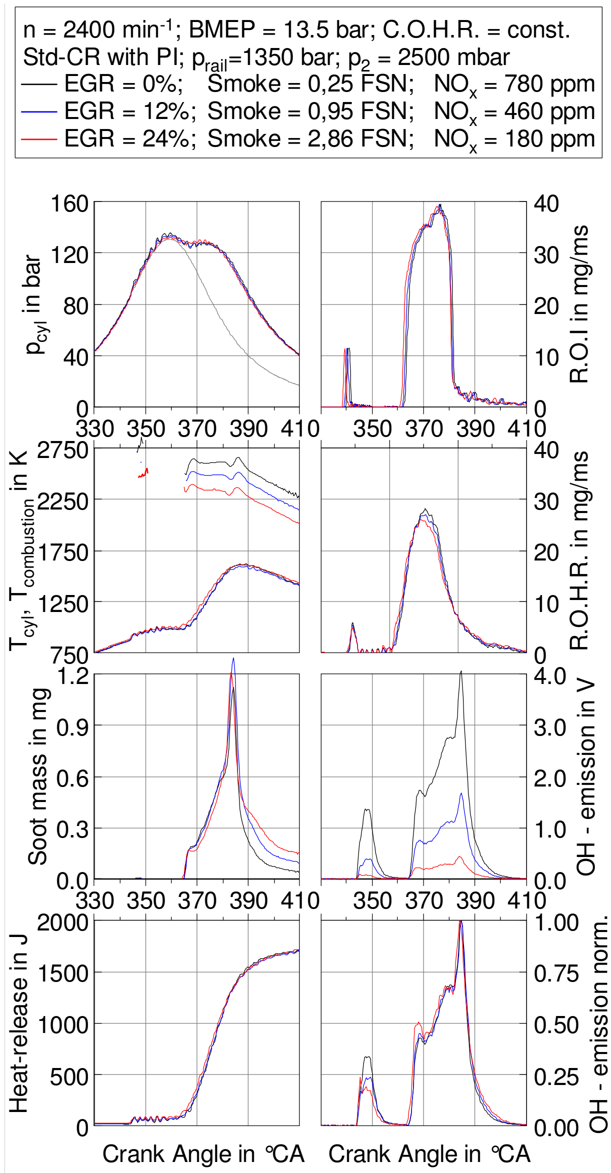


Fig. 6: *ILM results for a variation of EGR*

The normalised OH-traces confirm that combustion duration is nearly constant for the EGR-variation. With respect to the absolute radiation intensity, the reduced OH-build-up with EGR indicates a lower oxygen concentration and a decreased temperature level in the flame zone (due to the increased heat capacity of the load with EGR). The calculated soot particle temperature confirms the decreased combustion temperature with increased EGR. The soot mass curves indicate, how the soot oxidation rate degenerates with the increase of EGR. This EGR effect of a poorer in-cylinder soot post-oxidation late in the cycle is caused on one hand by the decreased oxygen concentration and on the other hand by the lower temperature level in the reaction zone.

3D-CFD Simulation:

The numerical CFD simulation tool used for this study is FIRE V8.2, with PSA added components such as the advanced combustion model ECFM-3Z. FIRE solves the reactive Reynolds Averaged Navier-Stokes (RANS) equations on unstructured grids and enables full 3D IC-engine computation including both gas and fuel spray dynamics. The ECFM-3Z combustion model (3-Zones Extended Coherent Flame Model) was developed at IFP [8] and implemented jointly by AVL and PSA into FIRE. This model is able to describe the three main combustion modes encountered in internal combustion engines: the auto-ignition of a premixed charge that controls the beginning of the combustion in Diesel engines and can also be found in SI engines (knock problems), the premixed propagation flame (premixed charge of fuel and air) and the non-premixed combustion also called diffusion flame (fuel and air are separated by a thin reaction zone). When pollutant models are added, it is possible increase the comprehension about the pollutant formation locations, conditions and processes.

In association with the spray modelling - including spray atomization, droplets evaporation and evaporated fuel mixing - this kind of numerical tool allows to describe the complete process from injection to combustion and is more and more used at PSA to support engine testing and concept investigations since it allows a better understanding how combustion takes place and how pollutants are formed in new combustion concepts, depending for example on the injection strategy.

4. Results and Discussion

Engine results:

For the engine operating conditions a mid-load point at 2400 rpm and $IMEP_{HP}$ of 15 bar was chosen. The constant $IMEP_{HP}$ has been retained as a criteria for comparing the injection strategies, because the single cylinder engine does not represent the serial engine in terms of BMEP. The operating point is representative for short auto-ignition delays and a high degree of diffusive combustion tending generally to poor NO_X/soot trade-offs. In order to evaluate the potential of rate shaping effects on the trade-off behaviour additional variations of basic engine parameters, such as injection timing, intake pressure, rail pressure, EGR-rate and pilot injection calibration have been conducted. The aim of this paper is to illustrate a methodology and not to discuss about the complete set of results. For that reason only two injection schemes are presented and discussed hereafter.

Fig. 7 shows the engine emissions, fuel consumption, noise and COHR for an injection timing sweep for two injection strategies:

- the first one is a single main injection realised with the standard common rail system,
- the second one is a single boot injection realized with the TwinCR system, equipped with the same nozzle.

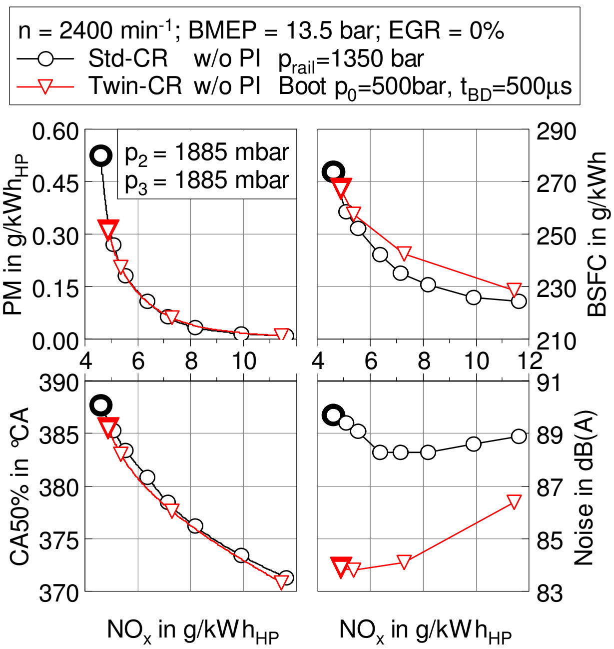


Fig. 7: *engine results*

In the remaining part of this paper we will focus on cases with an extremely late injection, as identified by the thick markers on the diagrams. The boot injection strategy results in a lower soot emission level, and a noticeable noise reduction, at a comparable level of NO_X. One can observe the course of the combustion process with the help of the heat-release analysis data illustrated in Fig. 8.

The red curves represent the combustion process in the case of the boot injection realized with the TwinCR system. The black one results from the standard CR system. On the left bottom part of the figure, one can notice the differences in the rates of injection and their effects on the rate of heat release. The boot injection scheme has a flatter rising slope with the result of a smother heat release and hence a reduced premixed peak.

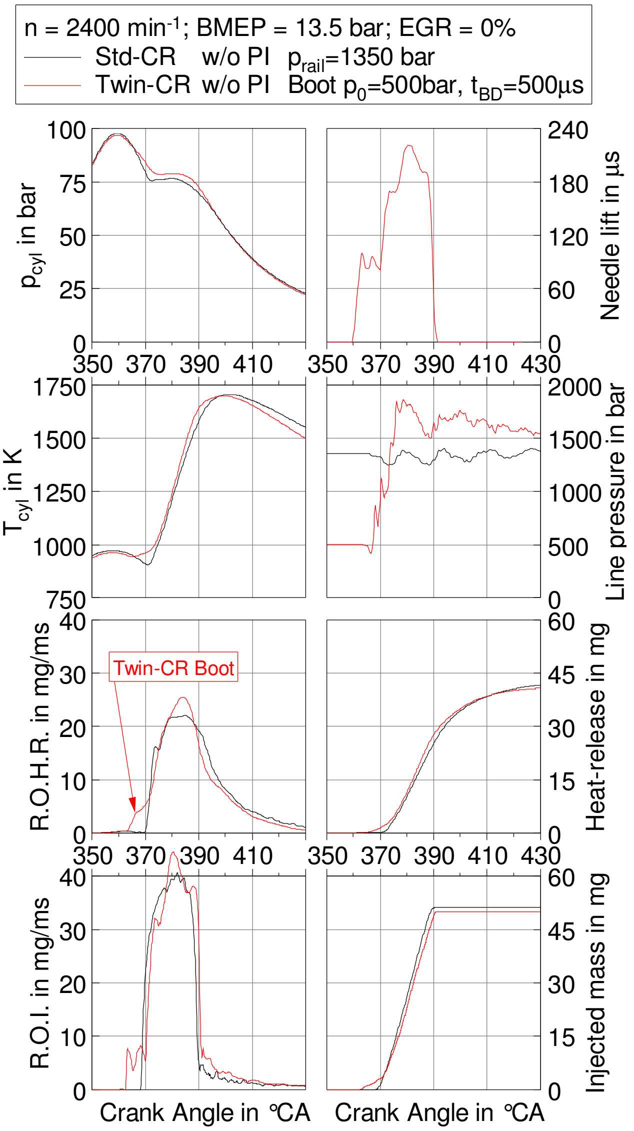


Fig. 8: *injection and combustion processes*

Validation of the 3D Calculation

The calculation was done on a sector mesh corresponding to a sixth part of the whole geometry, assuming the rotational symmetry of the combustion chamber and because a six hole nozzle was used. Only the compression, combustion and expansion phases of the complete engine cycle were simulated, between intake valve closure and exhaust valve opening.

The main initial thermodynamical properties of the in-cylinder gas were measured, such as the intake gas temperature and pressure, the rate of EGR and the intake flow rates. In order to determine more precisely the whole initial conditions (such as the in-cylinder gas temperature taking into account residual gas), as well as the walls temperature, a 0D thermo-dynamical modelling is used. This modelling of the engine cycle is based an internal energy balance using the Woshni [8] model for the wall thermal loss.

The compression phase of the cycle was first adjusted from the in-cylinder pressure measurement using a blow-by flow rate in the 3D calculation. Then the whole calculation is performed, including in-jection, combustion and pollutant formation.

The combustion modelling used in this study does not need any adjustment, so that no parameter had to be tuned to match the experimental results. The provision of precise starting conditions for the calculation (thermodynamical conditions and spray modelling in terms of injection rate, timing, velocity, etc.) result in a satisfactory response of the com-bustion model.

The outcome of this methodology is shown in Fig. 9 and Fig. 10 for the pressure curves of the two injection strategies. It confirms ability of the simulation to correctly reproduce the experimental auto-ignition delay and also the global combustion process. This point is supported by the total ROHR presented in Fig. 13 and Fig. 14. The 3D simulation correctly reproduces the intensity of the ROHR, but also the successive combustion phases that will be described more precisely in the next section. The simulation gives also crucial information in terms of combustion noise as illustrated in Fig. 11 and Fig. 12 with the pressure derivatives.

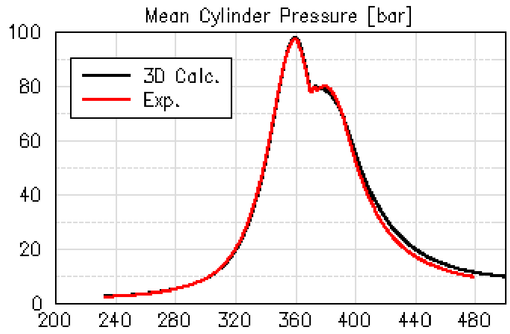


Fig. 9: *Mean Cylinder Pressure as a function of the crank angle [deg] for the standard injection (Prail=1350bars).*

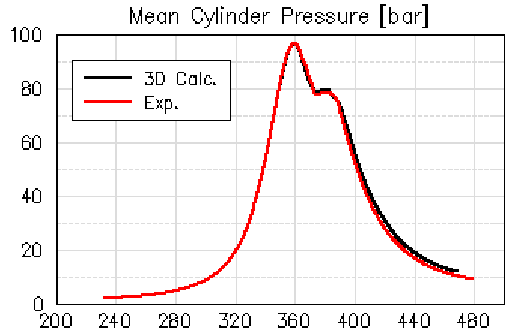


Fig. 10: *Mean Cylinder Pressure as a function of the crank angle [deg] for the boot injection.*

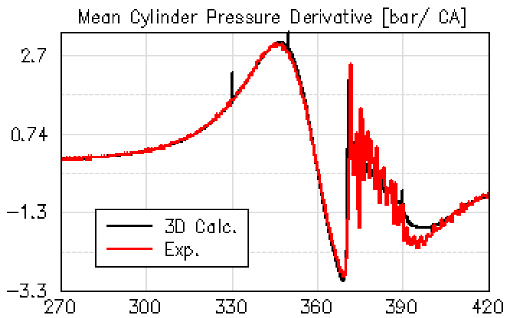


Fig. 11: *Mean Cylinder Pressure Derivative as a function of the crank angle [deg] for the standard injection (Prail=1350bars).*

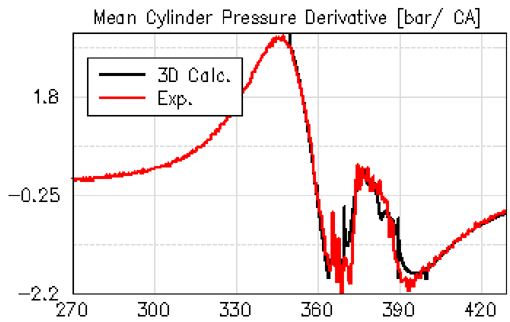


Fig. 12: *Mean Cylinder Pressure Derivative as a function of the crank angle [deg] for the boot injection.*

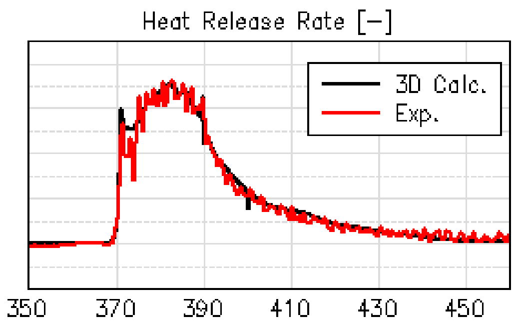


Fig. 13: *Mean Cylinder Heat Release Rate as a function of the crank angle [deg] for the standard injection (Prail=1350bars).*

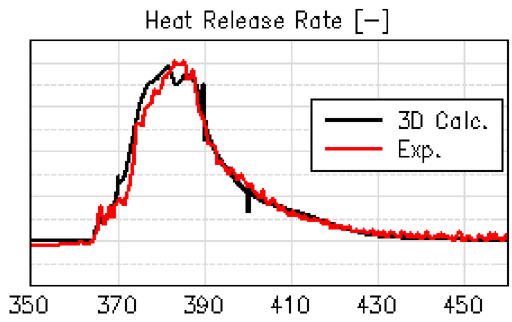


Fig. 14: *Mean Cylinder Heat Release Rate as a function of the crank angle [deg] for the boot injection.*

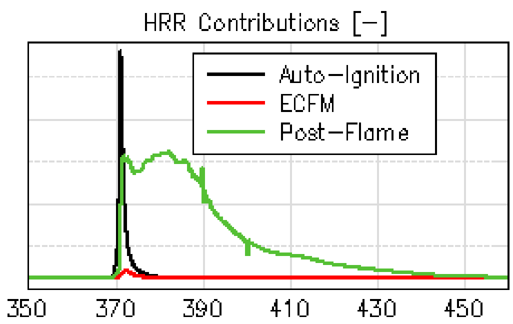


Fig. 15: *Contributions to the Mean Cylinder Heat Release Rate as a function of the crank angle [deg] for the standard injection (Prail=1350bars).*

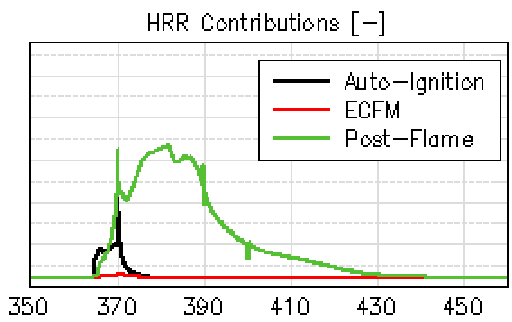


Fig. 16: *Contributions to the Mean Cylinder Heat Release Rate as a function of the crank angle [deg] for the boot injection.*

Detailed analysis of the combustion behaviour

As described in this section, the CFD allows to extend the detailed comprehension of the physical combustion processes.

For example it is possible to numerically distinguish the heat release rates of the three main combustion processes, which are the auto-ignition combustion of premixed fuel and air, the propagative combustion of premixing and together the rich post-oxidation of the fuel and the diffusion combustion (respectively called auto-ignition, ECFM and post-flame ROHR).

Fig. 15 and Fig. 16 show these three contributions to the total ROHR for the two injection strategies analyzed. The differences in terms of ROHR between these two cases appear between the start of combustion until 378 °CA. The rest of the ROHR is extremely similar and can be superposed. Before 378 °CA the main difference comes from the huge contribution of the auto-ignition ROHR in the standard injection case compared to the boot injection one. The fuel is injected earlier in the boot injection case but slower. The auto-ignition process starts earlier but is more progressive and less intense. In the two cases this phase leads to the same total ROHR at 378 °CA.

2D sections inside the combustion chamber give local information about these contributions to the total ROHR. Fig. 17 show the premixed combustion contribution to the total ROHR in the spray direction during the simulation. One can easily observe that the premixed combustion happens earlier, is less intense, but lasts longer in the case of the boot injection. This demonstrates that injection rate control during the beginning of injection is an effective way of controlling premixed combustion and thereby combustion generated noise. During the diffusive burning, the ROHR is similar for both injection strategies (Fig. 13 and 15).

Fig. 18 shows that the burnt gas temperatures differ to some extend. One can observe high temperatures from the very beginning of the combustion process in both cases. The high temperature zones are naturally favourable to pollutant formation, in particular to the NO_X formation in local lean conditions. They can also lead to soot formation at about 2000 K if the local equivalence ratio is larger than 2. In the boot case the high temperature zones seem always to be spread in the entire spray, whereas in the standard case the high temperature zones are located at the spray periphery.

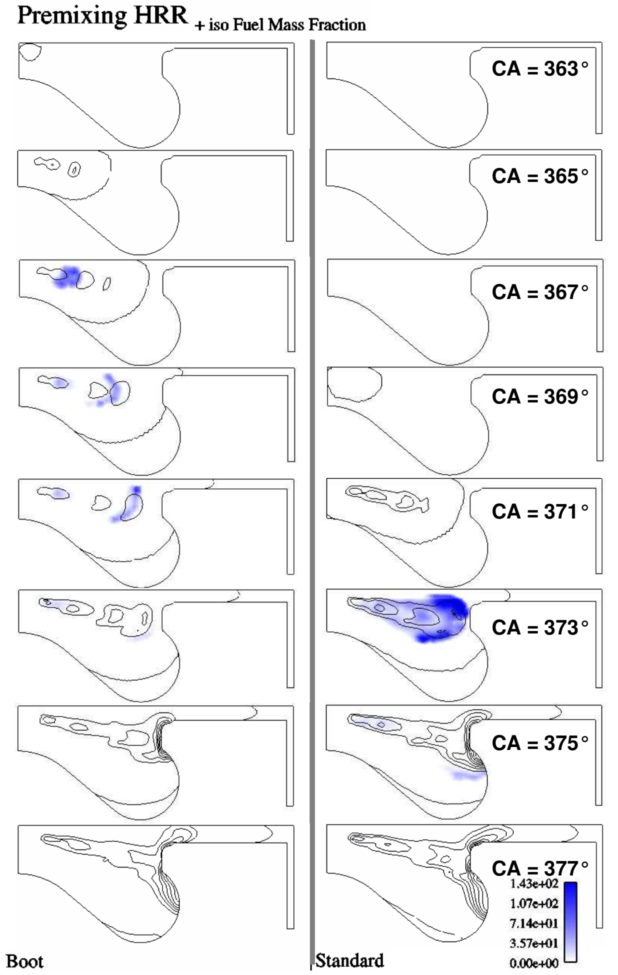


Fig. 17: *2D fields of Premixing Heat Release Rate in the spray direction for both standard (on the right) and boot (on the left) injections.*

Fig. 19 shows that a little more NO_X is formed in the boot case compared to the standard case, in accordance with the experimental measurements. The tendency is correctly reproduced and the levels are of the right order of magnitude. It is possible to correlate the NO_X production to the high temperature areas, as illustrated in Fig. 18 and Fig. 20.

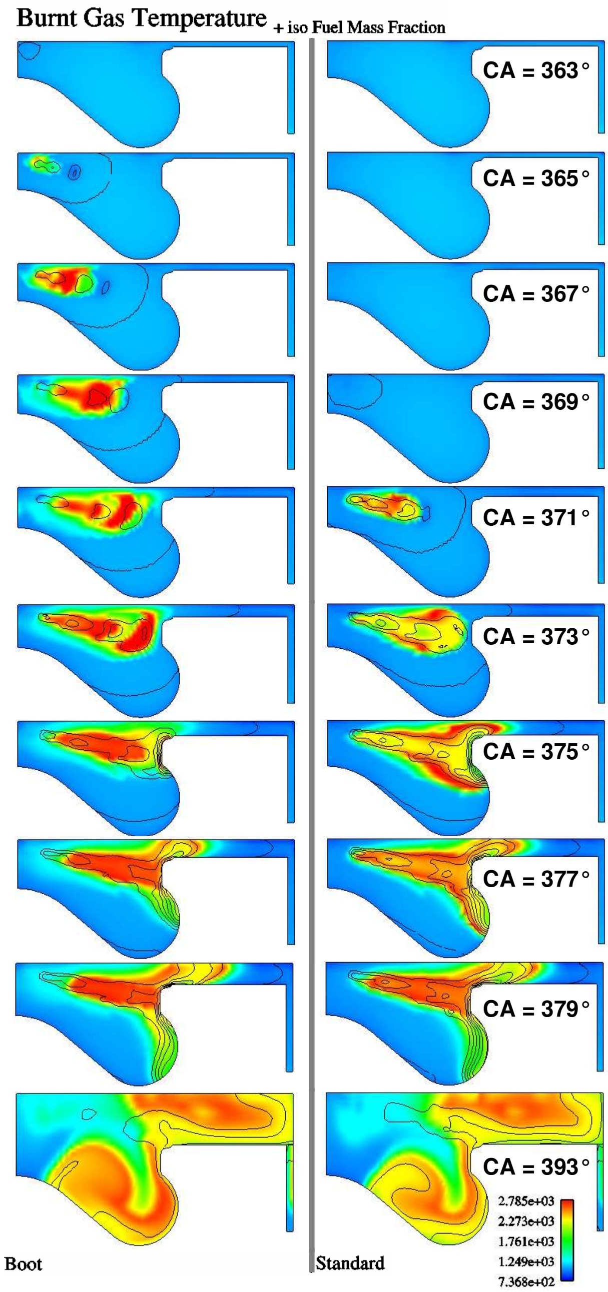


Fig. 18: *2D fields of Burnt Gas Temperature in the spray direction for both standard (on the right) and boot (on the left) injections.*

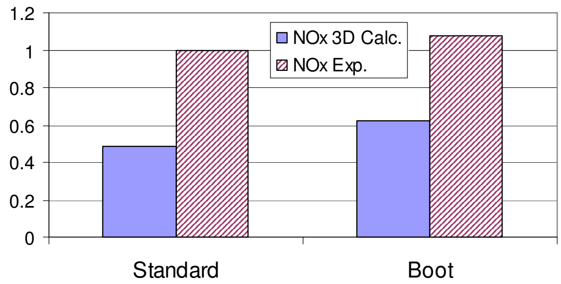


Fig. 19: *Normalized Mass of NOx at the end of the cycle for both standard (on the left) and boot (on the right) injections.*

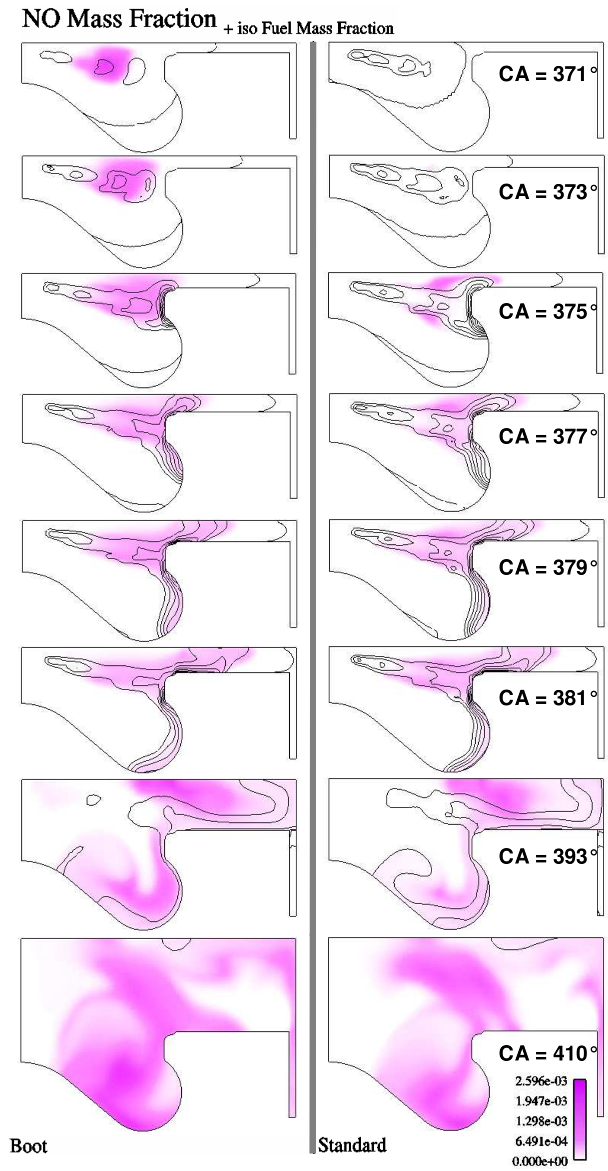


Fig. 20: *2D fields of NOx Mass Fraction in the spray direction for both standard (on the right) and boot (on the left) injections.*

On the opposite, the boot injection leads to a lower soot level at the end of the cycle as sown in Fig. 21. This tendency is correctly captured by the 3D simulation and the order of magnitude is satisfactory. The comparison between the ILM measurements and the simulation results in Fig. 22 confirms that the 3D simulation is able to reproduce correctly the soot formation history, even if the absolute values are affected by a factor of 4. As the temperature fields look similar for the two injection cases, the difference in the soot levels at the end of the combustion process should come from a difference in the soot formation. The soot formation rate is clearly higher in the standard case, see Fig. 23. Soot formation takes place especially at the vicinity of the piston bowl, in slightly different areas for the two cases. It seems that the boot injection strategy influences the soot formation only at the beginning of the whole pollutant formation phase. A deeper analysis can be performed using an equivalence ratio vs. temperature diagram.

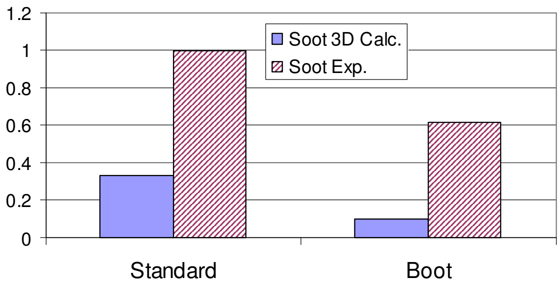


Fig. 21: *Normalized Mass of Soot at the end of the cycle for both standard (on the left) and boot (on the right) injections.*

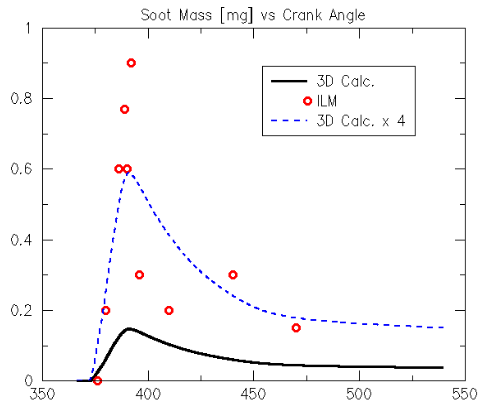


Fig. 22: *Mass of Soot in the combustion chamber as a function of the crank angle [deg].*

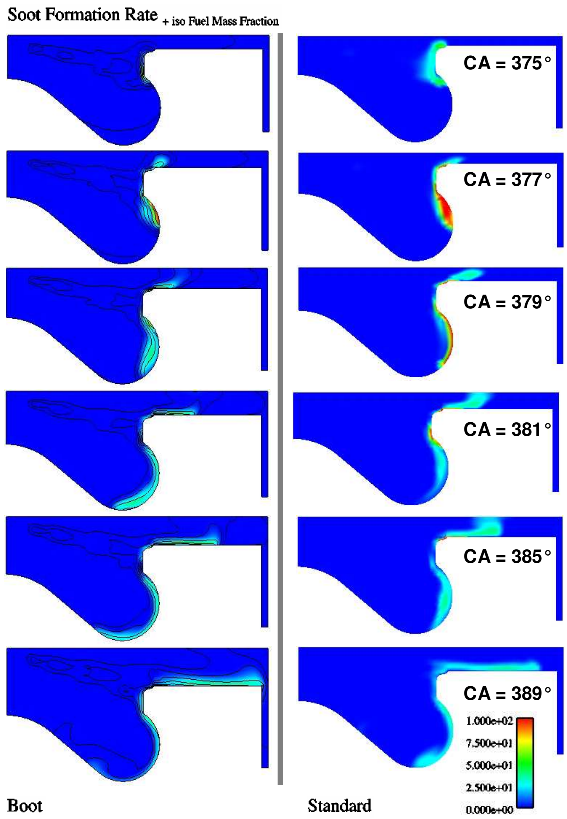


Fig. 23: *2D fields of Soot Formation Rate in the spray direction for both standard (on the right) and boot (on the left) injections.*

5. Conclusion

Through the combination of advanced experimental and numerical tools, it has been shown that a deep insight into Diesel injection and combustion is possible. On the injection system side, the IAV R&D tools have offered the opportunity to setup some particular injection schemes, which have been explored on a research single cylinder engine with a complete instrumentation. Coming from this experimental task, the generated dataset has permitted the validation of 3D CFD tools by PSA. At the end, the combination of all experimental and numerical results was used to compare two injection strategies: a standard CR injection rate and a TwinCR shaped injection rate via pressure modulation. The illustrated behaviour of the injection process and of the resulting combustion process make clear that injection rate control is effective to reduce combustion generated noise, at iso-NO_X emission with a benefit in soot emissions.

6. Acknowledgement

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7. References

[1] Stegemann, J: Dieselmotorische Einspritzverlaufsformung mit piezoaktuiertem Experimentaleinspritzsystem, Dissertation, Universität Hannover, 2004

[2] Stegemann, J.; Meyer, S.; Rölle, T.; Merker, G.P.: Einspritzsystem für eine vollvariable Verlaufsformung, MTZ 65, 114-118, 2004

[3] Seebode, J.: Dieselmotorische Einspritzratenformung unter dem Einfluss von Druckmodulation und Nadelsitzdrosselung, Dissertation, Universität Hannover, 2004.

[4] Marohn, R., Kwast, T., Roelle, T., Behnk, K.: Neue Möglichkeiten in der Entwicklung von Dieseleinspritzsystemen durch den Einsatz des Messsystems Injection Analyzer, Haus der Technik e. V., Berlin, 2004

[5] Predelli, O.; Kracke, T.; Schmidt, W.; Meyer, S.: FI^{2RE} – Neues Steuermodul für Piezoinjektoren, MTZ 65, 36-42, 2004

[6] Seiffert, A., Diezemann, M., Sommer, A., Kahrstedt, J., Integrale Lichtleit-Messtechnik (ILM) und Abbildende Lichtleit-Messtechnik (ALM) – moderne optische Werkzeuge für die Brennverfahrensentwicklung, Haus der Technik e. V., Essen, 2002.

[7] Schubiger, R., Boulouchos, K.: " Analysis of Combustion and Pollutant Formation in a Diesel Engine – Synergies of Thermodynamics and Optical Sensors", Dissertation ETH Zürich Nr. 14445, 2001

[8] Colin, O., Benkenida, A.: The 3-zones extended coherent flame model (ECFM3Z) for computing premixed/diffusion combustion. Oil & Gas Science and Technology - Revue de l'IFP, Vol. 59, No. 6, 2004, pp. 593-609.

[9] Heywood, J. B.: Internal Combustion Engine Fundamentals, p 680.

8. Glossary

CR: Common Rail
FIS: Fuel Injection System
NC: Needle Controlled
PC: Pressure Controlled
PPV: Proportional Valve
PCV: Pressure Control Valve
VCO: Valve Covers Orifice
MI: Main Injection
p_{cyl}: In-cylinder pressure
T_{cyl}: Mean in-cylinder gas temperature
$CA_{50\%}$: Crank Angle of 50% heat-release
ROI: Rate Of Injection
ROHR: Rate Of Heat Release
COHR: Centre Of Heat Release
R&D: Research & Development
CFD: Computational Fluid Dynamics
PM: Particulate Matter
$IMEP_{HP}$: Indicated Mean Effective Pressure
EGR: Exhaust Gas Recirculation
ECFM: Extended Coherent Flame Model
BMEP: Brake Mean Effective Pressure
SI: Stratified Injection
TDA: Thermo-Dynamical Analysis
IA: Injection Analyzer