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NOVEL CONCEPT FUEL INJECTION SYSTEMS FOR D.I. DIESEL ENGINES FOR PASSENGER CARS

by

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ABSTRACT

This paper presents the results of a study regarding the evaluation of the potential of new emerging fuel injection technologies in reducing the emissions of the small unit displacement Direct Injection Diesel engines for passenger car applications.

The research work started from the fundamental aspects of fuel spray combustion which were approached both theoretically and experimentally. An extended survey of existing automotive fuel injection technologies was also conducted and the results were organised using a specifically developed evaluation scheme. Based on the results of this ranking procedure, the three most promising fuel injection concepts were selected for further evaluation on research and production DI Diesel engines.

The results clearly showed the advantages of the high pressure common rail fuel injection systems which, thanks to their flexibility in controlling the individual injection pressure, timing and schedule, resulted in a very good control of engine-out emissions with simultaneous reduction of combustion noise and improvements in engine performance. The attributes of the variable geometry nozzle concept were also evaluated positively during this study and a proposal for combining this feature with common rail injection systems emerged.

INTRODUCTION

The Direct Injection (DI) Diesel engine is currently the most efficient user of fossil fuels and, consequently, the smallest CO₂ producer. However, despite its advantages compared to gasoline and IDI Diesel engines, its penetration to the light vehicle market is very limited due to the relatively high NO_x and particulate matter emissions and its characteristic (and unpleasant) combustion noise. The tighter emissions legislation foreseen in the not too distant future makes its survival questionable.

Available exhaust after-treatment technologies enable the small DI Diesel to meet

EEC 96 and Federal 87 standards, albeit using costly electronically controlled fuel injection systems (**FIS**), Exhaust Gas Recirculation (**EGR**) and particulate trap devices. An alternative, **and** certainly more radical, method to simultaneously control NO_x and particulate matter emissions concerns the optimisation of the in-cylinder combustion process. Since the entire combustion process in **DI** Diesel engines is primarily governed by fuel injection and **its** interaction with the in-cylinder air motion, the fuel injection system becomes the most critical engine component.

Current understanding of the **inter-relation** between fuel injection, combustion, engine performance and emissions is largely based on **phenomenological** trend observations in injection equipment and engine test beds. A review of the open literature on present research and development strategies in Japan [1–9], USA [10–12] and Europe [13–15] emphasises the growing awareness for the need of fundamental investigations of **all** aspects of Diesel fuel injection and combustion. The adoption by industry of CFD simulation tools [13, 16-18, 22-24] and of advanced laser-based spray and combustion diagnostics [4, 5, 8-11] as new design **tools** also allows the better understanding of mixture formation and combustion.

Recent research on Diesel engine combustion processes has focused attention on two major parameters of a **FIS**:

- a) Fuel injection pressure and
- b) its temporal modulation.

The Japanese ACE Inst. Ltd in collaboration with Nippon Denso Co, Hino Motors Co, and the Automobile Research Institute of Japan [1-5] are carrying out a long research programme focused on **medium-** to large-size **DI** Diesel engine Fuel Injection Systems. Their results show that, with injection pressures raised from the 600 bar of a conventional system to **1000–2000** bar, fuel atomisation improves significantly with beneficial effects on fuel/air mixing and soot reduction. Equally important **is** the fact that high momentum sprays are less affected by air charge motion and, since fuel atomisation is improved, swirl in a high pressure **FISDI** Diesel engine can be reduced by factors of the order of 4, resulting in higher engine breathing capacities and corresponding gain in power output.

The temporal modulation of the injection pressure (or spray injection rate) [21] is even more critical since it defines local stoichiometry and, therefore, soot formation as well as the rate of **heat** release, combustion temperature and **NO_x** emissions, Local stoichiometry also controls the ratio of pre-mixed and diffusion combustion in the spray with direct effects onto combustion noise. Finally, the use of Pilot Injection [25] is also considered as a means of controlling Diesel combustion quality. Other important parameters influencing spray combustion quality include nozzle hole size, number, and orientation within the combustion chamber. The optimisation of these characteristics, however, as it depends on the specific engine operating conditions, is **always** a **result** of a compromise.

The potential of high-pressure modulated-rate fuel injection techniques in reducing NO_x and particulate emissions without compromising the **DI** Diesel engine's fuel efficiency is fairly **well** documented in the technical literature and data published in [17] demonstrate the potential achievements at a representative engine operating point. They show a reduction of particulate emissions of more than 50% through high pressure **FIS** or a reduction of **NO_x** emissions by about 40% through improvement of

fuel injection rates. Even a simultaneous 25% reduction of both components has been demonstrated. However, although such examples encourage designers to further pursue these technologies, their implementation in systems applicable to the wide operating range of modern engines has still to be demonstrated.

The possible alternative approach for the reduction of NOX emissions is provided by specific exhaust gas after-treatment devices. The current status of such DENOX catalysts as described in the open literature (e.g. [17]) shows steady state engine NOX conversion rates of up to 30% which in a transient engine test cycle amount to a conversion efficiency of about 15%. Development targets, however, have to focus on conversion rates as high as 50 to 60% which are unlikely to be achieved in short time. Equally unsatisfactory is the fact that proper operation of DENOX catalysts implies a penalty in fuel efficiency.

On this background the present work aims to:

1 - define the optimal specifications (injection schedule, pressure level, nozzle design, etc) of a Fuel Injection System, in the entire operating range of a passenger car DI Diesel engine, capable of allowing the following targets to be reached or approached:

a reduction of in-cylinder produced particulate matter to the level requested by Federal 94 emissions standards (about 60% with respect to the present standards)

a reduction of NOX formation to the level requested by the Federal emissions standards expected within the next ten years (about 60%)

a substantial noise reduction

all the above with no, or very little, increase of fuel consumption.

2 - review and evaluate novel fuel injection systems suitable for achieving the required injection specifications. These are expected to be applicable to DI Diesel engines not only for passenger cars, but also for light duty vehicles and trucks.

3 - make available representative prototypes of some fuel injection systems which can meet or approximate the requested specifications.

TECHNICAL DESCRIPTION

Theoretical studies

The study regarding the identification of the ideal characteristics of a fuel injection system was conducted using simplified engine cycle simulation tools and the three-dimensional CFD code SPEED, [13]. During this parametric analysis, the effect of a large number of variables such as the injection rate, spray momentum, nozzle hole diameter, air swirl ratio, pilot injection etc, on spray atomisation and mixture formation and ignition were studied. The trends observed were analysed based on engineering experience and a set of specifications for an eventual ideal fuel injection system were

defined. It is clear that these specifications could hardly be met by a single existing system, but this data base clarified many hazy aspects of the fuel injection process and greatly assisted the definition of the ranking scheme developed at the second stage of the work.

The results of these numerical simulations were to a large extent validated by an experimental campaign on a current Fiat production 1.9 lt, 4-cylinder DI/TC engine equipped with a laboratory-type computer-controlled flexible fuel injection system. This FIS prototype allowed the variation of injection pressure, start of injection (SOI) angle, injection duration, injection schedule (eg pilot injection), pilot injection quantity, distance between pilot and main injection, etc. The variables that could not be modified during an engine test run were the shape of the injection rate curve, which remained nearly top-hat, and the discharge characteristics of the atomiser nozzle. This latter parameter, however, was also varied by substituting the injector atomiser from one test to the other.

Evaluation of available FIS technologies

Having established the desirable FIS characteristics by the above mentioned validated analysis, an extended survey of the available systems and technologies was undertaken, This survey took into consideration most published (and many unpublished) information on fuel injection systems, starting from well established products and ending to prototypes proposed by various inventors. The available information and FJS hardware prototypes which were finally considered and, to a large extent, tested on hydraulic test benches amounted to 31, covering the following 6 families:

- Mechanical Distributor type Pump-Line -Nozzle
- Electronic Distributor type Pump-Line -Nozzle
- In-Line Pump - Mechanical
- Electromechanical
- Electronic
- Unit Injectors - Mechanical
- Hydraulic
- Electromechanical
- Electronic
- Common Rail
- Other types

For each one of the above 31 systems considered, 29 characteristic properties were evaluated according to a specifically developed weighting scheme which made use of the results of the previous numerical and experimental studies with the flexible laboratory-type FIS.

This evaluation work demonstrated that the technology of the electronically-controlled accumulator-type FISs ranked first, followed by the FISs based on the Hydraulic Pressure Amplification principle and the Variable Geometry Nozzle concept.

Fundamental spray combustion studies

Given the results of this study, three prototypes, representative of the highest ranking

hardware of the above three families, were selected for subsequent work. This consisted of a detailed characterisation of the fuel spray in quiescent pressure vessels (bombs) and swirl chambers (optically accessed research engine). A number of classical and advanced laser-based spray and combustion diagnostic techniques were used for the characterisation of the reacting and non-reacting sprays. They included:

- Spray pattern photography
- Laser diffraction droplet sizing
- Line scan photography
- High speed flame photography
- Schlieren photography
- Laser induced incandescence
- Laser Doppler anemometry
- Phase Doppler anemometry
- Combustion pressure analysis techniques

The three selected Fuel injection systems were tested in a number of operating conditions as far as injection pressure, load, nozzle hole diameter etc were concerned. The main findings of this work are discussed in the following section.

FIS on-engine performance evaluation

The three selected FIS prototypes were installed on three different DI Diesel engines of 0.4 to 0.5 lt unit displacement. The electro-hydraulic Common Rail FIS prototype was installed on a 1.9 lt DI Diesel, four cylinder, TCI engine, the Hydraulic Unit Injector prototype on a 1.7 lt DI Diesel, four cylinder NA engine and the VGN injector prototype on a 16-valve DI, 2 lt engine configuration. The objective of this work was the benchmarking of the three FIS against the baseline engine and against each other. For this reason, the combustion system of each of these engines was modified in order to match the requirements of its specific FIS prototype. These modifications included adjustments in compression ratio, intake swirl level, atomiser nozzle characteristics, piston bowl geometry etc, in order to render the comparisons "fair". This was an issue of major importance since, as it is well known in the engine engineering community, a simple substitution of a component such as the FIS on an engine is not possible and engine optimisation is always necessary.

The tests conducted on the engine test bed included the classical parametric studies of the effect of main (and pilot where possible) injection advance, injection quantity (pressure and duration for the CR system), atomiser nozzle type (number/diameter of holes) etc. on engine performance and emissions. These studies were conducted under steady state conditions at full and partial loads. The combustion process has always been monitored and compared against the data of the corresponding fundamental experimental and theoretical studies in order to assist the further engine optimisation. The end result was the availability of three DI Diesel engines, each optimally matched with its own prototype fuel injection system. The availability of this hardware allowed the proper evaluation of the potential of each of the three selected FIS technology prototypes to reduce engine-out emissions and fuel consumption.

RESULTS

Fundamental theoretical and experimental studies

The fundamental theoretical work showed that an ideal Diesel combustion process is physically and chemically possible but the requirements for charge homogeneity are too difficult for current technology **FISs**. Despite that, very **small** atomiser nozzle holes tend to approach this ideal fuel distribution and, at the same **time**, the reduced spray momentum inhibits wall impingement. The necessary **fuelling** load in this case can only be achieved with high injection pressures which are **also** beneficial from the fuel atomisation point of view. High Cetane numbers of the Diesel fuel are also required to achieve ignition with the resulting nearly homogeneous lean mixtures. The following Table 1 summarises some findings of this **study**.

Test case	Curve no, in figs 1-3	b g/kWh	imep bar	Pmax bar	T m a x K	NO ppm
Short injection (heterogeneous)	1	208	11.0	67'	2722	1413
Long injection (heterogeneous)	2	204	11.2	53	2689	2233
Short injection (homogeneous)	3	201	11.4	71	2129	33

Table 1: Theoretical engine performance and NO emissions

The above Table, considered together with the results shown in Figures 1 - 3, indicates that, if autoignition of the lean homogeneous mixture of case 3 were possible, fuel consumption and NO emissions could drastically be reduced. This is due to the entirely different (and lower) temperature evolution in the cycle, as shown in Figure 3, resulting from the homogeneous mixture distribution,

Figure 4 presents sample results of the **CFD (SPEED)** spray and combustion simulations in terms of in-cylinder pressure and temperature. The specific graph shows the effect of nozzle hole diameter (**EOP1 = 5x0.2 mm** and **EOP3 = 5x0.1 mm**) at 2000 engine rpm with the same injection **quantity**, rate and advance . It is clear that the finer atomisation obtained in the second case reduces the ignition delay of the mixture and, as shown earlier, results in lower in-cylinder temperatures by approximately **200 K**, which implies lower NO emissions,

The experimental and theoretical spray combustion studies showed that the flame position at the start of combustion depends on **fuel** spray propagation and **vapour** convection during the ignition delay time. For a given ignition delay time the main parameters of influence are the injection pressure and nozzle hole diameter as well as the **in-cylinder** flow field. In the case of classical cam-driven **FISs** the **initial** flame position is rather independent of fuel load as injection always starts **at** a fixed nozzle opening pressure, Variations of ignition delay time due to varying thermodynamic

conditions, however, change this behaviour.

Contrary to this observation, in the case of the common rail FIS prototype, it was shown that rail pressure influences the initial flame position via its direct effect on the initial spray discharge velocity as shown in Figure 5 for injection pressures of 300, 400 and 800 bar. Throughout the combustion process, flame position depends on the local delivery of fuel and its mixing with in-cylinder air. With cam-driven FISs, the rise and fall of fuel injection pressure results in a wide distribution of the flame. In the case of the common rail system, the flame is more concentrated around the area targeted by the constant pressure spray.

In the pilot fuel injection mode, as also shown in Figure 5, the second portion of the spray is ignited as soon as it is propagating into the combustion chamber. This fast ignition is supposed to be supported by the local presence of burned gases from the pilot fuel portion which are rotating around the nozzle in the typical swirl type combustion chambers. This behaviour was not observed in quiescent combustion chambers where gas motion is only initiated by the fuel spray propagation and thus burned gas is not present around the nozzle to ignite the second portion of fuel injected.

Engine test bed results

The Flexible FIS prototype was successfully used in a pilot injection mode and allowed a preliminary parametric study in terms of the effect of relative and absolute pilot injection advance on gaseous emissions, smoke, combustion noise and specific fuel consumption. This work was supported by (but also provided support to) the parallel CFD and experimental analysis efforts.

The global benefit of the pilot injection process was found to be, as hinted by the results of the theoretical work, an increase of the engine tolerance to late main injection with beneficial effects on CO, HC and NO_x emissions as well as specific fuel consumption. Pilot injection was particularly advantageous in part load, low speed, engine operation where significant reduction (5-8 dBA) of the combustion noise levels was observed. Pilot injection timing with respect to the main injection was also shown to be crucial for the engine optimisation. Short injection intervals appear to be beneficial at partial loads from all points of view apart from combustion noise.

A representative sample of the results obtained by two of the three selected FIS prototypes on the corresponding optimised engines is presented in Figures 6 and 7. The performance of the third FIS prototype, namely the HUI based on the pressure amplifier principle, proved to be at the level of current fuel injection systems.

Figure 6 shows the benefits in terms of noise and NO_x emissions that were obtained by the common rail FIS prototype as compared to the baseline engine equipped with a current state-of-the-art pump-line injection system. It is clearly shown that combustion noise at 4000 rpm with varying load between 1 and 10 bar bmep is, in average, 3-4dBA lower with the common rail FIS in the pilot injection mode, while NO_x emissions are reduced by 30-50% up to loads of 8 bar. All this is achieved at constant smoke levels and with no penalties in terms of fuel consumption (bsfc), unburned hydrocarbons (HC) and carbon monoxide (CO) emissions.

Finally, Figure 7 demonstrates the **positive** effects of the **VGN FIS** prototype in terms of Soot and **NO_x** emissions in part load (1500 rpm/5 bar bmep). It is shown that switching the **VGN FIS** from the high load configuration (5x0.21 mm nozzle holes) to the low load configuration (6x0.14 mm nozzle holes) results in a drastic decrease of **NO_x** emissions of the order of 50- 60% at constant Soot emissions, **while** maintaining similar (if not lower) fuel consumption (**bsfc**). It is obvious that at high load operation the 6x0.14 mm holes are inadequate and, therefore, the **VGN FIS** is switched to its high load (5x0.21 mm) configuration,

CONCLUSIONS

The work summarised in this paper has addressed successfully the issue of the possibility of controlling and reducing **DI Diesel** engine emissions by means of combustion control through the appropriate design of the Fuel Injection System, In particular the following have been demonstrated:

- a) Advanced numerical and analytical combustion simulation tools and spray and combustion diagnostic techniques, when properly used, are reliable and useful for the in-depth understanding of the complex combustion processes in the **DI Diesel** engine. Industry can, and should, **use** these tools in order to advance the applied engineering aspects which are necessary for the development of future clean and efficient engines.
- b) Three **FIS** prototypes of different technologies have been assembled and tested on suitably optimised production **DI Diesel** engines. **Their** functionality in test cell environment has been proved.
- c) The **electro-hydraulically** activated Common Rail **FIS** concept proved to be the, currently, best suited for engine emissions control. Its main characteristic was its flexibility in optimizing injection pressure, timing and mode (pilot injection or not) for each engine operating speed and load.
- d) The variable geometry nozzle (**VGN**) concept, although lacking the flexibility of the **CR FIS**, exhibited optimum performance thanks to its ability to match the nozzle discharge characteristics to the engine operating conditions.
- e) The hydraulic pressure amplifier (**HUI**) **FIS** concept proved to be, at best, equal to the currently available state-of-the-art fuel injection systems.
- f) At steady state operation the **CR** and **VGN FIS** prototypes exhibited excellent potential in improving the trade-off between **NO_x** and particulate emissions. Reduction of **NO_x** emissions by 50% was shown to be feasible with no penalty in fuel consumption.
- g) The capability of the **CR FIS** to provide well-controlled and properly-timed pilot fuel quantities resulted in significant combustion noise reduction (**5dBA**) and better control of **NO_x** emissions.

h) A combination of the features of the CR FIS (ie the modulation of injection pressure, duration and timing) with the main feature of the VGN FIS concept (ie modulation of the nozzle discharge characteristics) should lead to an optimal future FIS for small and medium size DI Diesel engines.

In conclusion a "Smart Common Rail" FIS appears to be the characterisation of the future generation of fuel injection systems. This is expected to involve heavily the novel emerging actuator technologies and engine electronic control strategies.

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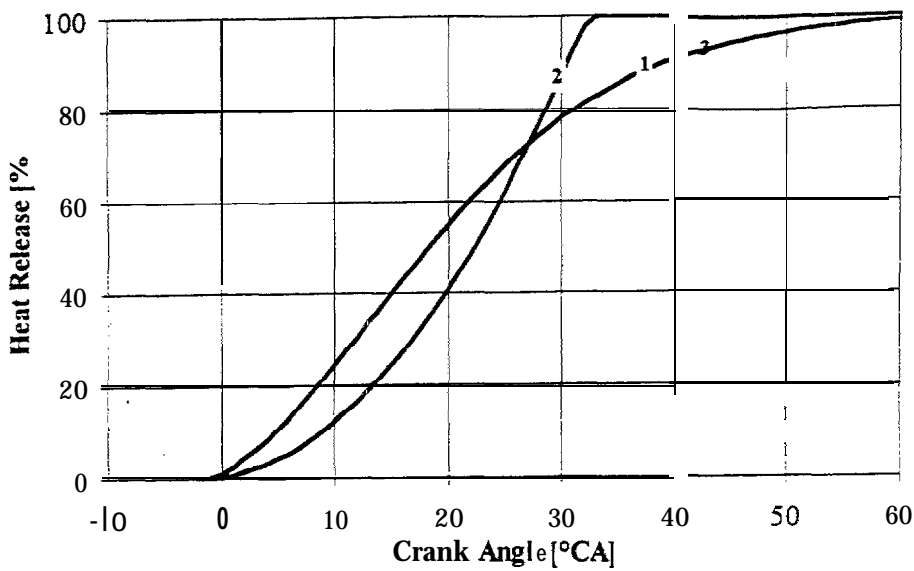


Figure 1: Heat release traces assumed in the simulations

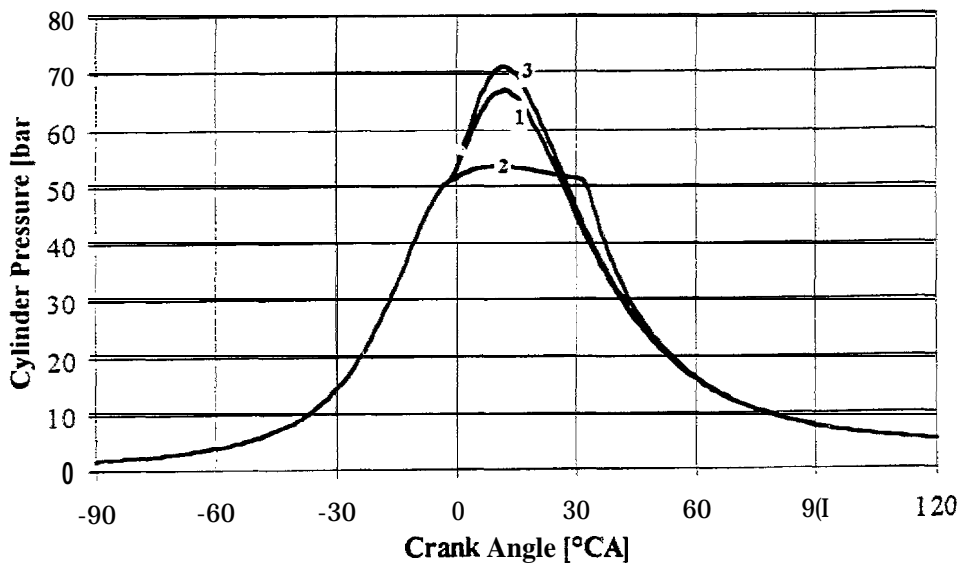


Figure 2: Resulting pressure traces

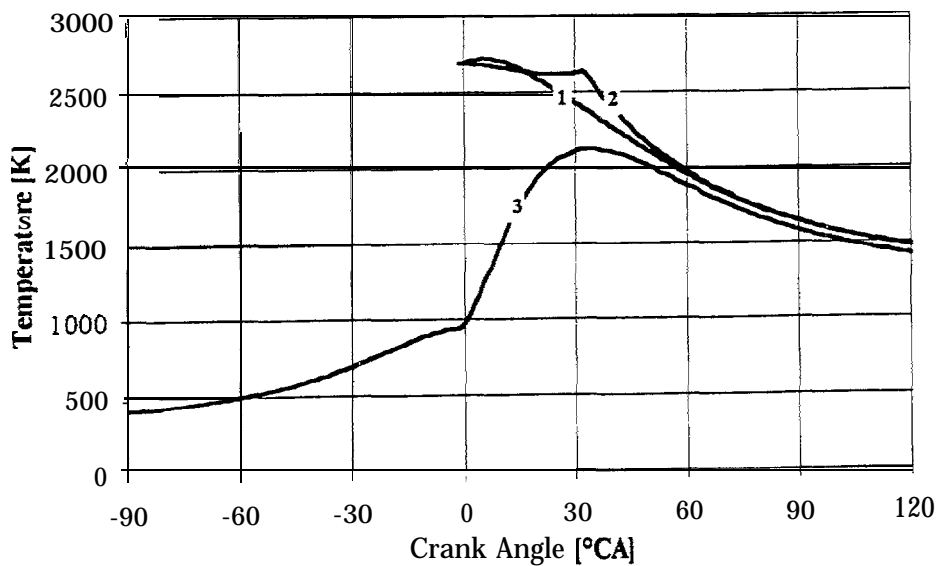


Figure 3: Resulting temperature traces

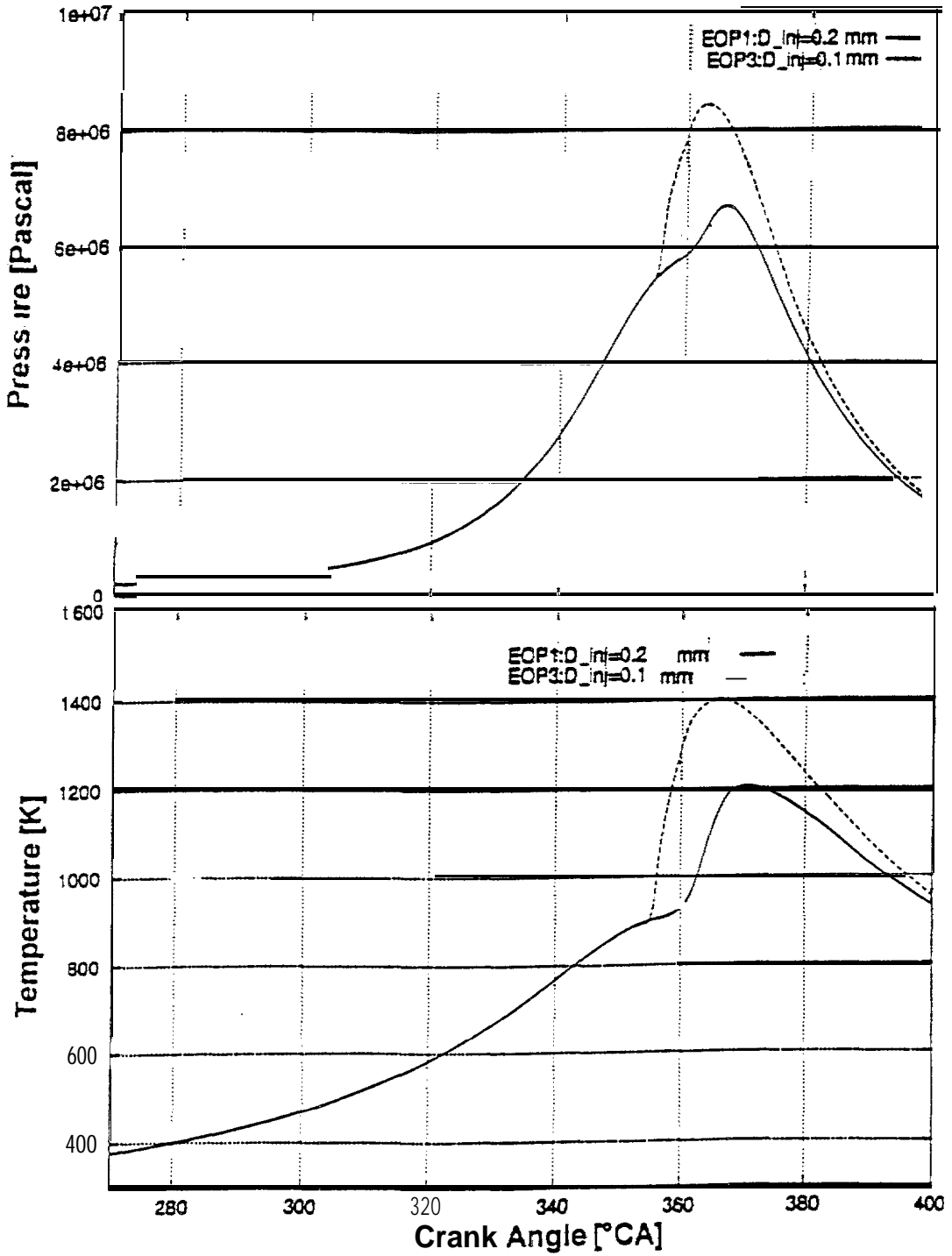


Figure 4 : Simulated cylinder pressure and temperature.
 S mg n-dodecane, -8°CA SOI, 1 mg/°CA injection rate

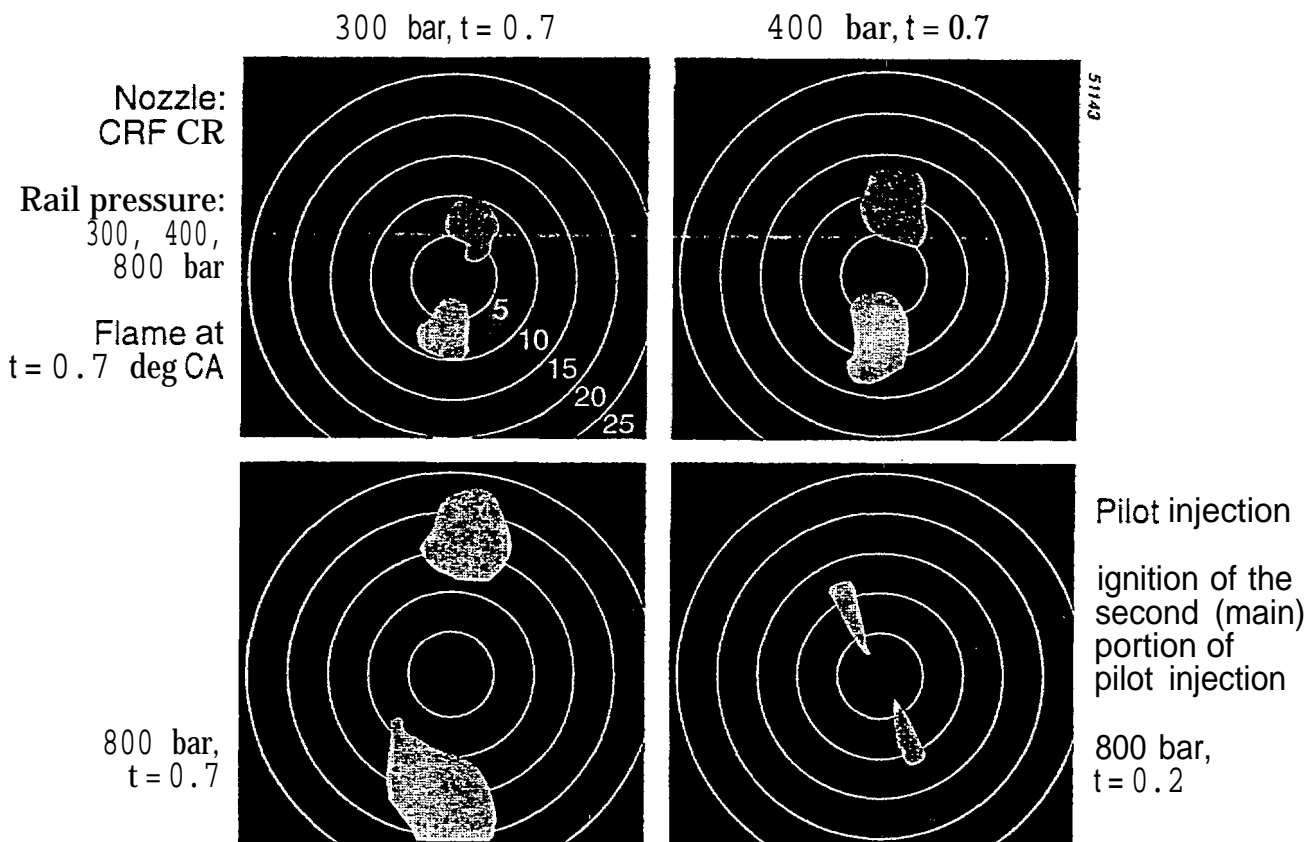


Figure 5: Flame positions at the start of combustion (twin-hole injector in swirling flow)

— HIGH PRESSURE F.I.S. with EGR and PILOT INJECTION; 5 holes 0.18 mm nozzles

--- EDC BOSCH VP37 / MSA11 F.I.S. with EGR; 5 holes 0.20 mm nozzles RPM=4000

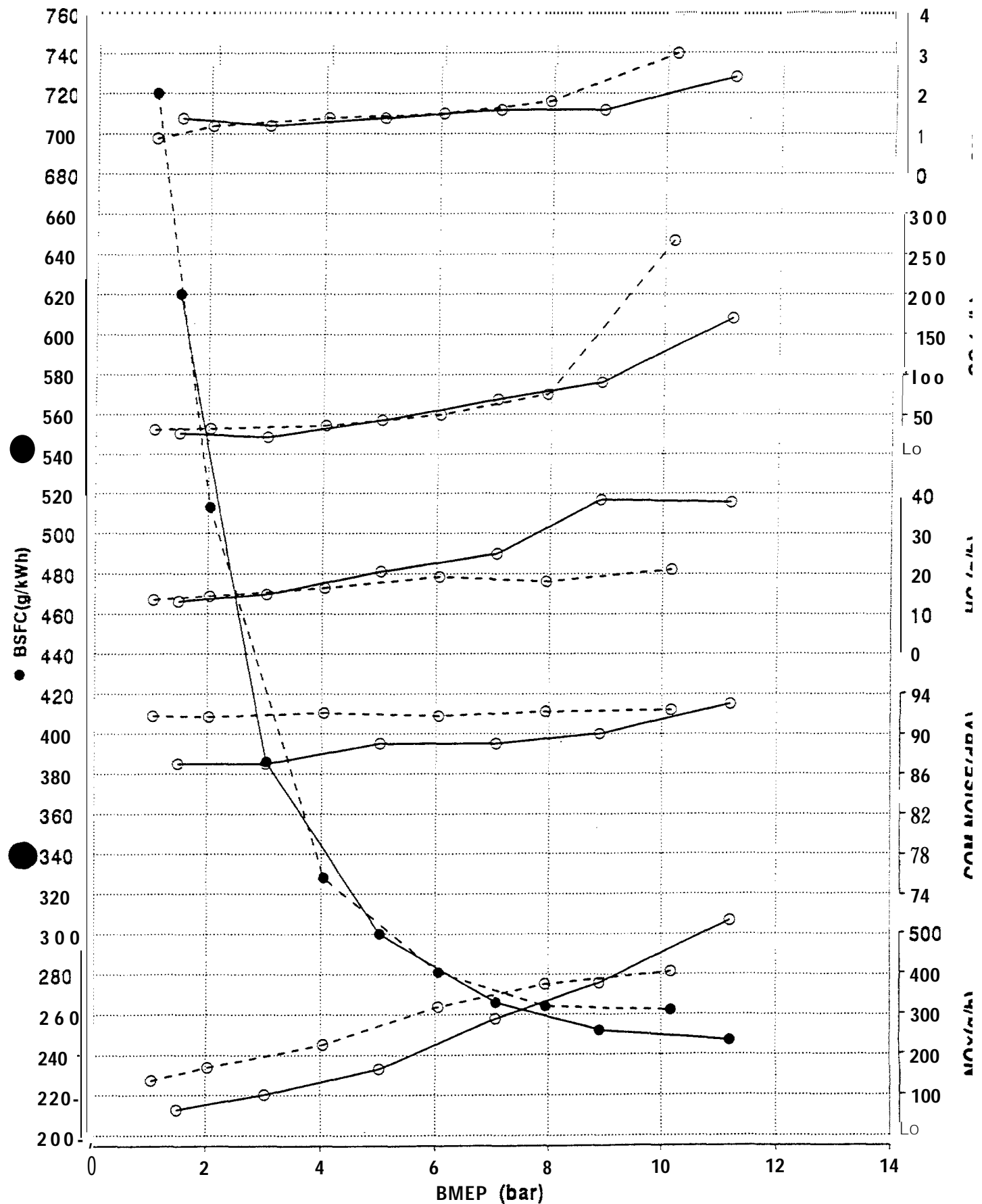


Figure 6: 1.9 lt DI Diesel engine : Comparison between Standard and Common Rail injection systems

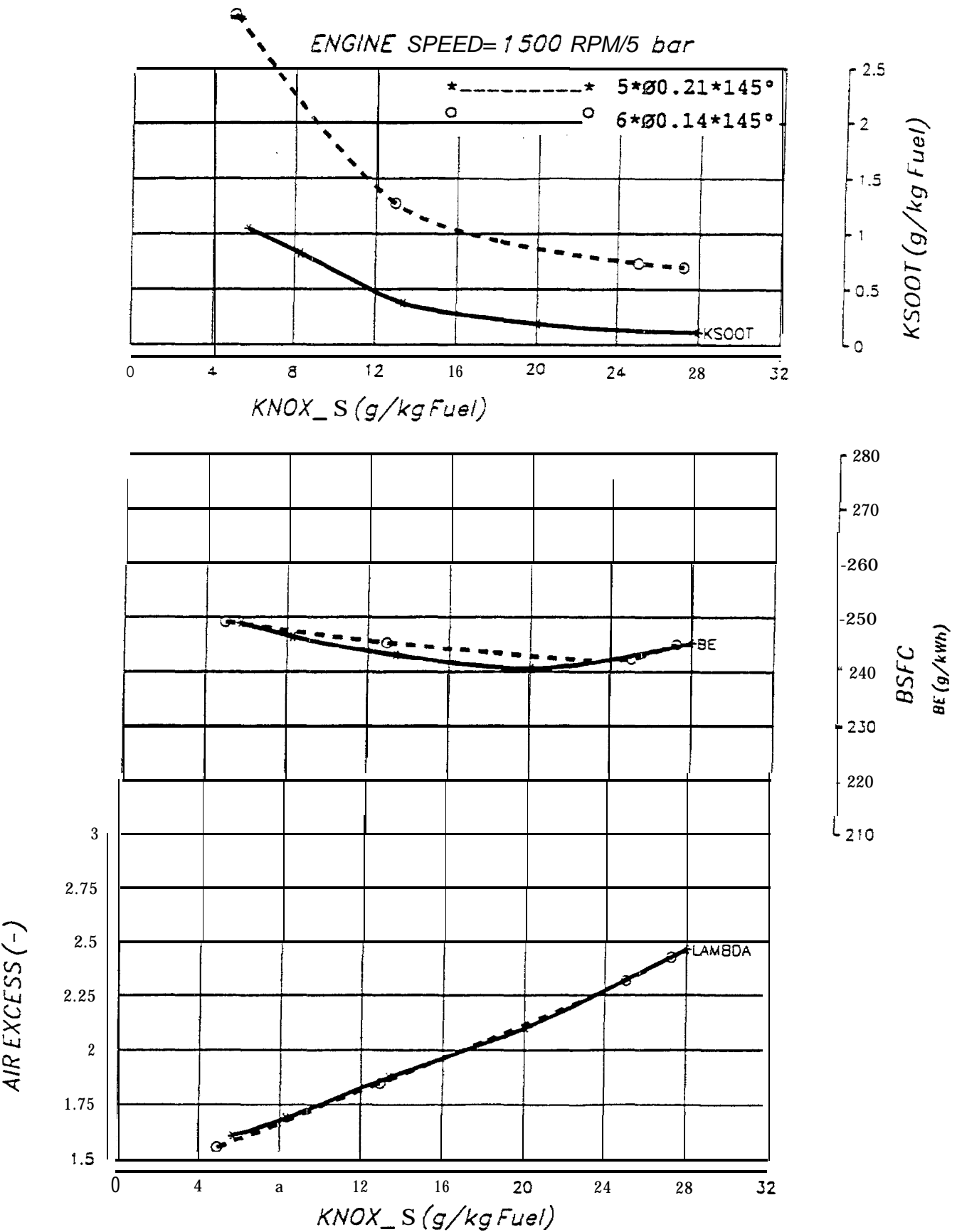


Figure 7 : 2.1 lt DI Diesel engine : Comparison between standard atomiser and low-load atomiser performance