Effect of Common Rail Injector Design on the Emission Characteristics of Passenger Car DI Diesel Engines

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ABSTRACT

The emission characteristics of future DI Diesel engines are strongly affected by the design and performance of its CR injection system. Therefore a fundamental study was performed to assess the key issues. In this study an experimental piezo Common-Rail system was used. Injection timing is controlled by using a piezoelectric actuator instead of the conventional solenoid. An optical research engine was used to analyze the combustion process under virtually real operating condition. Emissions were measured in a conventional companion single cylinder engine.

The overall spray patterns are crucially affected by the precision of the plunger guide. Injectors with highly symmetric spray patterns reduce soot emission by more than 50% compared to injectors with non-symmetric patterns. Soot emission also decreases with increasing injection rates. Reductions of have also been observed due to a pressure increase. However, there is a trade-off: engine noise increases with an increase in rate and/or pressure of injection, too, which must be compensated by suitable pilot injection and rate shaping strategies.

INTRODUCTION

In December 1997 Daimler Benz was the first passenger car manufacturer to launch a 4-Valve DI-Diesel Engine with a Common Rail (CR) injection system into the market. The CR injection system offers a range of unique attractive features not found in conventional injectors being essential for achieving future emission standards (e.g. EURO IV). The main reasons for introducing the CR system were its independence of injection pressure on engine speed and the possibility to implement dedicated pilot, main and post injection. Nevertheless, there are still limitations in injection pressure flexibility and control of minute pilot injection quantities which have dramatic effects on emission characteristics and combustion noise.

The paper addresses the needs and challenges of future Common-Rail systems and discusses the fundamental aspects of their implications on combustion issues.

EXPERIMENTAL SETUP
Injection Systems

Figure 1 shows schematic drawings of a conventional, solenoid controlled 2/2-way valve CR injector and a specially designed research type injector with a piezo-electric actuator, respectively. In both injectors the control piston and the needle were pressurized by the same rail pressure. In the closed position all forces acting on piston and needle cancel each other. By actuating the solenoid valve or the piezo-actuator the ball valve opens and due to the resulting pressure drop at the control piston the needle opens, too. In case of the conventional solenoid injector a compromise had to be found between providing a minimum fuel quantity during pilot injection and a high enough injection rate during main injection. This compromise is a major drawback for optimizing Diesel combustion for future requirements.

The piezo-electric actuator has two main advantages over the conventional solenoid actuator. Firstly, the piezo actuator requires only half the time for the same lift. Secondly, the piezo is capable to exert a much higher working force. Thus it is possible to enlarge the cross section of the flux limiting outlet orifice and to increase the injection rate thereby.
Solenoid controlled CR  Piezo controlled CR

Fig. 1 Schematic drawing of injection system layout for a standard CR (left) and a piezo CR (right), respectively

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Fig. 2 Standard and dual guide nozzle, respectively

Nozzle Effects

In an earlier investigation it was demonstrated already that the design and the manufacturing quality of the nozzle have a dramatic effect on emission characteristics [1,2,3]. Therefore, for both systems analyzed a nozzle with a dual guide was used (see Figure 2). The dual guide serves to force the plunger to open and close highly symmetrically with respect to the seat axis (see Fig. 8 for its effect on the symmetry of the overall spray pattern and on combustion).

The Optical Engine

For the investigations an optically accessible research engine was used providing fluid-dynamical and thermo-dynamical properties being identical to the production type companion. Figure 3 shows the major technical features. In Figure 4 the details of the optical access and the applied diagnostics are given. The engine has a specially designed full view quartz window in the piston. The combustion chamber shape is identical to the production type engine providing relevant and reliable detailed studies in the piston bowl and in the squish area. The combustion images were taken by a conventional high speed movie camera with a time resolution of 7,000 frames per second. For visualizing the liquid and the vapor phase of sprays, resp., a specially developed simultaneous Mie scattering and Schlieren technique was used. Fiber optics were applied to provide the necessary light sources. Chemo-luminescence of the OH-radical was used as an indicator for reaction processes occuring during ignition and combustion of pilot injection.

To operate the optical engine as realistically as possible it was first motored for a few minutes using electrically preheated air to raise the combustion chamber walls to the correct surface temperatures. Optical measurements were
Fig. 4  Details of the optically accessible single cylinder research engine and measuring techniques: (A) full view photomultiplier setup for OH measurements, (B) high speed movie camera with calibration lamp for spray, combustion and 2D two-color analysis, (C) flash lamp for Mie scattering diagnostics, (D) full view fiber optics for 1D 2 color method
taken subsequently after the 7th fired cycle which proved to bring the engine into a steady state condition without adverse soot deposits on the optical surfaces. This ensured correct, reliable, high quality optical and conventional test bench data. For evaluation purposes a calibrated tungsten lamp was recorded simultaneously on the combustion film to allow for quantitative data of the recordings. A conventional 1D and a dedicated 2D two-color method were used to extract crank angle resolved surface temperatures and relative concentrations of the soot formed in combustion. From these data exhaust NOx and soot emissions could be extracted with good accuracy using correlation functions.

RESULTS
Hydraulic characteristics

Figures 5 and 6 show injection rates and fuel quantities of the conventional and the piezo system, resp., measured by a specially designed precision fuel metering system [4,5]. The piezo CR-system exhibits higher rates of injection corresponding well with its larger orifice of the outlet throttle. The fuel injection maps clearly show the benefits gained by piezo CR-systems over solenoid systems with respect to the

Fig. 5 Measured injection rates of a piezo and a conventional CR-system, resp., total injected amount of fuel 15mm³/st, p_rail = 600bar

CR with solenoid actuator

CR with piezo actuator

Fig. 6 Effect of rail pressure on the timing of injected fuel for conventional and piezo CR- injection systems, respec.

accuracy of controlling small amounts of injected fuel at high rail pressures. The minimum pilot quantity reproducibly achieved was < 1mm³ at 1,350 bar rail pressure. This corroborates that the piezo injector has an unmatched potential for precise control of rates and amounts of injected fuel.
Standard VCO with single guide  

![Spray Pattern]  

VCO with dual guide  

![Spray Pattern]  

Combustion  

![Combustion Image]  

![Combustion Image]  

Fig. 7  Spray patterns and combustion characteristics for nozzles with single and dual guide, resp., \( p_{\text{ail}} = 600 \) bar, \( Q_c = 15 \text{ mm}^3/\text{s} \). *Spray pattern* at 1 ms in Nitrogen at \( p_g = 25 \) bar, *Engine combustion* at 1.8\(^\circ\)CA ATDC, \( n = 2000 \text{ 1/min}, \) BMEP = 10 bar  

**COMBUSTION CHARACTERISTICS**  

**Effect of spray pattern**  

Figure 7 shows the effect of using a single and a dual guide nozzle, resp., on the overall spray patterns of a conventional CR-system. The sprays were visualized in a constant pressure bomb operated at 25 bar Nitrogen pressure to mimic engine conditions (density) near TDC. The corresponding combustion images were taken in the optical engine.

Conventional machining tolerances for single guide nozzles lead to very asymmetric spray patterns with each hole producing a different spray characteristic with respect to droplet size distribution, impulse, angle and penetration depth. This well known effect is caused by an irregular offset of the plunger axis with respect to the seat axis - especially in the early phase of needle opening - leading to large variations in inflow conditions into the different nozzle holes which in turn cause highly irregular sprays (Fig. 7a). In consequence poor combustion and high soot emissions result. By narrowing the machining tolerances and introducing a second guide (dual guide nozzle) the plunger can be centered reliably and high quality symmetric sprays are obtained (see Fig. 7b). The effect on combustion is displayed in Figs. 7c,d. Whereas the regular sprays of the single guide nozzle produce little soot, the short irregular ones ignite close to the nozzle and produce large amounts of soot due to short penetration depths and bad mixing (Fig. 7c). In contrast, the dual guide nozzle establishes a highly symmetric clean combustion pattern of all its sprays (Fig. 7d). This is corroborated by tail pipe measurements shown in Fig. 8. A good dual guide nozzle produces less than 50% soot in the relevant part load test region compared to a single guide nozzle. It must be noted, however, that the dual guide nozzle must be machined.

![Graph](Bosch Number vs BMEP)  

Fig. 8  Soot emissions of nozzles of single and dual guide CR injectors, \( n = 2000 \text{ 1/min} \)  

(A) Nozzle with dual guide, badly machined  

(B) Nozzle with dual guide, well machined  

![Graph](OH Signal)  

Fig. 9  OH and soot signals during pilot injection and auto-ignition for a badly (A, high soot) and well (B, low soot) machined dual guide nozzle, respectively
to a very high degree of precision to give the desired results. If the second guide is not precisely manufactured these benefits may not be realized as demonstrated in Fig. 9. Although the bad nozzle ignites more readily (more OH near the nozzle) its penetration depth is shorter and more soot is produced due to even minute manufacturing deficiencies.

Effect of injection rate

At typical part load operation (n = 2000 1/min, IMEP = 3.2 bar) the piezo CR injector offers a reduction of 70% in soot emission and a few % in fuel consumption over the conventional CR injector, however, at the expense of an increase in engine noise. The reasons are clarified by the high speed combustion movies and the simultaneous OH and soot radiation measurements shown in Figs. 10 and 11. To avoid ambiguity the comparison was made with the identical nozzle operated with the conventional solenoid and the piezo actuator, respectively.

Due to the slower opening characteristics of the solenoid (see Fig. 6) the effective injection pressure over the nozzle holes during pilot phase is small and therefore fuel is deposited close to the nozzle at low spray speeds. Accordingly, autoignition takes place early and close to the nozzle since shear forces are low. (see Fig. 10, left hand side). Subsequently injected fuel is heated up very quickly due the hot combustion gases it penetrates and evaporates thus early. The spray loses inertia and hence penetration depth and mixing is poor. In consequence more soot is produced also in the piston bowl.

In contrast, the piezo actuator opens much faster so the pressure loss is small. The spray jets gain higher speeds and penetrate deeper into the chamber. Mixing takes place closer to the walls of the piston bowl encountering more air and autoignition is starting from a leaner mixture. Much more "homogenized" combustion results with lower soot emission.

This analysis is supported by the data in Fig. 11 where the effect of injection pressure on ignition of pilot injection was studied. At low injection pressures fuel will be deposited near the nozzle. Significant amounts of premixed charge are formed emitting high and steep OH signals on ignition. Due to the lack of air in the non-premixed part soot is formed already at ignition timing. (see Fig. 11, A)

At high injection pressures the premixed mass is spread out over a larger volume at higher strain rates. Mixing is better and autoignition takes place in leaner, more homogenized regions. Hence OH signals are much smaller and less steep. However, during the start of the main injection (about TDC) the slope of the OH signal is much higher indicating a faster overall combustion rate due to better mixing.

This explains why the noise level increases when using a piezo injector inspite of a successful pilot injection. The same effect is observed also if the injection rate is increased at the same injection pressure. This apparent disadvantage of the piezo operated CR injector is a challenge for further optimising its operational characteristics. Preliminary results are very encouraging when proper pilot injection and rate shaping strategies are taken into consideration. Due to the convenient electrical control of a piezo actuator no major problems are foreseen to utilize the full potential of such a system in future engines even with respect to noise reduction.
CONCLUSIONS

A fundamental study has been conducted to clarify the differences in smoke and noise emission as well as fuel consumption between solenoid and piezo operated CR injectors. The following conclusions may be drawn:

1) increasing the injection pressures and/or injection rates reduces smoke emission very effectively.

2) higher rail pressures and/or higher injection rates increase engine noise.

3) the symmetry of the overall spray pattern of a nozzle has an major influence on smoke emissions. Non-symmetric sprays produce more than twice the soot levels obtainable by symmetric sprays.

4) symmetric sprays can be obtained only by well machined nozzles with much lower tolerances than currently accepted and by introducing a dual guide.

4) piezo operated CR injectors have a promising potential for meeting emission standards beyond EURO III if proper injection strategies are envisaged.

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REFERENCES


