

Diesel Emission Characteristics Using High Injection Pressure with Converging Nozzles in a Medium-Duty Engine

Prashanth Karra and Song-Chang Kong

Iowa State University

Copyright © 2008 SAE International

ABSTRACT

Effects of high injection pressure and converging nozzles on combustion and emissions of a multi-cylinder diesel engine were investigated. The engine uses a common-rail injection system that allows a maximum injection pressure of 200 MPa. Various injection pressures were tested to explore the benefits of high injection pressure in achieving low exhaust emissions in diesel engines. Injectors used in this study include conventional straight-hole nozzles and converging nozzles with a K factor of 3. Parametric studies were performed including variations in injection timings, number of injection pulses and EGR levels. It was found that low temperature combustion can be achieved by using high EGR with 1) late single injection or 2) double injection with an early pilot and a late main injection. Investigations revealed that high injection pressures significantly reduced soot emissions with an increase in NO_x emissions under conventional injection timing ranges. However, under late injection conditions (i.e., SOI=5 ATDC), an increase in the injection pressure from 150 MPa to 200 MPa did not result in further soot reduction. The use of injectors with converging nozzles allows achieving a higher injection pressure due to better flow coefficients. However, the effect on overall emission reduction was not significant for the converging nozzle used in this study.

INTRODUCTION

Diesel engine manufacturers are facing challenges in exhaust emissions mandates. New standards require simultaneous reduction in various exhaust emissions including particulate matter (PM), nitrogen oxides (NO_x), hydrocarbon (HC) and carbon monoxides (CO). For example, the US EPA 2010 mandates for on-road heavy-duty diesels include a 0.268 g/kW-hr limit on NO_x, a 0.0134 g/kW-hr limit in PM and a 0.188 g/kW-hr limit on non-methane hydrocarbons (NMHC)[1]. For non-road diesel engines with a rated power between 56 and 130 kW, the Tier 4 emissions standards are 0.40 g/kW-hr for NO_x, 0.02 g/kW-hr for soot, 5.0 g/kW-hr for CO, and 0.19 g/kW-hr for NMHC. The emissions challenge is

further compounded by the request in improving fuel economy by customers.

Many approaches have been proposed to reduce emissions including both in-cylinder control and after-treatment. Methods for in-cylinder control encompass exhaust gas recirculation (EGR), air management and flexible fuel injection schemes. Particulate filters and NO_x reduction catalyst have also been tested as after-treatment devices. This study will focus on the use of high injection pressures and novel fuel injection schemes with various levels of EGR for in-cylinder control.

EGR has been demonstrated to reduce NO_x emissions by lowering combustion temperatures. However, soot emissions increase as the amount of EGR is increased to a moderate level. It was found that soot emissions could be reduced if a high level of EGR was used [2]. The critical EGR levels beyond which soot starts to decrease depends on the engine configurations and fuel injection parameters. In other words, high EGR can be used as a means to reducing soot and NO_x simultaneously without the need of implementing after-treatment devices.

Low temperature diesel combustion was achieved by using high EGR (up to 60%) for various engine loads (up to 50%) and injection timings [3]. Appropriate levels of EGR can be used to achieve premixed charge compression ignition (PCCI) combustion. Boyarski et al. demonstrated that EGR along with well controlled intake temperatures could provide stable steady state combustion [4]. Okude et al., using high levels of EGR and a reduced compression ratio, were able to achieve optimal spray targeting for rapid mixing before the start of combustion. The rapid mixing produced very low NO_x and PM emissions [5].

Simultaneous soot and NO_x reductions were also obtained by using 55% EGR while fuel injection timings were adjusted such that combustion started at top-dead-center [6]. It was proposed that sufficient mixing time (interval between the end



Documents

Document Sharing Hub

of injection and the start of combustion) was needed to achieve low soot and NOx emissions [7]. The above study also used high EGR (70%) to properly phase combustion with very early injection timings (60 BTDC). Various multiple injection configurations were also used for high load and high speed operations for a heavy-duty diesel engine [8].

Another important method of reducing emissions is by enhancing the mixing by using high injection pressure [9,10]. High pressure injection combined with micro hole nozzle increases turbulent mixing for better fuel vaporization and soot reduction [11]. It appears that high fuel injection pressures, small injector nozzle holes and reduced injection duration (due to the high injection pressure) with appropriate spray targeting were important in soot reduction. High levels of EGR with appropriate equivalence ratios were important in NOx reduction. Thus, using high injection pressures with high EGR can potentially reduce the soot and NOx simultaneously.

There are many other studies that deal with diesel emissions reduction. Different strategies were studied including fuel effects [12,13], variable valve timing [14], near-stoichiometric combustion for the use of three-way catalyst [15].

This study aims at using high EGR and high injection pressure in a multi-cylinder, turbocharged, production diesel engine for simultaneous PM and NOx reductions. EGR gas will be cooled and different injection strategies along with different injectors will be investigated.

EXPERIMENTAL SETUP

Experiments were performed using a John Deere 4045HF475 off-road 4-cylinder 4.5 L engine. The engine is rated at 129 kW at 2400 rpm. Detailed engine parameters are given in Table 1.

Table 1 Engine specifications

Engine	John Deere 4045 HF475 4-cylinder 4-valve direct injection
Bore and Stroke (mm)	106 x 127
Total engine displacement (L)	4.5
Compression Ratio	17.0:1
Valves per Cylinder Intake/Exhaust	2 / 2
Firing Order	1-3-4-2
Combustion System	Direct Injection
Engine Type	In-line, 4-stroke
Aspiration	Turbocharged (located on engine)
Injection System	Common Rail
Piston	Bowl-in-piston

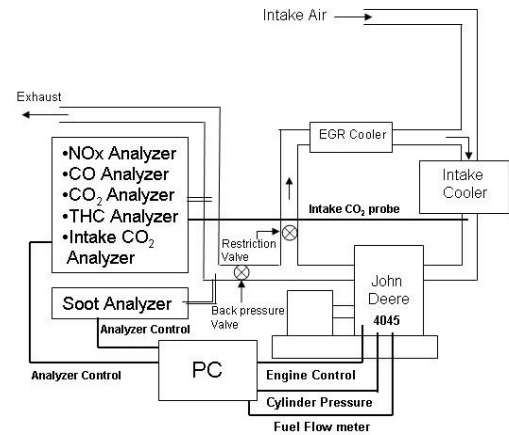


Figure 1 Schematic of the engine test facility.

As shown in Figure 1, exhaust gas is re-circulated into the intake using the back pressure created by a valve in the exhaust pipe. The exhaust gas flows through a heat exchanger before entering the intake. The mixture enters the turbocharger and then goes through an intercooler for further cooling. The charge entering the cylinder is maintained at 23°C for all the EGR levels. A probe placed just after the intercooler takes the sample of the intake charge to measure CO₂ in the intake manifold (to measure EGR CO₂ %). The present analyzer is capable of measuring both intake and exhaust CO₂ simultaneously using different probes. The following formula is used to calculate the EGR percentage,

$$EGR\% = \frac{[CO_2]_{\text{intake}} - [CO_2]_{\text{atm}}}{[CO_2]_{\text{Exhaust}} - [CO_2]_{\text{atm}}} \quad (1)$$

The gaseous emissions were measured using a HORIBA MEXA 7100DEGR emissions analyzer. The emission data recorded were CO, CO₂, NOx, THC, O₂ and EGR CO₂. The smoke number was measured using an AVL 415S soot meter.

The cylinder pressure was measured using a Kistler 6125B piezo-electric transducer. The signal was amplified using a Kistler 5010 charge amplifier. The cylinder pressure was measured every 0.1 crank angle.

EXPERIMENTAL CONDITIONS

Emissions tests were performed at 1400 rpm which is the engine speed that produces the peak torque. The injectors were manufactured by Denso. The injectors tested include 6X133X1200, 6X133X800 and 6X133X800 with a K-factor of 3. In the above notation, the first number defines the number of holes on the injector tip. The second number indicates the included spray angle. The third number indicates the flow number which has the units of cc/min. Here, K factor is defined as $100(D_{\text{in}} - D_{\text{out}})/L$ with $L=0.8$ mm.

Table 2 gives detailed descriptions of the variables that were tested. Most, but not all, combinations were tested, as either combustion did not sustain at certain cases or it was not

necessary to test certain conditions due to apparently high emissions. Among the conditions that were not tested were:

1. 5 ATDC for single injection at high EGR and/or low injection pressures such as 100 MPa due to combustion instability.
2. Zero percent EGR conditions were not tested for nozzles with k-factor 3 as those conditions would yield very high NOx emissions.

A fuel mass of 50 mg/injection was injected. The engine was controlled and monitored using DevX software provided by John Deere.

Table 2 Test matrix in this study

Main SOI	-20 to 5 ATDC
Pilot SOI	-40 to -15 ATDC
EGR	0% to 30%
Injection pressure	100 to 200 MPa
Injectors	6X133X1200 (d = 181 μ m) 6X133X800 (d = 148 μ m) 6X133X800 K= 3
Pilot fuel	15%, 25%, 40%

RESULTS AND DISCUSSIONS

The emission results will be presented in the unit of g/kW-hr or g/kgf. The latter is used such that the experimental results can be readily used for model validations. The Tier 4 standards for the present engine are 0.4 g/kW-hr for NOx and 0.02 g/kW-hr for soot that are approximately equivalent to 2.0 g/kgf for NOx and 0.1 g/kgf for soot. Note that this study will emphasize on soot and NOx emissions although CO and HC emissions were also measured in the experiments. Effects of CO and HC emissions are reflected in the BSFC data that will also be shown.

6X133X1200 INJECTORS

Effects of Injection Pressure

Results of using the “6X133X1200” injectors will be presented in this section. Figure 2 shows the NOx emissions at different injection pressures for single injection with 0% EGR. The increase in injection pressure from 100 MPa to 150 MPa and 200 MPa increased NOx emissions. This can be attributed to the increase in spray velocity at higher injection pressures leading to better atomization. Higher injection velocities (because of higher injection pressure) will lead to more rapid premixed burn and a higher local temperature which will increase NOx emissions.

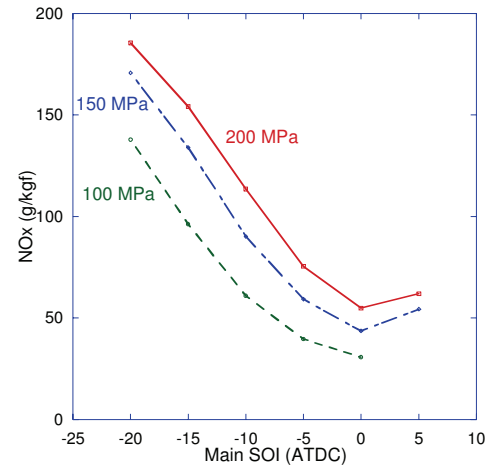


Figure 2 NOx Emissions at different injection pressures for single injection with 0% EGR.

Soot emissions shown in Figure 3 were found to be the lowest for the 200 MPa injection pressure. As mentioned earlier, high injection pressures can help attain better combustion of fuel which will result in low soot emissions. With this type of injectors, only the cases with start of injection at 5 ATDC for injection pressures 200 MPa and 150 MPa were able to achieve the Tier 4 soot emission standard.

Figures 4 and 5 show the emissions and BSFC data in g/kW-hr. In general, a high injection pressure will reduce soot emissions with an increase in NOx emissions, as expected. However, the effect of using a 200 MPa injection pressure for SOI 5 ATDC in soot reduction is found to be insignificant. The effects of ultra-high injection pressure in soot reduction in the low-temperature combustion regimes will require further investigations.

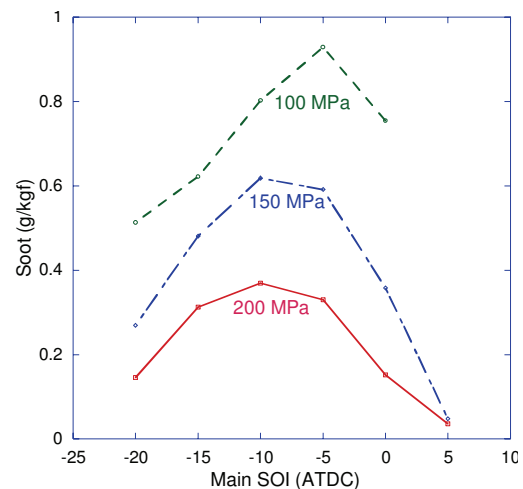


Figure 3 Soot emissions at different injection pressures for single injection with 0% EGR.

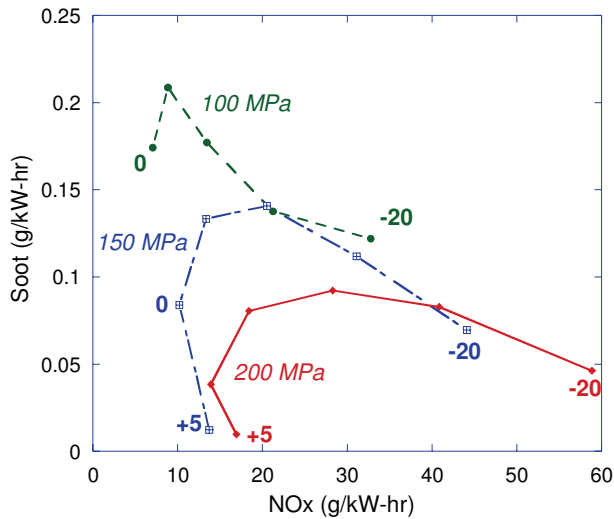


Figure 4 Soot vs NOx emissions at different injection pressures (single injection, 0% EGR). Numbers at the data points represent the injection timing.

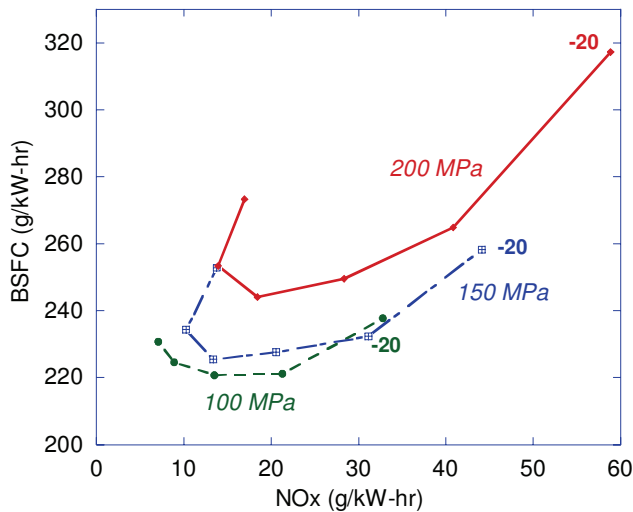


Figure 5 BSFC vs NOx at different injection pressures (single injection and 0% EGR).

Effects of EGR

Figures 6 and 7 show the comparisons of NOx and soot emissions between different EGR levels for 200 MPa injection pressure. As expected, EGR reduces NOx emissions but increases soot emissions. It can be seen that the low temperature combustion can be achieved by using high EGR with a late SOI (e.g., 5ATDC) for simultaneous soot and NOx reductions.

Among the tested cases, NOx emissions were the lowest when 30% of EGR was used. Among the cases studied using a 200 MPa injection pressure, SOI of 0 ATDC produced the least NOx emissions (5.4 g/kgf). For soot emissions, 0% EGR cases performed the best. Although the cases with 30% EGR produced the highest amount of soot, at retarded SOI (e.g., 0 ATDC), soot emissions were relatively low. It is thought that the combustion temperature was not in the soot formation

temperature zone explained by Kitamura et al. [16] thus reducing the amount of soot produced.

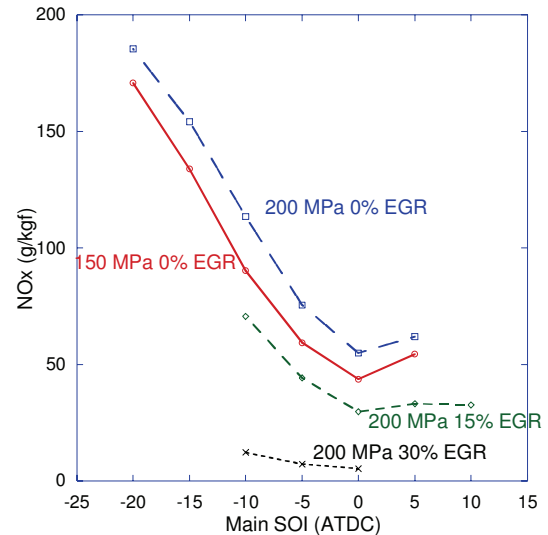


Figure 6 Comparisons of NOx emissions using different EGR levels.

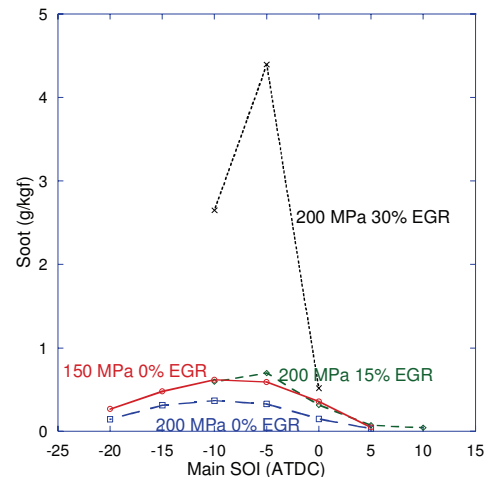


Figure 7 Comparisons of soot emissions using different EGR levels.

Effects of Double Injections

The double injection cases presented here used 25% pilot fuel. The SOI of the main injection was fixed at 0 ATDC which was found to result in the lowest soot and NOx emissions. The pilot SOI was varied between -40 and -15 ATDC, as shown in Figures 8 and 9.

NOx emissions were around 50 g/kgf for double injections for both injection pressures. Soot and NOx emissions are not very sensitive to the pilot SOI. It is thought that a majority of emissions may be produced by main combustion since the main SOI was not varied. The effects of high injection pressure on soot and NOx emissions using double injections are the same as those using single injections. Introduction of pilot injection does not seem to change the NOx levels significantly but does change soot levels. The soot levels changed with pilot injection especially when soot is compared at high injection pressures for single and double injections.

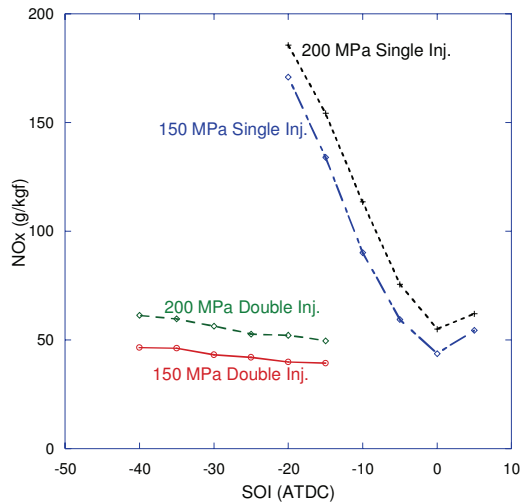


Figure 8 NOx emissions for 150 and 200 MPa injection pressures with single and double injections with 0% EGR. The double injection cases used 25% pilot fuel.

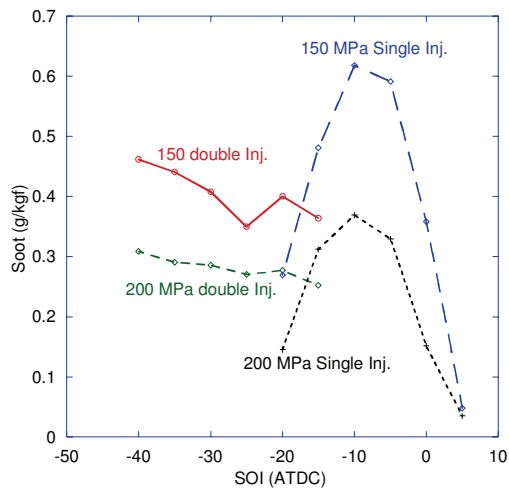


Figure 9 Soot emissions for 150 and 200 MPa injection pressures with single and double injections using 25% pilot fuel with 0% EGR.

Cylinder Pressure and Heat Release Rate

Figures 10 and 11 show the cylinder pressure and heat release rate data for two injection pressures of 150 and 200 MPa for SOI = -15 and 5 ATDC with 30% EGR. It can be seen that higher injection pressures result in slightly earlier ignition and higher cylinder pressures. Figure 11 shows that 200 MPa injection pressure also results in a higher heat release rate spike. This is believed to be due to better fuel atomization which, in turn, produces rapid combustion and reduces soot emissions.

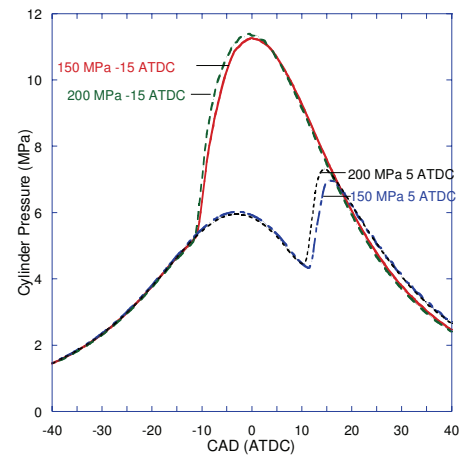


Figure 10 Comparisons of cylinder pressure at two injection pressures of 150 and 200 MPa at -15 ATDC and 5 ATDC SOI (30% EGR)

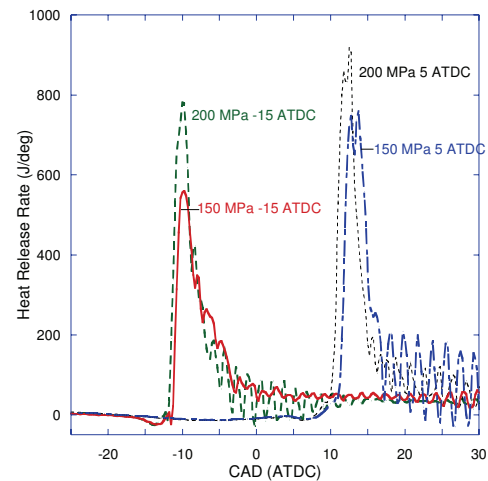


Figure 11 Comparisons of heat release rate data at two injection pressures of 150 and 200 MPa at -15 ATDC and 5 ATDC SOI (30% EGR)

Cylinder pressures and heat release rate data for double injection cases using 200 MPa injection pressure with 0% EGR are shown in Figures 12 and 13, respectively. It can be seen that low temperature heat release (i.e. cool flame) is very noticeable for pilot SOI at -40 ATDC, for both 25% and 40% pilot conditions. Such low temperature heat release is due to the long ignition delay during which cool flame chemistry releases a small amount of energy leading to ignition. By comparing results of pilot SOI at -40 ATDC and -20 ATDC, it can be seen that the case with pilot SOI at -20 ATDC produces a more stratified mixture resulting in rapid combustion and higher cylinder pressures. For the cases with pilot SOI at -40 ATDC, the mixture tends to be smoothed out due to the long ignition delay.