

Studies on the Impact of 300 MPa Injection Pressure on Engine Performance, Gaseous and Particulate Emissions

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ABSTRACT

An investigation has been carried out to examine the influence of up to 300 MPa injection pressure on engine performance and emissions. Experiments were performed on a 4 cylinder, 4 valve / cylinder, 4.5 liter John Deere diesel engine using the Ricardo Twin Vortex Combustion System (TVCS). The study was conducted by varying the injection pressure, Start of Injection (SOI), Variable Geometry Turbine (VGT) vane position and a wide range of EGR rates covering engine out NO_x levels between 0.3 g/kWh to 2.5 g/kWh. A structured Design of Experiment approach was used to set up the experiments, develop empirical models and predict the optimum results for a range of different scenarios. Substantial fuel consumption benefits were found at the lowest NO_x levels using 300 MPa injection pressure. At higher NO_x levels the impact was nonexistent.

In a separate investigation a Cambustion DMS-500 fast particle spectrometer, was used to sample and analyze the exhaust gas. The effect of the above engine variables on particle size distribution and total number was studied. Results indicate that increasing injection pressure has limited impact on the total particle number. The Air Fuel Ratio (AFR) however, appears to be a parameter that could be exploited for the control of particle number emissions.

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INTRODUCTION

The continued reductions of pollutants and the search of the best technology match for a given application promotes the research and development of both new and more mature technologies. The off-highway Tier 4 final legislation, [Table 1](#), can be met in different ways ranging from mainly in-cylinder emissions control to aftertreatment only solutions.

Table 1. Off-highway Tier 4 Final legislation

NO _x	PM	NMHC	CO
g/kWh	g/kWh	g/kWh	g/kWh
0.4	0.02	0.19	3.5

Over the years, a significant contribution to the development of low emissions combustion systems has been the ever increasing pressure capabilities of the fuel injection equipment. High injection pressure combined with very

refined combustion chamber geometries and air motion has achieved very low engine out regulated gaseous and PM emissions [[1](#), [2](#), [3](#)]. In this paper, investigations into the impact of very high injection pressures, up to 300 MPa, on engine performance and emissions are reported, and a range of scenarios discussed.

Many studies on particle size distribution and total number have been conducted and reported [[4](#), [5](#), [6](#), [7](#), [8](#), [9](#), [10](#), [11](#), [12](#), [13](#), [14](#), [15](#), [16](#), [17](#)], with a recent focus on legislative control of non-volatile particle emissions from both light-duty vehicle and heavy-duty engines made within the Particle Measurement Programme (PMP) [[10](#), [11](#), [12](#)]. As European legislation now acts to limit particle numbers (PN), see [Table 2](#), a part of this study's experimental work was focused on particle size, and especially on ways to control the level of engine-out PN.

Table 2. Total Particle number legislation for World Harmonized Stationary Cycle (WHSC)

Test Cycle	NOx	PM	NMHC	CO	PN
WHSC	g/kWh	g/kWh	g/kWh	g/kWh	1/kWh
	0.4	0.01	0.013	1.5	8.0×10^{11}

EXPERIMENTAL

A John Deere 4045 series 4.5liter 4-cylinder diesel engine was used for this study. The production diesel engine was modified with a TVCS swirl level cylinder head and piston bowls, [Figure 1](#). The detailed engine specifications are shown in [Table 3](#).

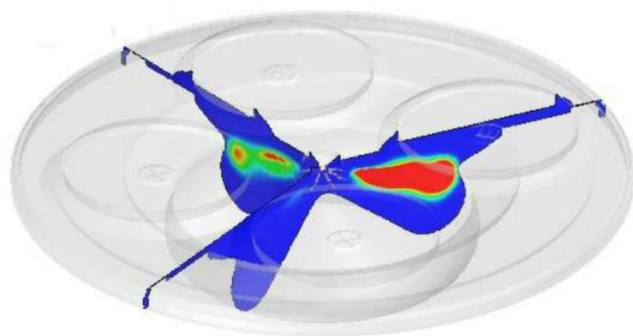


Figure 1. Piston bowl and fuel spray. Sprays shown counterclockwise starting from right, the first is positioned in line with the injector hole, the second 15° after another injector hole, and the third 30° after another injector hole (in the direction of swirl).

Table 3. Engine Specification

Displaced volume	4543 cc
Stroke	127.5 mm
Bore	106.5 mm
Compression ratio	15.5:1
Number of Valves	16
After treatment	None
Swirl Ratio	1.8 Rs
High Pressure Fuel Pump	Denso HP6s
Injectors	Denso G4
Number of Holes on Nozzle	7
Spray Cone Angle	141°
Nozzle Flow	760 cc/min

The engine was run with US ultra low sulfur diesel fuel during this study. The fuel properties have been summarized in [Table 4](#). The engine was maintained at a constant speed and torque condition while other parameters such as injection pressure, EGR and start of injection were varied. The detailed engine operating conditions are shown in [Table 5](#).

Table 4. Fuel Properties

Fuel	US ultra low sulfur diesel
Cetane Number	41
Sulfur level	< 15 ppm
Density	840 kg/m ³

Table 5. Engine operating conditions

Speed	2000 rev/min
Torque	454 Nm
Start of injection	0°ATDC to -8°ATDC
Injection Pressure	200 MPa to 300 MPa

All Particulate Matter (PM) mass emissions data shown are from measured values collected on a 70mm TX40 filter from a partial-flow dilution tunnel. The filters were allowed to stabilize in a controlled environment before being weighed according to current (2010) US legislative procedures. EGR rate reported was calculated from wet Carbon Dioxide (CO₂) concentrations measured in intake manifold and exhaust pipe.

A Cambustion DMS-500 fast particle spectrometer was used to sample raw exhaust gas. The DMS500 dilutes raw exhaust in two steps: close to the sampling point, then following transition down a thermally controlled sample line, a second stage of dilution is applied. In this study the overall dilution ranged from a dilution factor (DF) = 400 to DF = 800. Particle size distributions were, therefore, measured at fixed DF independent of exhaust flow. No additional steps for thermal conditioning, such as the use of a thermodenuder, evaporation tube or catalytic stripper, were employed. The instrument corrected particle number concentrations (#/cm³) to Standard Temperature and Pressure (STP) conditions before reporting them. The integrated accumulation mode particle number was calculated from the particle concentration and test cell exhaust flow.

Data collected on the DMS 500 was quality checked to ensure engine stability during sampling. The standard deviation of all the points collected during sampling period was calculated to check if the differences between size distributions were real or just test-to-test variability. The standard deviation for total PN was observed to be in the range of 2.8% to 4.9%, with an average standard deviation of 4%. The standard deviation for the accumulation mode PN was observed to be in the range of 4.2% to 8.7% with an average standard deviation of 5.5%. The standard deviation for accumulation mode mean diameter was observed to be in the range of 1.5% to 4.8%, with an average standard deviation of 2.5%.

The particle size distribution was observed to have two peaks which were classified into nucleation mode and accumulation mode. Nucleation mode was defined as particles less than 40 nm with a peak mean diameter close to 25nm. Accumulation mode was defined as particles larger than 50nm.

RESULTS

The results of the test data analyses have been divided into two main parts:

1. Overall engine performance and emissions study,
2. Detailed investigation of particle numbers and size distribution.

Where the first section describes the overall potential benefits of high, up to 300 MPa injection pressures, the second part focuses on identifying potential approaches to achieve low particle numbers.

Part 1. Impact of Injection Pressure on Engine Performance and Emissions

The impact of injection pressure on engine performance and emissions was studied using Design of Experiment (DoE) techniques. Test matrices were designed for a limited number of test variables. The variables were injection pressure, start of injection, EGR (to vary NOx) and vane position of variable turbine. Stochastic Process Models (SPM) were developed in parallel with the testing and validated for a range of response parameters such as Brake Specific Fuel Consumption (BSFC), NOx and Smoke. The developed models formed the basis for the optimized trade-offs shown below.

Historically, increased injection pressure has been an essential part of emission reduction. An increase from the current state of the art of 200 MPa to 300 MPa enables the final Tier 4 NOx levels to be achieved at manageable smoke levels. A reduction from 0.6 FSN to 0.3 FSN was observed at 0.4 g/kWh NOx, [Figure 2](#).

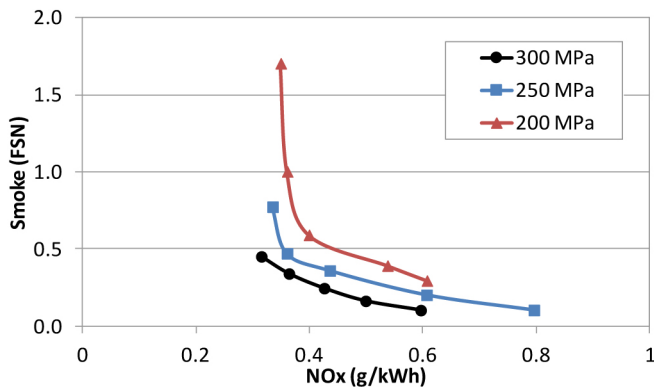


Figure 2. NOx - smoke trade-off at rated power (Fuel injection pressure shown in legend).

At higher engine out NOx levels, suitable for SCR equipped engines, the benefits in smoke at very high injection pressure are less pronounced. An increase in injection pressure from 200 MPa to 300 MPa reduces the smoke from 0.15 FSN to 0.10 FSN at a NOx level of 2.0 g/kWh, [Figure 3](#).

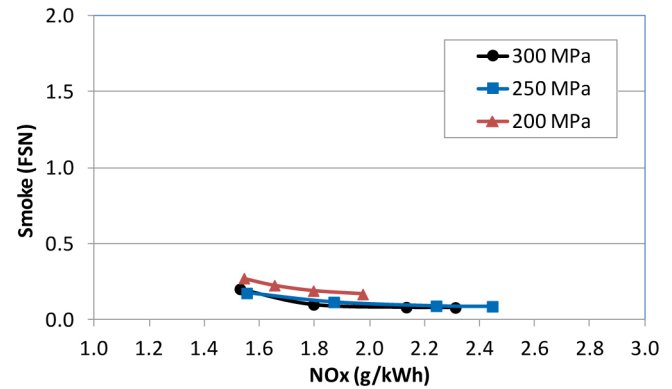


Figure 3. NOx - smoke trade-off at rated power (Fuel injection pressure shown in legend).

There are a number of potential emissions solutions available for final Tier 4, ranging from maximal in-cylinder NOx reduction and DPF to NOx exhaust aftertreatment only. Mainly dependant on application with importance of fuel economy or packaging constraints one solution is favored over another. For example a low emissions solution shown in [Figures 2](#) and [3](#) may be beneficial in applications where fuel consumption is not of highest priority due to usage profile and duty cycle.

The minimum fuel consumption for a given emissions level provides a more complete picture of the benefits with high injection pressures. The high pressure smoke reduction can be traded for an increased level of EGR and more advanced injection timing at constant NOx. Hence, increased injection pressure (above 200 MPa) substantially reduces the fuel consumption. At higher NOx levels there are less benefits with 300 MPa compared to 250 MPa, see [Figure 4](#). The gains in efficiency can be quantified and compared to the increase in cost associated with very high pressure injection systems.

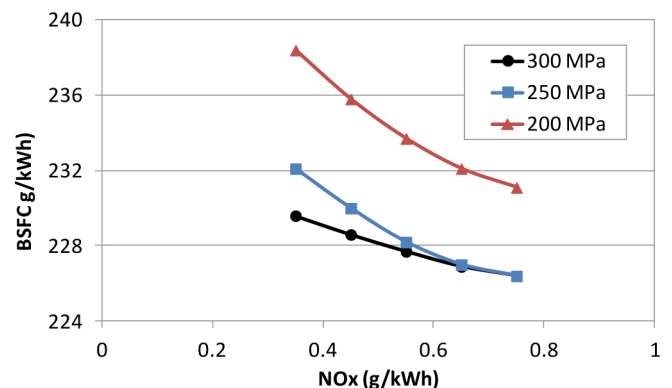


Figure 4. NOx - Fuel Consumption trade-off at rated power (Fuel injection pressure shown in legend).

The injection pressure trends were also investigated at other speed and load conditions, as well as using a more conventional combustion system.

geometry and swirl level) and alternative injection strategies. The results at higher loads were generally the same, giving a fuel consumption improvement at constant emissions. At lighter loads only limited or no benefits were found, [Figure 5](#).

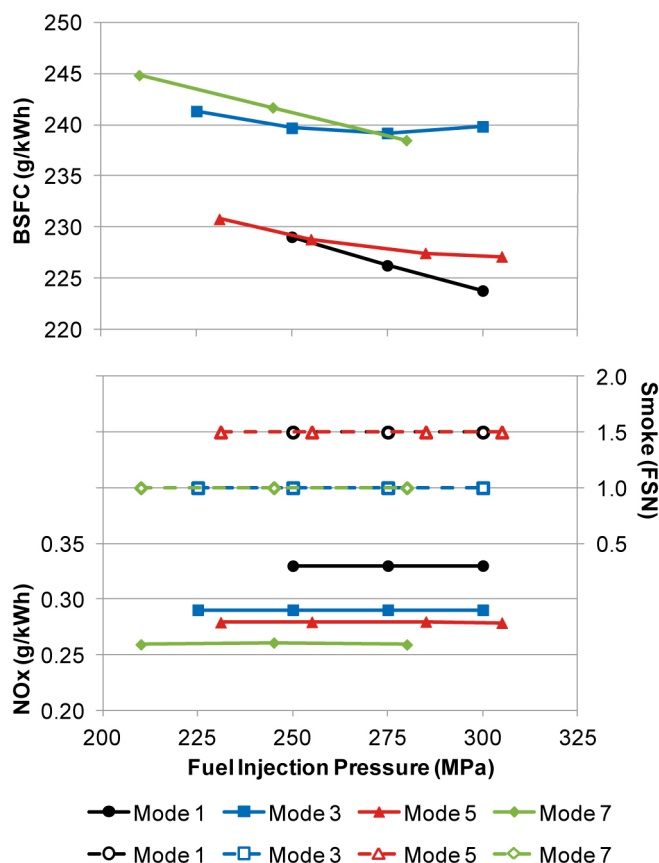


Figure 5. NOx - Fuel Consumption trade-off at a range of speed and load conditions from the 8-mode cycle. NOx and smoke are kept constant for each individual condition.

Based on the results from the available speed / load conditions included in the study, 8-mode tests were performed and the results shown in [Table 6](#).

Table 6. Results from 8-mode tests using 300 MPa fuel injection pressure

Test Cycle	NOx	Soot	BSFC
	g/kWh	g/kWh	g/kWh
8-Mode	0.36	0.092	251

Part 2. Detailed Investigation of Particle Numbers and Size Distribution

The work reported here was subdivided into three sections, the effect of SOI at constant AFR level, effect of SOI at constant FSN level and the effect of injection pressure at constant NOx level. In the following sections, particle size distributions plots on a linear-linear scale are shown to enable

small changes in peak height and mean diameter to be clearly seen.

The Effect of Start of Injection at Constant AFR Level

In this study the AFR was maintained at constant level of 21.4 whilst the SOI was changed from -8° ATDC to 0° ATDC. The corresponding results have been summarized in [Table 7](#). The BSFC at an SOI of 0° ATDC was 5.4% greater than that at SOI -8° ATDC. Retarded SOI produced hotter exhaust, due to the later combustion, which spins the turbocharger faster, resulting in a slightly higher air flow. The HC level was observed to be below 35 ppm throughout the SOI sweep.

Table 7. FIE and emissions data for SOI sweep at constant AFR at 2000 RPM and 454 Nm

Injection pressure	MPa	300	300	300
Start of injection	0° ATDC	-8	-4	0
Air Flow	Kg/h	444	455	468
FSN	-	1.57	0.96	0.25
AFR	ratio	21.4	21.5	21.5
EGR	%	31.6	31.6	31.4
NOx	g/kWh	1.06	0.87	0.75
Filter weight PM	g/kWh	0.54	0.31	0.09
BSFC	g/kWh	223	229	235

Particle size distribution results

Particle size distribution results, [Figure 6](#), showed dominant accumulation modes associated with soot agglomerates.

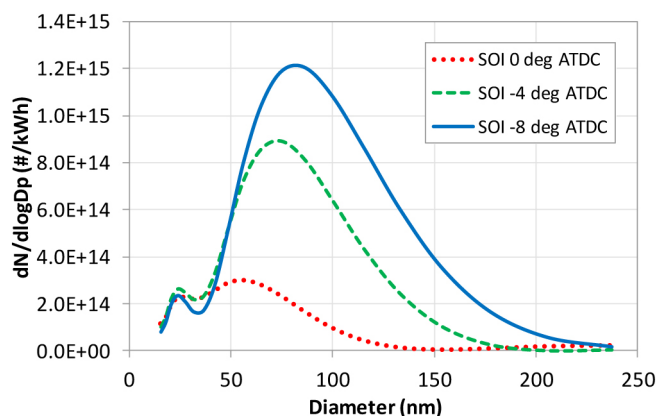


Figure 6. Particle size distribution - SOI sweep at fixed AFR

Also, as the SOI was retarded at fixed AFR, both the total PN and mean particulate diameter exhibited significant reductions, [Figure 7](#). This showed directional agreement with particulate mass from the filter measurements, [Table 7](#).

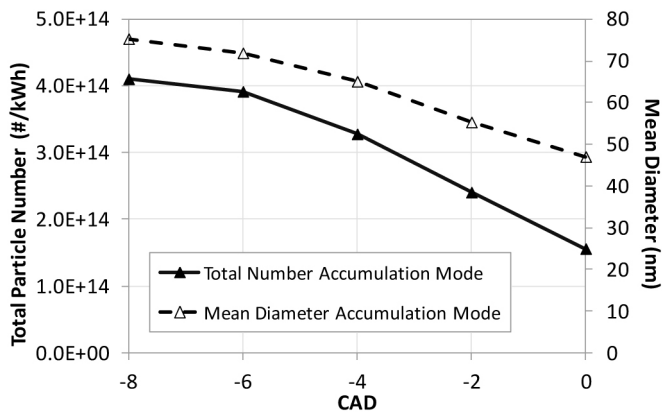


Figure 7. Particle mean diameter and total particle number for the SOI sweep at constant AFR

The particle number vs. diameter was converted into a particulate volume vs. diameter, Figure 8. The advanced SOI had a larger particulate volume at higher diameters, shifting the particle volume based mean diameter to a higher value than that based on the particle diameter. The area under these curves showed a directional agreement between volume integrals and the filter based mass shown in Table 7.

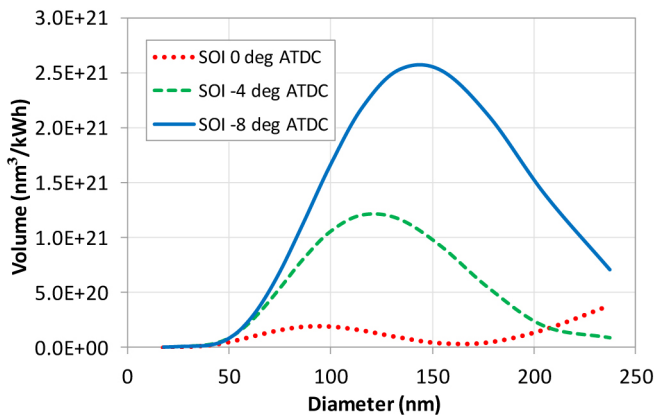


Figure 8. Particle volume distribution for the SOI sweep at constant AFR

Ignition delay

The ignition delay was calculated as the difference between the start of injection and start of heat release. No change in ignition delay was observed as the SOI was swept from 0°ATDC to -8°ATDC, Figure 9.

The Crank Angle Degrees (CAD) overlap between start of heat release and end of injection was calculated in order to identify differences in flame-spray interaction. No significant changes were observed in this overlap duration, Figure 9.

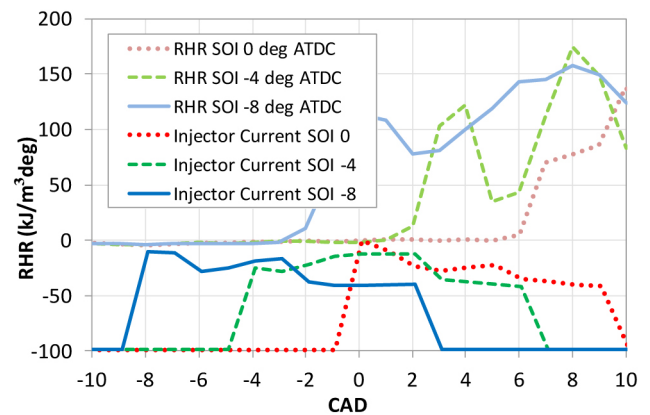


Figure 9. Ignition delay for the SOI sweep at constant AFR

In-cylinder pressures, temperatures and RHR

Initially, the SOI -8°ATDC conditions at higher injection pressure and temperature, as heat release is closer to TDC. Since the AFR and EGR level is same throughout the sweep, the higher PM for SOI -8°ATDC is believed to be partly due to a combination of lower air flow and mixing differences resulting from piston spray interaction. This is because all injection events were very close to TDC, where the vertical piston movement is minimal. The magnitude of FSN change observed was higher than that expected for spray targeting differences alone.

Studies have shown that high temperatures and pressures favor the soot initiation steps [13]. The higher temperatures, Figure 10, and pressures, Figure 11, observed at SOI -8°ATDC, due to the earlier heat release, Figure 12, are believed to be the primary cause for the higher level of PM and PN relative to 0°ATDC.

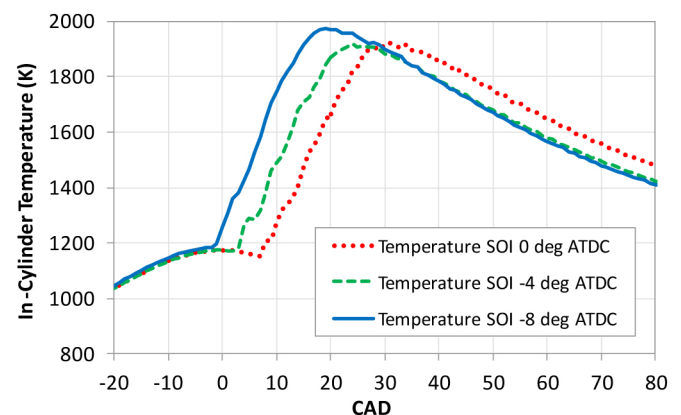


Figure 10. In-cylinder temperatures for the SOI sweep at fixed AFR