

Particle Size Distribution Measurements from Early to Late Injection Timing Low Temperature Combustion in a Heavy Duty Diesel Engine

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ABSTRACT

The use of early and late injection Diesel Low Temperature Combustion (LTC) strategies in the low to mid load operating range are becoming increasingly popular options for production Diesel engines to reduce oxides of nitrogen (NO_x) and particulate matter (PM) emissions. Although opacity-based filter smoke number (FSN) PM measurements in these operating conditions have been reduced to near zero for many instruments (which are standard and very useful in most engine combustion research laboratories), significant changes can still be seen in the particle size and number measurements (such as a 2.5 - 4.5 fold variation in total particle number concentration, depending on engine operating condition).

The current work presents particle size distribution measurements from early to late injection timing LTC, varying the start of injection (SOI) by three crank angle degrees (CAD) per data point, for two exhaust gas recirculation (EGR) rates, 45% and 50%. For all test points, the end of injection occurred before the initiation of the high temperature heat release. With both EGR rates, an increase in the PM FSN measurement could be noticed while retarding the injection timing from early-LTC, followed by a sharp decrease in PM upon further retard. Throughout these changes in injection timing test points, there was a strong correlation between PM FSN measurement and accumulation mode particles ($<50\text{nm}$). Analysis was also made of the total particle number concentration for each data point.

The earliest injection timing measured was limited by high in-cylinder pressure rise rate ($>22\text{ bar/CAD}$) for 45% EGR and high hydrocarbon (HC) emissions ($>10.5\text{ g/kg}_{\text{fuel}}$) for 50% EGR, while the latest injection timing for both EGR

rates was limited by decreases in indicated mean effective pressure (IMEP) greater than 10%. For early injection timings, a SOI was found with low NO_x and very low PM emissions ($<0.05\text{ FSN}$) before large increases in HC and carbon monoxide (CO) could be seen. The latest injection timing case (also with $<0.05\text{ FSN}$), exhibited large number increases in particles smaller than 100nm by up to an order of magnitude. Further emissions and combustion analyses were performed on these early and late injection timings.

INTRODUCTION

In recent years, many Diesel engine researchers throughout the world have contributed greatly to the reduction of engine-out particulate matter (PM) and oxides of nitrogen (NO_x) emissions in an effort to meet imposing governmental regulations in the most efficient ways possible. One means to meet the NO_x requirement has been the employment of exhaust gas recirculation (EGR). In conventional Diesel combustion strategies, increased EGR has been shown to cause the engine-out PM emissions to increase. However, further increases in EGR (reductions in intake oxygen concentration) to further reduce adiabatic flame temperature, accompanied by changes in injection timings, allow for a great reduction in PM emissions.[1,2,3] As a result, the potential for simultaneous reduction in engine-out PM and NO_x emissions has been found in comparison to conventional Diesel combustion. Many researchers have begun to refer to this operating regime as Low Temperature Combustion (LTC) because of its reduced adiabatic flame temperatures during the combustion process relative to conventional Diesel combustion.

Increased EGR results in increased hydrocarbons (HC) and carbon monoxide (CO) emissions. Further research has been

performed to decrease HC and CO emissions while maintaining very low levels of PM and NO_x emissions. Variation of injection timing has been one of the key tools used in optimizing LTC for simultaneous low PM, NO_x, HC, and CO emissions.[4,5] Minimal PM emissions operating conditions, at the minimum detection limits of most typical opacity-based measurement instruments, have been found for very early and late injection timings.[1,2,3,4,5] Other work has found that although the PM emissions at these engine operating conditions have reached the minimum detection limits of various opacity-based instruments, other instruments are able to capture the characteristics of the still existent PM emissions.[6,7]

Researchers have used particle size distribution measurements to better characterize conventional Diesel PM emissions for some time already.[8,9] Figure 1 shows a hypothetical break-down of a typical bi-modal particle size distribution from conventional Diesel combustion. One can find large soot agglomerates contributing to the accumulation mode (>50nm), with smaller core particles and volatile species constituting the nucleation mode (<50nm).

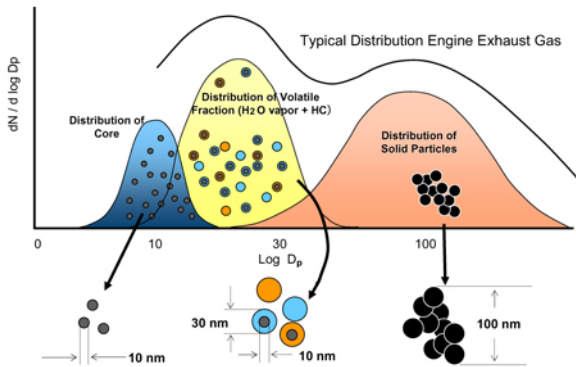


Figure 1. Conceptual Model of Conventional Diesel Particle Size Distribution [9]

The focus of the current publication is to help increase understanding of injection timing effects on particle size distribution measurements within the LTC regime. It is hoped that this additional information will not only be helpful to LTC engine researchers, but as well to after-treatment researchers expected to develop the most efficient post-treatment systems possible for all Diesel engine operating conditions.

EXPERIMENTAL SETUP

RESEARCH ENGINE

The research engine used was a single-cylinder, four-stroke, direct-injection Diesel research engine to more accurately control the combustion parameters than a multi-cylinder engine.[10] The 1.8 liter displacement of this engine is

characteristic of a medium to large heavy duty (HD) truck engine. Basic specifications of the engine are included in Table 1.

Table 1. Engine Specifications

Engine Type	Single cylinder Direct-injection 4 Stroke
Bore x Stroke [mm]	123 x 152
Displacement [liter]	1.806
Compression Ratio [-]	14.4:1
Valve Timing [°aTDC]	IVO 375 / IVC 535 EVO 147 / EVC 347

The main characteristics of the injection system are contained in Table 2 together with specific data related to the nozzle configuration used in this work. With this injection hardware, the common-rail fuel pressure for the main injection can be amplified by means of a hydraulic piston directly installed inside the injector.[11]

Table 2. Injection System and Nozzle Characteristics

Injection System	Common-Rail Pressure Amplified Piston Solenoid Injector
Injector Nozzle	Mini-Sac 7 x 0.190 mm
Nozzle Flow [cc/30s at 100bar]	840
Included Angle [°]	120

An oil-free screw compressor and air dryer were used to supply the engine with low-humidity intake air at a constant pressure. The intake air pressure was adjusted within the intake surge tank, while intake manifold temperature (after the EGR and fresh air mixing point) was controlled via heaters before the fresh air intake surge tank and inside the EGR surge tank. Engine back-pressure, such as that from a turbo-charger, was replicated by an electronic control valve after the exhaust surge tank. The EGR passed from the exhaust surge tank, was cooled, and mixed with fresh intake air between the intake surge tank and engine intake manifold. A schematic of the laboratory layout is included in Figure 2.

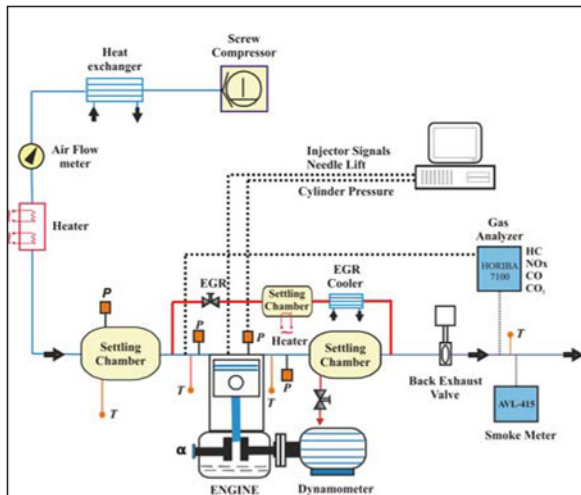


Figure 2. Schematic of Laboratory Layout

In-cylinder pressure traces were recorded with a piezo-electric transducer and averaged over 50 engine cycles. All engine operating condition information (temperatures, pressures, flows, etc.) were recorded at least three times for every test point. An additional daily reference point was measured at the start of each test session to ensure repeatability throughout the study.

The in-cylinder pressure values were post-processed by means of a combustion diagnosis code, CALMEC.[12,13] Valuable information can be extracted, especially the heat release (HR) and the rate of heat release (RoHR). The adiabatic flame temperature has been calculated at equivalence ratio equal to one and by considering a constant pressure at each step of the calculation, while 13 species were taken into account in the reaction following the scheme proposed by Way.[14]

The fuel injection rates for the cases presented in the paper were measured in a commercial test rig based on the Bosch system.[15] From those measurements, the actual injection duration and real start of fuel introduction into the combustion chamber were obtained. The ignition delay presented corresponds to the time elapsed from the actual start of fuel introduction until the start of the high temperature heat release (HTHR).

DIESEL FUEL

A commercially-available European Diesel fuel was used during this research. Due to the influence of fuel composition on Diesel combustion generated particulate matter emissions, this fuel was analyzed and its most relevant characteristics are summarized in [Table 3](#).

Table 3. Diesel Fuel Characteristics

Cetane Number	53.5
Sulfur Content [ppm]	8.9
PAH Content [% (m/m)]	1.3
T95 [°C]	356

The fuel sulfur and polycyclic aromatic hydrocarbon (PAH) content was maintained below current standards because of their significant influence on Diesel combustion generated PM emissions.[16,17,18,19,20]

ENGINE TEST CONDITIONS

An engine test plan has been designed to improve understanding of the effect of injection timing on particle size and number emissions within the LTC engine operating regime. Thus, the engine test conditions included in [Table 4](#) were selected.

Table 4. Engine Operating Conditions

Case	1	2
Speed [RPM]	1200	1200
IMEP [bar]	~7	~7
m_f [mg/cycle]	70	70
SOI [°aTDC]	-27→0	-33→-3
P_{injection} [bar]	1450	1450
EGR [% vol]	45	50
X_{O2,intake} [% vol]	13.7	12.1
Φ [-]	0.75	0.83
T_{intake} [°C]	45	45
P_{intake} [bar]	1.35	1.35
T_{exhaust} [°C]	365-418	365-410
P_{exhaust} [bar]	1.45	1.45

A baseline indicated mean effective pressure (IMEP) of 7 bar was selected because it corresponds to 25% of the production engine full load, and was still suitable for operating within the LTC regime. The IMEP varied by ± 0.5 bar depending on the given engine test point.

Increased EGR rate has caused a large reduction in intake oxygen concentration to obtain lower adiabatic flame temperature during the combustion process. Two intake oxygen concentration levels, 13.7% and 12.1% by volume, have been considered during this investigation. These intake oxygen concentrations are inside the range commonly observed in the frame of LTC research. [21,22,23,24,25,26,27]

Finally, very wide sweeps of injection timing were chosen at relatively small intervals, three crank angle degrees (CAD), to increase the data resolution throughout both test cases.

Earliest injection timings were limited by high pressure rise rates and high HC/CO emissions, while the latest injection timings were limited by unacceptable decreases in IMEP accompanied by increases in HC/CO emissions.

EMISSIONS MEASUREMENT

Four emissions measurement instruments were used in this research: gaseous emissions, opacity-based PM mass, two-stage exhaust dilution, and particle size distribution.

Gaseous and PM Mass Emissions

A Horiba MEXA 7100 was used for exhaust carbon dioxide (CO₂), CO, HC, and NO_x analysis. Two internal CO₂ analyzers permitted measurement of engine EGR rate. The engine intake CO₂ analyzer was also used to measure CO₂ concentrations after exhaust dilution to improve exhaust dilution ratio accuracy. An AVL 415 Smoke Meter was used to perform PM paper filtration and opacity-based approximation of the raw exhaust PM mass concentration.

Exhaust Dilution

Exhaust dilution is necessary before performing high precision PM measurements, such as particle size distributions, due to the volatile nature of raw Diesel exhaust. Therefore two-stage exhaust dilution was performed with a Dekati FPS-4000. [Figure 3](#) shows the dilution system and its exhaust system position in relation to other emissions measurement sample probes, which is similar to the one the author helped develop in previous research.[28,6] The dilution system was placed first so that sample line purging of the gas analyzer or smoke meter would not affect particle size distribution or dilution ratio measurements.

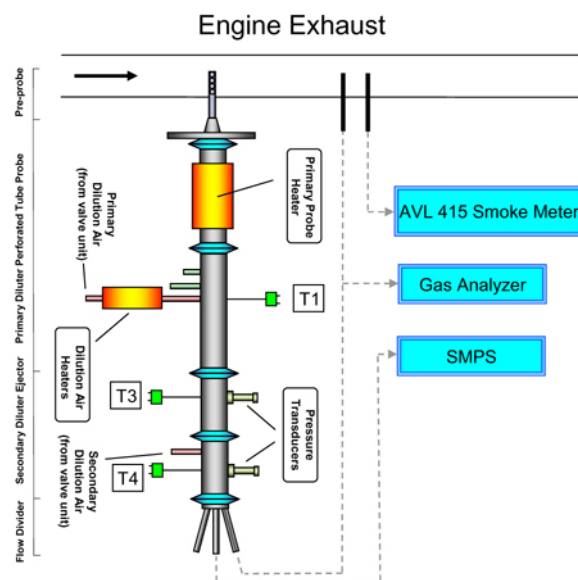


Figure 3. Two-Stage Dilution System and Layout of Sample Probes

With this system, the raw exhaust sample is extracted through a short isothermal heated pre-dilution probe and enters the perforated tube primary diluter. After a very short transfer time, an ejector diluter secondary dilution is performed.

Table 5. Exhaust Dilution Conditions

Case	1	2
EGR [% vol]	45	50
Exh. Sample T [°C]	305-340	295-325
Probe T [°C]	300	290
PDT Setpt. [°C]	300	300
PDT [°C]	195-230	180-200
SDT [°C]	28	28
TDR [-]	40	40, 65

Exh. Sample T: Exhaust temperature at diluter sample probe Probe T: Diluter sample probe temperature PDT Setpt: Set-point temperature of primary dilution air heater PDT: Primary dilution air temperature in diluter, just before dilution SDT: Secondary dilution air temperature TDR: Total dilution ratio

[Table 5](#) shows the exhaust dilution conditions used for the two engine cases studied. The sample pre-probe temperature was maintained just below that of the minimum exhaust sample point temperature, which varied with the various injection timings examined. For both cases, the primary dilution temperature (PDT) air heater was set to the maximum temperature recommended by the diluter manufacturer, 300°C. Isothermal primary dilution was attempted to reduce volatile specie concentration in an isothermal environment. However, the actual dilution air temperature inside the diluter, just before passing through the

perforated tube to mix with the exhaust gases, was reduced due to heat transfer losses during the transfer from the primary dilution air heater. The actual primary dilution air temperature, as recorded by the internal thermocouple 1 (T1), is displayed in Table 5 as PDT, which also varied slightly depending on exhaust sample point temperature. The secondary dilution was performed with a larger amount of ambient temperature air to conserve the PM characteristics. A total dilution ratio (TDR) of 40:1 was initially chosen based on particle concentration measurements from Case 1 to give good particle number resolution while maintaining a high enough TDR to avoid volatile condensation effects. However, the TDR had to be increased to 65:1 for some of the high PM injection timings of Case 2 to avoid the particle size distribution measurement instrument's high concentration alarm.

Particle Size Distribution Measurement

A TSI Scanning Mobility Particle Sizer (SMPS) 3936, composed of the TSI 3080L electrostatic classifier with a long Differential Mobility Analyzer (DMA) and TSI Condensation Particle Counter (CPC) 3010, was used to measure particle size distribution in the diluted exhaust. The distribution had a particle size range from 7.64 to 289 nm, with a 1 lpm sample flow and 10 lpm sheath flow. After testing multiple scan up and scan down times and seeing their effects on LTC PM, a scan up time of 100 sec and scan down time of 90 sec were selected. Particle size distribution data was graphed in units of $dN/d\log D_p$ (particle number/cm³), while utilizing the TSI SMPS multiple charge and diffusional loss corrections. Particle concentrations in terms of $dN/d\log D_p$ signify that the particle number concentration has been weighted by particle number (the instrument's base measurement), and normalized to one decade of particle size so that particle size distributions can be compared with other instruments independent of their channel resolution.[29]

Measurement Considerations

Measurements of particle size distributions from Diesel LTC can be a difficult task due to low PM mass and high volatile material concentrations. Therefore, extra measures were taken to remove as many measurement artifacts as possible. All injection timing sweep data for a given engine case were taken within the same test day. All transfer lines were made from electrically conductive silicone and stainless steel tubing to prevent particle charging or transfer losses. Transfer distances (engine exhaust port to exhaust sample point, sample point to dilution point, and dilution outlet to SMPS inlet) were all minimized to reduce residence time effects. The engine exhaust system was insulated and constructed of stainless steel. The EGR was maintained within $\pm 0.2\%$ of the desired rate for each case during measurements. A daily particle size distribution check was performed on the dehumidified and high efficiency particulate air (HEPA) filtered dilution air as well as a daily engine reference

operating condition before starting measurements. Accuracy of dilution ratio was verified with a CO₂ calculation before and after each size distribution measurement.

RESULTS

IN-CYLINDER ANALYSES

Instantaneous in-cylinder pressure data was recorded for each of the injection timings tested. Figure 4 shows the simultaneous increase in pressure rise rate and peak in-cylinder pressure for advancing injection timing. The rate of heat release (RoHR) also increased in peak value and slope, while RoHR peak width decreased. Though it may be difficult to see in the figure, a distinct low temperature heat release (LTHR) and HTHR were measured for all injection timings. Finally, the adiabatic flame temperature (Flame T_{ad}) was found to increase with injection timing advances, which can be attributed to advances in the RoHR and increases in the peak in-cylinder pressure. Data was recorded for every 3 crank angle degrees (CAD) in Cases 1 and 2, but some were removed in the graphs to better present the details of individual measurements.

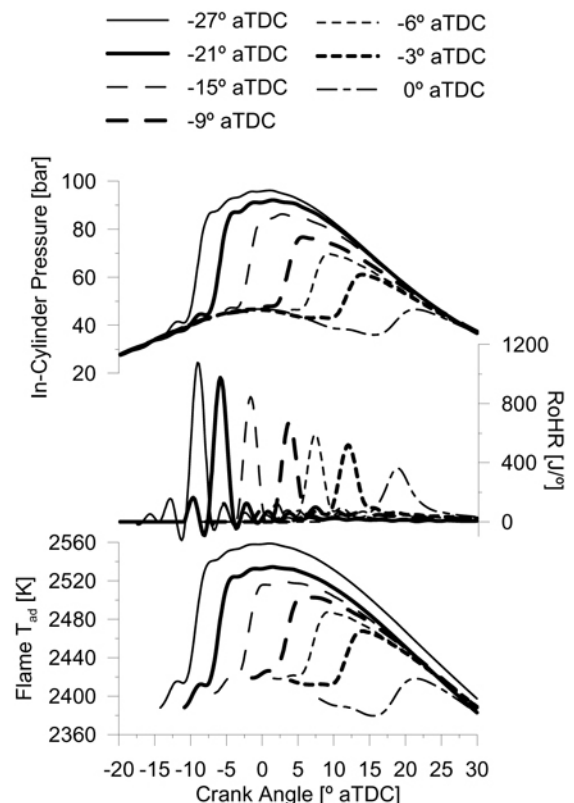


Figure 4. Instantaneous In-Cylinder Data for Case 1.

Figure 5 displays the effect of injection timing in Case 2 (increased EGR) on in-cylinder pressure, RoHR, and approximated adiabatic flame temperature. The same trends, as in Case 1, are still seen, with increases in peak in-cylinder