

Effect of Intake Oxygen Concentration on Particle Size Distribution Measurements from Diesel Low Temperature Combustion

2011-01-1355

Published
04/12/2011Francisco Payri, Jesús Benajes, Ricardo Novella and Christopher Kolodziej
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doi:10.4271/2011-01-1355

ABSTRACT

Concepts of premixed Diesel Low Temperature Combustion (LTC) have been shown to be advantageous in greatly reducing engine-out nitrogen oxide (NO_x) and particulate matter (PM) emissions, even below the minimum detection limit of standard opacity-based PM mass instruments. Previous research has revealed that significant changes to the PM size and number emissions still occur for changes to the LTC engine operating conditions. This work investigates the influence of reductions in intake oxygen concentration on PM (mass, size, and number), NO_x , hydrocarbon (HC), and carbon monoxide (CO) emissions from select LTC engine operating conditions.

Exhaust particle size distributions were measured for multiple engine operating conditions of premixed Diesel LTC within a range of five intake oxygen concentrations from 9% to 13% (by volume) at three intake pressures from 1.325 to 1.6 bar. For each intake oxygen concentration and intake pressure engine operating condition, particle size distributions were measured at the early-LTC injection timing of minimum PM mass concentration emissions. Reductions in inlet oxygen concentration limited the oxygen available during the combustion process. This prolonged the fuel and air premixing time before the start of combustion, and decreased the temperatures during the combustion process. At the early minimum PM injection timing (-27 and -24°aTDC , depending on intake pressure), decreasing engine intake oxygen concentration caused emissions of higher numbers of smaller particles. In addition, a comparison is made between the particle size and number emissions with the in-cylinder combustion processes and exhaust HC emissions for

reductions in intake oxygen concentration within the premixed Diesel LTC operating regime.

INTRODUCTION

Diesel internal combustion engines offer reduced specific fuel consumption in comparison to other types of internal combustion engines used for transport. Conventional Diesel engines have also been known for increased particulate matter (PM) and nitrogen oxide (NO_x) emissions, inherent to conventional diffusive (mixing-controlled) Diesel combustion. Progressively stricter emissions regulations of PM and NO_x emissions around the world have led to a great increase in combustion and exhaust aftertreatment research in recent years.

Local high temperature regions within conventional diffusive Diesel combustion engines have been shown to be the source of high NO_x emissions, while the combination of both high local temperature and fuel richness (both regarding conditions inside the flame) has been shown to be the source of in-cylinder PM formation. [1,2] Thus a great deal of research has been performed in recent years to combust Diesel fuel in internal combustion engines at lower flame temperatures and local fuel richness. [3, 4, 5, 6, 7, 8, 9, 10, 11] In these studies, premixed Diesel Low Temperature Combustion (LTC) engine operating conditions have been shown to simultaneously reduce in-cylinder flame temperature and local fuel richness through relatively higher rates of exhaust gas recirculation (EGR) and increased ignition delay compared to conventional Diesel combustion.

Although engine-out LTC PM mass concentration emissions have been shown to be greatly reduced in comparison with conventional diffusive Diesel combustion, it has been shown

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that LTC PM can have very different size, number, and chemical composition characteristics. [12, 13, 14, 15] It has also been demonstrated that these LTC PM characteristics can change appreciably within the LTC regime for changes to engine operating parameters (injection timing, injection pressure, swirl ratio, and intake oxygen concentration). [16, 17, 18]

Previous research with opacity-based PM mass instruments have shown the effects of reduced intake oxygen concentration (by use of real or simulated EGR) on engine-out PM mass concentrations from Diesel LTC. [8, 10, 19, 20, 21] In these publications, initial decreases in the intake oxygen concentration caused increased PM mass emissions due to decreased in-cylinder PM oxidation. But at some point, further decreases in intake oxygen concentration caused decreased in-cylinder PM formation and resulted in decreased overall engine-out PM mass emissions, possibly even below the minimum detection limit of the opacity-based measurement device. The intake oxygen concentration where the peak in PM mass emissions lied depended on many factors, but was shown in these publications to have existed between 9% and 14% intake oxygen concentration. This information has been useful in better understanding the overall engine-out PM mass emissions from Diesel LTC for decreases in engine intake oxygen concentration.

Past research has suggested that premixed Diesel LTC PM contains higher numbers of smaller and volatile particles. [12, 13, 14, 15, 16, 17, 18] Other research has indicated that smaller particle sizes could penetrate deeper into the human (or animal) respiratory system and change diesel particulate filter (DPF) filtration performance, while higher PM volatile content could affect DPF regeneration performance. [43, 44, 45] Therefore additional information about the size, number, and chemical composition of these particles still being emitted is needed. The goal of the current study is to analyze the effects of reductions in intake oxygen concentration (by use of EGR) on the particle size and number emissions from premixed Diesel LTC. The exhaust dilution strategy and particle size distribution measurements were performed in a way to best understand the particle characteristics as they existed in the exhaust stream. It is hoped that this information will not only be helpful to in-cylinder combustion researchers, but to after-treatment researchers as well.

EXPERIMENTAL SETUP

RESEARCH ENGINE

A single-cylinder Diesel research engine has been used in this study for better control and understanding of LTC concepts. Limiting the exhaust particle measurements to only one cylinder removed the complexities of particles formed from slightly different combustion conditions by other cylinders. Details of this engine are shown in [Table 1](#).

Table 1. Characteristics of Diesel Research Engine

Engine Type	Four-stroke, Direct Injection, Single-Cylinder
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 characteristics of the injection system and the injector nozzle used on this engine are shown in [Table 2](#). A hydraulic piston located inside the injector allows further amplification of the injection pressure above the pressure in the common rail. More details of this type of injector can be found in [22].

Table 2. Injection System and Nozzle Specifications

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

The engine test cell ([Figure 1](#)) is equipped with an intake air conditioning system that uses an oil-free screw compressor and dehumidifier to provide the desired engine intake pressure at reduced humidity. Sets of heat exchangers and electrical resistance heaters control the fresh intake air as well as the EGR flow loop temperatures before mixing to provide greater combustion and emissions measurement repeatability from day to day. Settling chambers are used in the intake, exhaust, and EGR lines to dampen pressure pulsations created by the single-cylinder engine and provide steady flows. An electronically controlled exhaust back pressure valve is used to drive exhaust gas into the high pressure EGR loop as well as simulate the effects of engine back pressure caused by a turbocharger normally used in production engines. The emissions measurement instruments were placed after the engine back pressure control valve, on the low pressure side of the exhaust system. The dilution system sample port was placed upstream of the gas analyzer and smoke meter sample ports so the particle size distribution measurements wouldn't be affected by purging operations of the other instruments.

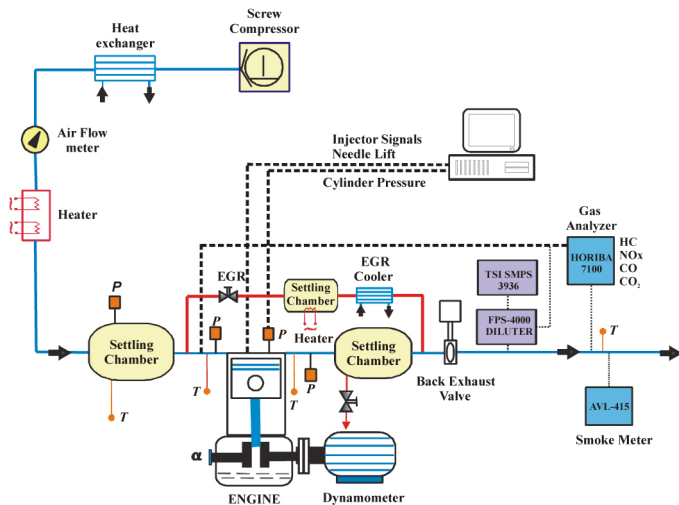


Figure 1. Layout of Engine Test Cell

An in-cylinder piezo-electric pressure transducer was used to record and average the pressure traces of 100 engine combustion cycles. The cycle averaged data (pressures, temperatures, flows, etc.), as well as the in-cylinder pressure averages, were recorded five times for each test point. An established engine reference condition was measured at the start of each test day to watch for changes in engine performance.

After testing, in-cylinder and cycle averaged data were post-processed with a 0D combustion diagnosis code, CALMEC. [23,24] This provided information of the combustion heat release. The adiabatic flame temperature was calculated by considering the maximum adiabatic flame temperature at an equivalence ratio equal to one, constant pressure at each step of the calculation, and taking 13 reaction species into account (as proposed by Way, et. al.).[25]

The fuel injection rate profiles for the tests discussed in this work were measured in a commercial test rig based on the Bosch system. [26] These measurements obtained the true fuel injection duration and actual fuel liquid start of injection (upon entering into the combustion chamber). Therefore calculation of the ignition delay could be performed from the true start of liquid fuel injection to the start of the combustion high temperature heat release (HTHR).

DIESEL FUEL

Relevant parameters of the commercially available Diesel fuel used in this study are shown in Table 3. Values of the fuel sulfur and poly cyclic aromatic hydrocarbon (PAH) content are shown because of their important influence on Diesel engine PM emissions.[27, 28, 29, 30, 31] All of these values comply with current commercial European Diesel fuel specifications.

Table 3. Test Fuel Properties

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

ENGINE TEST CONDITIONS

The engine operating conditions chosen to test the effects of engine intake oxygen concentration on LTC engine combustion and exhaust characteristics are displayed in Table 4. The base range of intake oxygen concentrations (9-13% in Case 1) was selected to be within the range of LTC where PM mass emissions have been shown by previous researchers to decrease due to reductions in PM formation from further decreases in intake oxygen concentration (increased EGR). [8,10,19, 20, 21] A maximum intake pressure of 1.6 bar at the minimum intake oxygen concentration of 9% was chosen based on what was believed could be attainable by a corresponding multi-cylinder development engine (with complete intake air management systems) for the given test engine load and speed. The resulting fuel-air equivalence ratio (Φ) of 0.88 at the 1.6 bar intake pressure and 9% intake oxygen concentration engine operating condition was set as the maximum equivalence ratio allowed in Cases 2 and 3. Therefore the intake pressures of Cases 2 and 3 were derived from the operating conditions which matched a 0.88 fuel-air equivalence ratio at each case's minimum intake oxygen concentration (10% in Case 2 and 11% in Case 3). The start of injection (SOI) was decided for each test case to be that of the early-injection LTC minimum PM mass emissions timing, -27°aTDC for Case 1 and -24°aTDC for Cases 2 and 3. It is believed that the SOI of minimum PM mass emissions advanced to -27°aTDC in Case 1 due to reduced liquid spray-piston surface interactions caused by the increased in-cylinder charge density at higher intake pressure.[17,18] Thus it is consistent that the particle size distributions and total number concentrations discussed later are those of the minimum PM mass emissions for each intake pressure and oxygen concentration setting. The engine exhaust pressure (upstream of the electro-pneumatic control valve) was set to approximately 0.1 bar higher than the engine intake pressure to drive the high pressure EGR loop and simulate the presence of a turbocharger.

Table 4. Tested Engine Operating Conditions

Case	1	2	3
Speed [RPM]	1200	1200	1200
IMEP [bar] *	7.25→7.53	7.28→7.46	~7.4
X_{O2,intake} [%_vol]	9→13	10→12	11→12
EGR [%_vol]	61.8→50.5	56.6→50.8	50.9→48.5
Φ [-]	0.88→0.71	0.88→0.78	0.88→0.82
m_{fuel} [mg/stk]	70	70	70
SOI [°aTDC]	-27	-24	-24
P_{injection} [bar]	1450	1450	1450
T_{intake} [°C]	45	45	45
P_{intake} [bar]	1.6	1.46	1.32
T_{exhaust} [°C]	324→335	349→353	372
P_{exhaust} [bar]	1.70	1.57	1.42

EMISSIONS MEASUREMENT

Gaseous and particulate exhaust emissions were measured by the use of four instruments: gas-phase emissions (CO₂, CO, HC, and NO_x), opacity-based PM mass, two-stage exhaust dilution, and particle size distribution.

Gaseous and PM Mass Emissions

Gaseous engine exhaust emissions of carbon dioxide (CO₂), carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) were measured by a Horiba MEXA-7100. The engine EGR rate was determined by coordination with the instrument's second CO₂ analyzer, which measured the CO₂ concentration in the engine's intake manifold.

Particulate matter mass concentration emissions were measured by an AVL 415 Smoke Meter. For a given exhaust sample volume, this instrument correlates the opacity (magnitude of reflected light) of filtered PM with an exhaust PM mass concentration. Thus the higher the mass of PM filtered on the standardized filter paper, the lower the level of light reflection detected off the filter paper, and the higher the correlated PM mass concentration.

Exhaust Dilution

It is necessary to dilute the exhaust gas sample (reduce the volatile species' saturation ratios) before sensitive particle size and number measurements can be performed.[32] A two-stage Dekati FPS-4000 exhaust dilution system made this possible. This study utilized a heated primary dilution and ambient temperature secondary dilution. The objective in this work was to perform the primary dilution as close as possible to isothermal with the exhaust conditions and use the maximum flow of ambient temperature secondary dilution air to cool and “freeze” the particle size and number characteristics.

Table 5. Two-Stage Dilution Properties

Case	1	2	3
P_{intake} [bar]	1.6	1.46	1.32
X_{O2,intake} [%_vol]	9-13	10-12	11-12
Exh. Sample T [°C]	237→266	269→276	279→293
Probe T [°C]	250→270	300	300
PDT Setpt. [°C]	350	350	350
PDT [°C]	121-148	148-170	139-165
SDT [°C]	22-26	21-34	25-34
TDR [-]	70-115	84-132	88-152

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 point

SDT: Secondary dilution air temperature

TDR: Total dilution ratio

The sample probe temperature and primary dilution temperature were set with respect to the exhaust temperature at the dilution sampling point. Since the exhaust temperature changed between each test, these adjustments to exhaust flow temperatures caused slight variations in the exhaust sample and primary dilution air volumetric flows entering the diluter. Precision of the primary dilution air flow was also dependent on the electronic selection of a combination of 5 differently sized flow orifices. The combination of these two factors contributed to the variations noticed in the total dilution ratios (TDR). Prior dilution ratio and primary dilution temperature tests of the sensitivity of LTC particle size distribution measurements determined that the variations seen at these high levels of exhaust dilution did not cause a statistically significant effect on the particle measurements.

Particle Size Distribution Measurement

The particle size distributions of the diluted exhaust were measured by a TSI Scanning Mobility Particle Sizer (SMPS) 3936, composed of the TSI 3080L long Differential Mobility Analyzer (DMA) electrostatic classifier and TSI 3010 Condensation Particle Counter (CPC). A 1 lpm sample flow and 10 lpm DMA sheath flow allowed for particle mobility diameter classification from 7.64 to 289 nm. Multiple electrostatic classifier scan up and scan down times, and combinations of both, were tested to ensure that a 100 sec scan up time and 60 sec scan down time were able to accurately capture the particle numbers of the entire particle size distribution. Units of dN/dlogDp (particles per cubic centimeter) signify that the particle concentrations have been number-weighted and normalized to one decade of particle size by the SMPS software. These normalized particle concentration units permit comparisons with other particle size distribution test instruments, independent of their

measurement channel resolution. Corrections for multiple particle charging and diffusional losses in the measurement system were also employed. [33]

Measurement Considerations

Particle size distribution measurement equipment and procedures were optimized to reduce the uncertainty of measuring what was possibly highly volatile LTC PM. All exhaust sample transfer lines were made of electrically conductive silicon or stainless steel to reduce particle charging and transfer loss effects. The engine exhaust system itself was also constructed of stainless steel and thermally insulated. Transfer distances between engine exhaust valve to dilution sample point, extraction of raw exhaust to primary dilution, between dilution points, and from exit of diluter to entrance of SMPS were minimized to reduce effects of residence time. The engine intake oxygen concentration was maintained within $\pm 0.1\%$ of the desired value during engine combustion and exhaust measurements. The particle size distribution of the filtered and dehumidified dilution air was measured daily before testing began, and subtracted from the tested LTC exhaust particle size distributions seen in the results section. Verification of the exhaust dilution ratio was performed between each engine test point by comparison of the CO_2 concentrations of the raw and diluted exhaust flows.

RESULTS

COMBUSTION ANALYSES

Instantaneous pressure data was recorded for each intake oxygen concentration of the three test cases. Figure 2, Figure 3, Figure 4 illustrate the effect of intake oxygen concentration on the in-cylinder pressure, rate of heat release (RoHR), and adiabatic flame temperature ($\text{Flame } T_{\text{ad}}$) of each test case. Each figure indicates that decreased intake oxygen delayed the start of combustion (SOC). The later SOC caused decreased pressure at top dead center (TDC). Reduced intake oxygen also simultaneously broadened the width and decreased the maximum height of the RoHR curves. All RoHR curves indicated the presence of low temperature exothermic reactions prior to the onset of the main combustion HTHR. Although adiabatic flame temperature curves had similar tendencies for each intake pressure case, reduced intake oxygen concentration caused the curves to appear at lower temperatures.

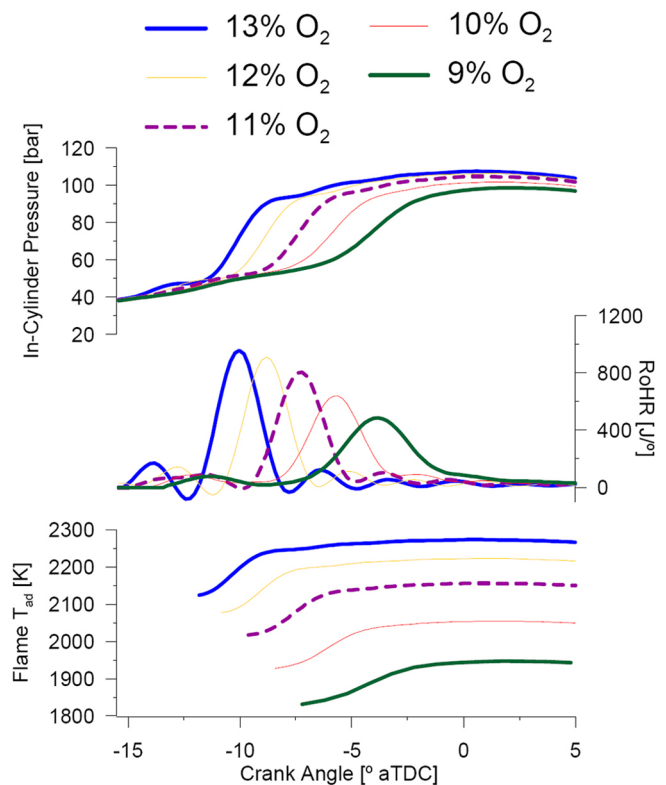


Figure 2. Instantaneous Combustion Data of Case 1 with 1.6 bar Intake Pressure and -27° aTDC SOI

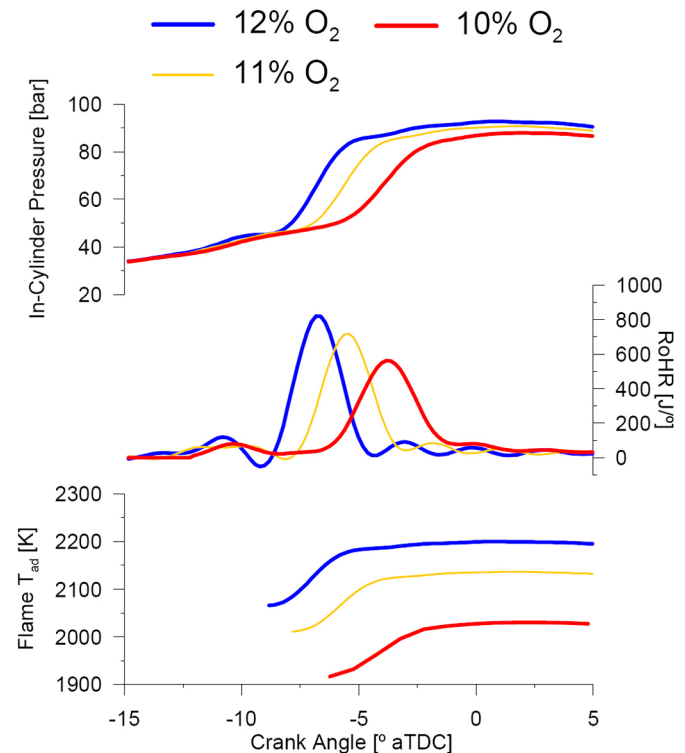


Figure 3. Instantaneous Combustion Data of Case 2 with 1.46 bar Intake Pressure and -24° aTDC SOI