

Effects of High Injection Pressure, EGR and Charge Air Pressure on Combustion and Emissions in an HD Single Cylinder Diesel Engine

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ABSTRACT

When increasing EGR from low levels to a level that corresponds to low temperature combustion, soot emissions initially increase due to lower soot oxidation before decreasing to almost zero due to very low soot formation. At the EGR level where soot emissions start to increase, the NO_x emissions are low, but not sufficiently low to comply with future emission standards and at the EGR level where low temperature combustion occurs CO and HC emissions are too high.

The purpose of this study was to investigate the possibilities for shifting the so-called soot bump (where soot levels are increased) to higher EGR levels, or to reduce the magnitude of the soot bump using very high injection pressures (up to 240 MPa) while reducing the NO_x emissions using EGR. The possibility of reducing the CO and HC emissions at high EGR levels due to the increased mixing caused by higher injection pressure was also investigated and the flame was visualized using an endoscope at chosen EGR values. In addition, flame temperatures and soot volume fractions were determined using two-color pyrometry.

A single-cylinder heavy duty direct injection Diesel engine equipped with an electronically controlled unit injector with variable needle opening pressure was used in the investigations, with geometry based on the Volvo D12C production engine but with the compression ratio reduced from 18.5 to 14.

The results from the studied cases showed that increasing EGR from 0 to 30% reduces both soot formation and oxidation resulting in higher engine-out soot emissions. Also, an increase in NOP for a case without EGR was found to give both high soot formation and high soot oxidation, resulting in reduced engine-out soot emissions. When EGR was added, increased NOP resulted in increased soot oxidation and thus in lower engine out soot emissions. An increase in NOP was also found to reduce HC and CO emissions at high EGR levels.

INTRODUCTION

The Diesel engine is the most efficient type of internal combustion engine, offering good fuel economy and low carbon dioxide (CO_2) emissions. Unfortunately, the diesel engine is also a source of particulate matter (PM) and nitrogen oxide (NO_x) emissions, both of which are subject to legislative limits because of their adverse effects on the environment and human health. In order to meet the requirements of future legislation, emissions of these substances, as well as those of carbon monoxide (CO) and hydrocarbons (HC), will have to be significantly reduced. This can be accomplished either by improving the combustion process or by using external devices, e.g. a De NO_x catalyst and/or a particulate filter. Ideally, the reduction in emission levels should be achieved without significantly increasing fuel consumption, thus avoiding undesirable increases in operating costs and CO_2 emissions.

One way to avoid both soot and NO_x emissions is to keep the local temperature during combustion below approximately 1650 K. Then both the NO and soot formation zones are completely avoided, regardless of the equivalence ratio [1]. This concept is referred to as Low Temperature Combustion (LTC) [e.g. 1, 2, 3, 4, 5] or Modulated Kinetic (MK) combustion [e.g. 6 and 7]. LTC is often achieved by using high levels of EGR. The most significant direct effect of EGR is the reduction in oxygen flow rate to the engine. This results in a reduced local flame temperature during combustion [8]. Unfortunately, LTC using high levels of EGR often results in problems with high CO and HC emissions and (thus) high fuel consumption [e.g. 1, 2, 5].

Henein et al [9] investigated the effects of injection pressure on low temperature combustion (with EGR levels between 60 and 64%), and found that increasing the injection pressure from 60 to 80 MPa led to a reduction in NO_x emissions, but further increases in injection pressure increased NO_x emissions. There was, however, a significant reduction in soot emissions. There were also slight increases in HC and CO emissions, and the cited authors concluded that higher injection pressures enhance the mixing, but increase the turbulence and cooling losses, with consequent temperature reductions that reduce NO formation but increase HC emissions.

The purpose of this study was to investigate the possibilities of shifting the so-called soot bump to higher EGR levels or to reduce the magnitude of the soot bump using very high injection pressures (up to 240 MPa) while reducing the NO_x emissions using EGR. The possibility of reducing the CO and HC emissions at high EGR levels due to the increased mixing caused by higher injection pressure was also investigated, as well as the effects of increasing the charge air pressure (CHP).

EXPERIMENTAL DETAILS

ENGINE – The research engine is a fully equipped two liter single cylinder engine manufactured by AVL with a cylinder head based on the geometry of a Volvo Powertrain D12C engine and a compression ratio of 14. Specifications of the engine and fuel injection systems are presented in Table 1.

Table 1 Engine and fuel injection system specifications

Engine	Single cylinder AVL 501
Cylinder head	4 valves, low swirl (swirl no app. 0.2)
Bore	131 mm
Stroke	150 mm
Displacement	2.022 l
Compression ratio	14
Fuel injection system	Electronically controlled Unit Injector (EUI)
Nozzle	6 orifices, spray umbrella angle: 152°
Injection pressure	Strain gauge
Max air flow, compressor	159 l/s
Max charge air pressure compressor	750 kPa

TEST CELL SET-UP AND EGR SYSTEM –The engine is equipped with an air conditioning system in which the intake air is compressed, dehumidified and then mixed with EGR, see Figure 1. The EGR is cooled by the engine's cooling water before entering the intake system. The temperature of the exhaust gas after cooling depends on the amount of EGR used and the engine load. In this series of experiments, the former typically varied between 65 and 80°C. The intake air temperature was kept at 25°C. By using a throttle in the exhaust pipe, the exhaust back pressure can be adjusted to simulate the effect of a turbocharger. For a more detailed description of test cell, see [1]

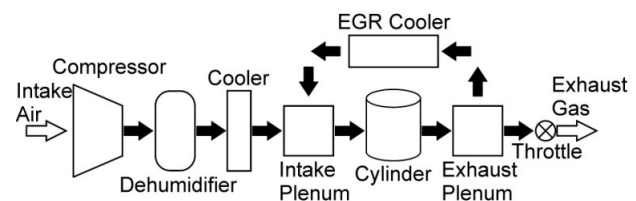


Figure 1 Air and gas management system

The amount of EGR was calculated from the CO₂ levels measured in the exhaust and intake systems. Engine out soot emissions were calculated from measured smoke number using an AVL 415 smoke meter, while NO_x, CO, CO₂ and HC were measured using an AVL Combustion Emissions Bench.

The global averaged in-cylinder temperature and the rate of heat release were derived from the cylinder pressure data.

To visualize the combustion, an AVL visioscope 1.1 was used together with a 30 degree endoscope and a PCO pixelfly CCD camera. Crank angle-resolved images were taken during consecutive engine cycles. Figure 2 shows a schematic diagram of the sprays observed during the measurements, and an image from the visioscope can be seen in Figure 3, showing the three sprays and the

injector. The AVL visioscope uses two color pyrometry to determine the flame temperature and soot level (or more precisely the KL factor; a product of an absorption coefficient and optical length that is often used as an indication of the instantaneous soot mass in the cylinder). This method is a line of sight method based on measurements of radiation at two wavelengths from which crank angle resolved flame temperature and the in-cylinder soot concentration can be estimated with the help of a number of assumptions. Furthermore, many factors can reduce the accuracy of the calculated temperatures and soot concentrations, such as soot deposition on the viewing window and non-uniform temperature and soot concentration distributions within the combustion chamber [10]. For more detailed information on the AVL visioscope and two color pyrometry, see [10 to 12]

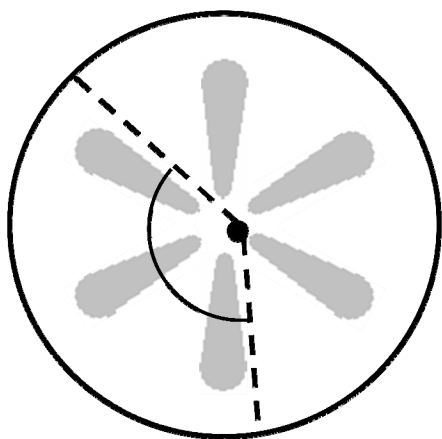


Figure 2 A schematic view of the observed sprays in the engine. The black dot indicates the position of the endoscope.

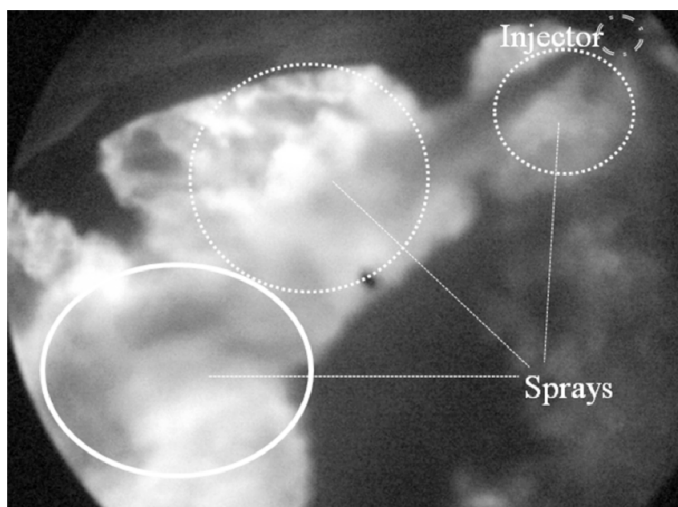


Figure 3 Image of actual view from the endoscope.

The crank angle resolved in-cylinder soot measurements presented below are averages over the entire image to capture the soot oxidation. The measurements are taken with an interval of 0.1 CAD and averaged for one CAD for both soot and flame temperature. The results presented here are averages of three measurements. In addition, when the flame is no longer visible no calculations can be made so the soot concentrations are shown as being zero despite the presence of engine-out soot emissions.

FUEL PROPERTIES - The fuel used in the experiments was Swedish MK1 diesel fuel (Environmental Class 1). Analysis of this fuel shows that it has a lower heating value of 43.1 MJ/kg, a C:H ratio (by mass) of 6.27, a cetane number of 51.2, a density of 814.5 kg/m³ at 15 °C, and sulfur contents < 1 mg/kg.

RESULTS AND DISCUSSION

The experimental matrix is listed in Table 2. An engine speed of 1500 rpm was used for all points, and the engine was run at constant load (25%). For the low EGR cases (0 - 40%), optical measurements were also made. Measurements were also made at higher EGR levels and at higher loads but due to problems with sooting of the endoscopic window, these results are not presented here. Engine inlet temperatures for the measurement points discussed below are listed in Table 3.

Table 2 Measurement points for engine experiments.

LOAD	SOI [CAD]	CHP [kPa, abs]	NOP [MPa]	EGR [%]
25% (74 Nm)	2 ATDC	150	175 240	0 - 50
		200	175 240	0 - 50

Table 3 Inlet temperatures for discussed measurement points.

LOAD	SOI [CAD]	CHP kPa, abs]	NOP [MPa]	EGR [%]	T _{in} [°C]
25% (74 Nm)	2 ATDC	150	175	0	25
				31	33
				42	39
				51	44
		240		0	26
				31	34
				42	38
				49	45
		200	175	0	25
				31	35
				41	41
				64	51

INCREASED EGR LEVELS - Since the trends are similar for the two injection pressures, only results obtained with a NOP of 240 MPa are presented here.

When the EGR level is increased from 0 to 30% (corresponding to a decrease in oxygen availability from 21 to 19%, see Figure 4), the NO_x emissions decrease significantly (by more than 80%), see Figure 5. According to Glassman, NO_x emissions are affected by both oxygen concentration and temperature, but reducing the temperature provides a more efficient way to reduce them than reducing the oxygen concentration. NO_x emissions are formed mainly in the post combustion gases but some are also formed in the flame zone [13]. John Dec [14] has shown that NO_x emissions are created mainly at the edge of the spray where the temperature is highest. This can also be seen in the temperature galleries in the Appendix, which show that flame temperatures are maximal at the edge of the sprays. Thus, both the maximum flame temperature and the global temperature are important for NO_x formation.

The temperature distributions of the flames, calculated using the AVL visioscope, show that an increase in EGR results in lower maximum flame temperatures, see Figure 6. Figure 7 shows that the global in-cylinder temperature is reduced during the early parts of the expansion stroke. This is a result of the reduced oxygen availability which lowers the maximum rate of heat release (Figure 8) leading to lower temperatures and consequently less NO formation. The increase in global temperature with 40% EGR (Figure 7) is a result of a larger injected fuel mass compared to 30% EGR, resulting in a larger heat release to keep the load constant with increased EGR despite the later combustion phasing (Figure 8).

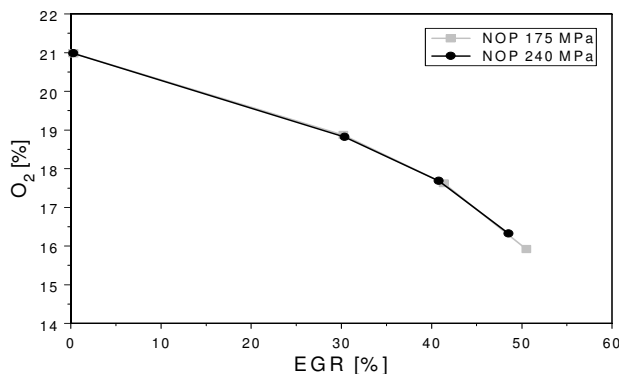


Figure 4 Oxygen concentration in the inlet as a function of EGR level for both needle opening pressures and a charge air pressure of 150 kPa [abs].

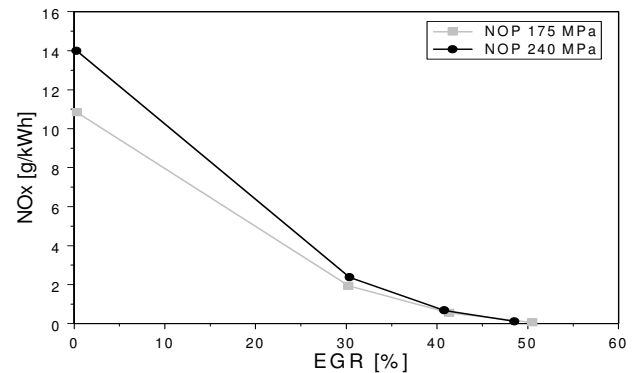


Figure 5 NO_x emissions as a result of increased EGR level for both needle opening pressures and a charge air pressure of 150 kPa [abs].

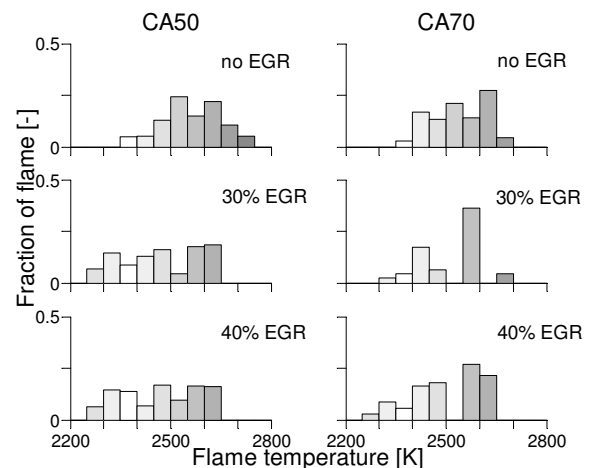


Figure 6 Temperature distribution in the flame (fraction of the flame in a given temperature interval) at 50 and 70% burned (CA50 and CA70) for three EGR levels, a NOP of 240 MPa and a charge air pressure of 150 kPa [abs].

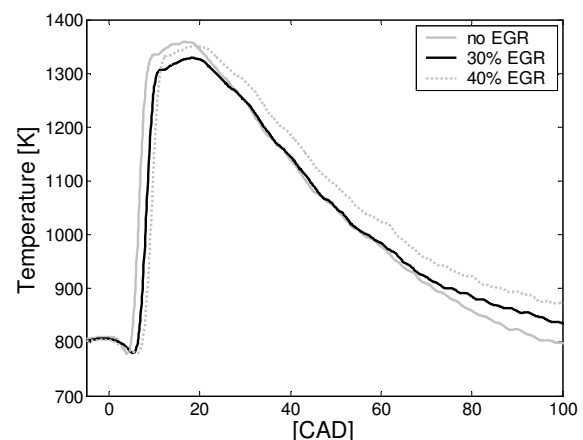


Figure 7 Global in-cylinder temperature in Kelvin for EGR levels of 0, 30 and 40%, with a NOP of 240 MPa and a charge air pressure of 150 kPa [abs].

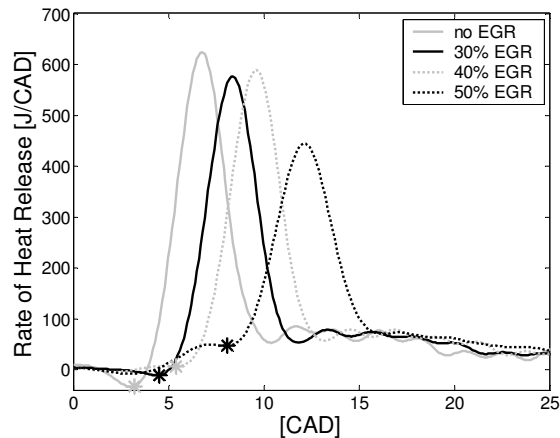


Figure 8 Rate of heat release in J/CAD for EGR levels of 0, 30, 40 and 50%, with a NOP of 240 MPa and a charge air pressure of 150 kPa [abs]. The stars indicate the start of main (high temperature) combustion.

Soot levels measured in the exhaust are very low for all cases illustrated in Figure 9. However, the soot concentrations calculated using the AVL visioscope data (the KL factor normalized with respect to density and averaged over 1 CAD across the images) show that soot formation is relatively high, but subsequent soot oxidation is also relatively high for the case with no EGR (see Figure 10). The high rates of soot formation and oxidation in this case are believed to be due to a short ignition delay, resulting in combustion at high local equivalence ratios since there is relatively little premixed combustion. This corresponds to a path through the upper part of the soot formation island in an equivalence ratio–temperature diagram, resulting in high soot formation, see Figure 11. However, it also results in high temperatures which, together with higher oxygen availability, are responsible for the high soot oxidation. The soot oxidation occurs around the NO formation area in Figure 11.

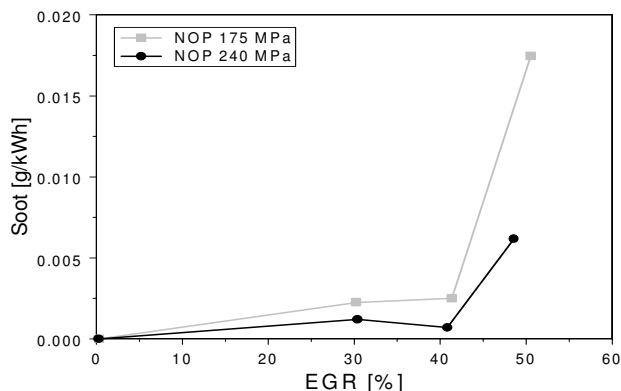


Figure 9 Engine out soot emissions as a function of the EGR level for both needle opening pressures and a charge air pressure of 150 kPa [abs].

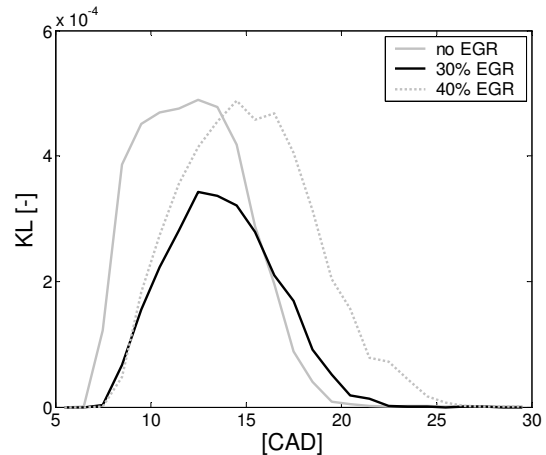


Figure 10 Image-averaged crank angle resolved soot concentrations calculated using the AVL visioscope data as a function of CAD for 0, 30 and 40% EGR, NOP of 240 MPa and a charge air pressure of 150 kPa [abs].

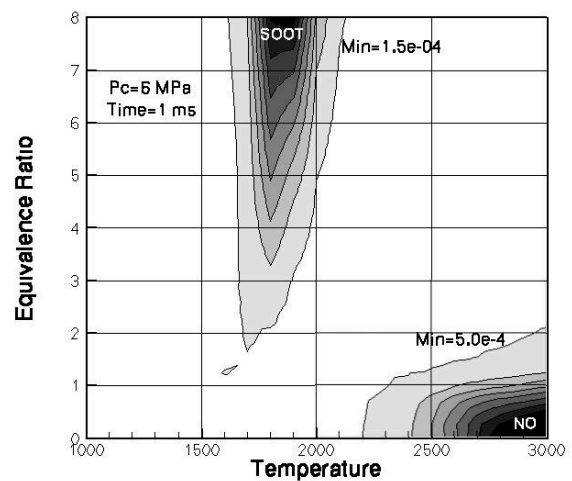


Figure 11 Soot and NO concentrations with no EGR as a function of local equivalence ratio and temperature after 1 ms. Soot in g/m³, NO in mole fractions and temperature in degrees Kelvin [1].