

An Empirical Study to Extend Engine Load in Diesel Low Temperature Combustion

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ABSTRACT

In this work, engine tests were performed to realize EGR-enabled LTC on a single-cylinder common-rail diesel engine with three different compression ratios (17.5, 15 and 13:1). The engine performance was first investigated at 17.5:1 compression ratio to provide baseline results, against which all further testing was referenced. The intake boost and injection pressure were progressively increased to ascertain the limiting load conditions for the compression ratio. To extend the engine load range, the compression ratio was then lowered and EGR sweep tests were again carried out. The strength and homogeneity of the cylinder charge were enhanced by using intake boost up to 3 bar absolute and injection pressure up to 180 MPa. The combustion phasing was locked in a narrow crank angle window (5–10°ATDC), during all the tests. The results indicate that a lower compression ratio helps to extend the engine load, while a combination of both intake boost and injection pressure is necessary to maintain low-NO_x and low-soot emissions, and to mitigate the fuel efficiency penalty. This research intends to identify the major parameters that affect diesel LTC performance and to provide guidelines for improving the performance of such combustion modes.

INTRODUCTION

Low-NO_x and low-soot emissions can be achieved simultaneously in diesel engines when operating in the low temperature combustion (LTC) mode [1–6]. The fundamental enabler for LTC is the separation of the fuel-injection events from the combustion process as highlighted in Figure 1 [7]. With multiple injections early in the compression stroke, the ensuing ignition delay provides the much-needed time for the fuel-air mixing and the formation of a cylinder charge with high homogeneity at the initiation of the combustion event. To prevent early auto-ignition that is usually characterized by high rates of pressure rise and even knocking combustion at high engine loads, exhaust gas recirculation (EGR) is usually applied to modulate the intake oxygen and to increase the heat capacity of the cylinder-charge that results in delayed combustion phasing with a prolonged ignition delay [3,8–10]. Such

homogeneous charge compression ignition (HCCI) combustion, however, lacks adequate controllability on the timing of the combustion events unlike conventional high-temperature diesel combustion, where the injection timing provides a direct control on the phasing of the combustion [11,12]. The HCCI combustion therefore, typically suffers from a lowered energy efficiency due to the off-phasing of the heat release from the crank angle window for best efficiency, normally reported as 5–10°CA after top-dead centre (ATDC) [3–8,13].

An alternate strategy to enable LTC cycles is to employ a single-injection near the TDC to which heavy amounts of EGR are usually applied to attain separation of the fuel-injection and combustion events [2,3,14–17]. While the EGR-enabled LTC allows improved controllability of the combustion phasing, however, the highly diluted combustion is prone to increased cycle-to-cycle variations that tend to escalate with the EGR application and typically result in unstable combustion and may also cause an excessive reduction in the fuel efficiency [2,15,18,19].

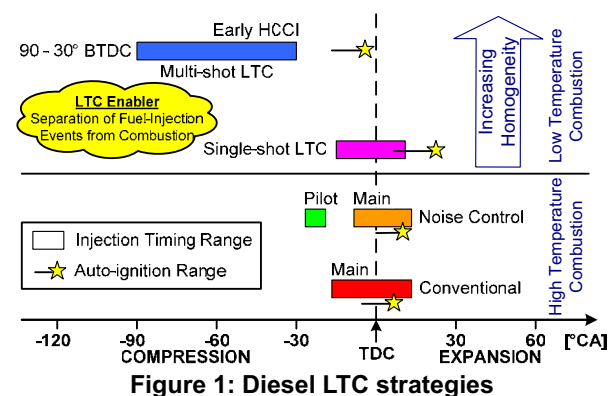


Figure 1: Diesel LTC strategies

Both the HCCI and EGR-enabled LTC result in increased emissions of hydrocarbons (HC) and carbon monoxide (CO) that may drain away a substantial amount of fuel energy. However, the EGR-enabled LTC is more prone to decreased combustion efficiency because of the high dilution rates and the decreased expansion ratio with the late burning of the cylinder charge. Such modes of combustion are therefore, generally limited to

low-to-mid load operation, when implemented on conventional high-compression ratio diesel engines [3].

As the fuelling rate is increased under HCCI cycles, a high level of homogeneity can still be achieved using multiple-early injections. The primary limitations to increasing the load range of HCCI combustion are the maximum allowable cylinder pressure, the rate of pressure rise and the peak combustion temperature. On the other hand, the load range of the EGR-enabled LTC is limited by the time delay that can be achieved between the end of the fuel injection and the commencement of the combustion events. The low combustion temperature and high homogeneity are more difficult to achieve as the engine load, and thus the fueling rate, increases. The excess oxygen depletes with higher fueling rates and the proportion of the premixed fuel reduces within the given ignition delay period. Without employing higher EGR rates to push the temperature down and to prolong the ignition delay, any non-homogeneity may therefore increase the local flame temperature in regions close to the stoichiometric air/fuel ratio. A higher intake pressure is generally beneficial to reduce the incomplete combustion in addition to lowering the equivalence ratio of the cylinder charge [18]. However, the use of a higher intake pressure is dependent on the compression ratio (CR) and the maximum cylinder pressure limit.

The modeling and empirical results on '*smokeless rich diesel combustion*' by Akihama et al. are considered as the seminal work on EGR-enabled LTC [2]. Kook et al. also carried out a detailed investigation on the influence of charge dilution and injection timing on the performance and emissions of LTC cycles using an optical engine [15]. The results showed that the lowered combustion temperatures under highly diluted in-cylinder conditions suppress the formation of soot but adversely affects the fuel-conversion efficiency. Moreover, such LTC cycles were limited to low engine loads when implemented on high CR engines.

A number of strategies have been reported in the literature to withhold the cylinder charge from ignition in combination with EGR, the common ones being lower CR [20] and variable valve timing (VVT). Mendez et al. [21] achieved an indicated mean effective pressure (IMEP) of 7 bar and low indicated NO_x (0.06 g/kWh) with a CR 14:1 engine using 2 injections per cycle and 45% EGR. Dronniou et al. [13] used a CR 14:1 engine, single injection per cycle and 47% EGR to achieve a brake mean effective pressure of 10 bar with low NO_x and soot emissions. In all the above cases, the CO and HC emissions were very high. Li et al. [22] used a diesel fuel blended with 'ethyl tert-butyl ether' (ETBE) to achieve ultra-low emissions with smokeless diesel combustion with thermal efficiency higher than 40% at 6.7 bar IMEP.

In this work, the authors have investigated the attainment of 10~12 bar IMEP under EGR-enabled LTC cycles at three different compression ratios, that represent the CR range for modern diesel engines. The intake and injection pressures were modulated to achieve ultra-low NO_x and soot while reducing the energy efficiency penalty of LTC cycles. This research intends to identify the major parameters that affect diesel LTC performance and emissions.

EXPERIMENTAL SETUP

A modern single cylinder research engine coupled to a DC dynamometer was instrumented for the LTC tests. The engine specifications are given in Table 1 and the overall system setup is shown in Figure 2. The system is configured for both naturally aspirated and boosted intake conditions. Clean and dry combustion air was provided from an oil-free compressor and the intake pressure was precisely controlled by electro-pneumatic pressure regulators. The exhaust backpressure was controlled through combination of a pneumatically-actuated flow-control valve and an electro-pneumatic pressure regulator. This allowed independent control of the boost and exhaust backpressures. A mass air flow meter was placed upstream of the intake surge tank while EGR was introduced downstream of the tank.

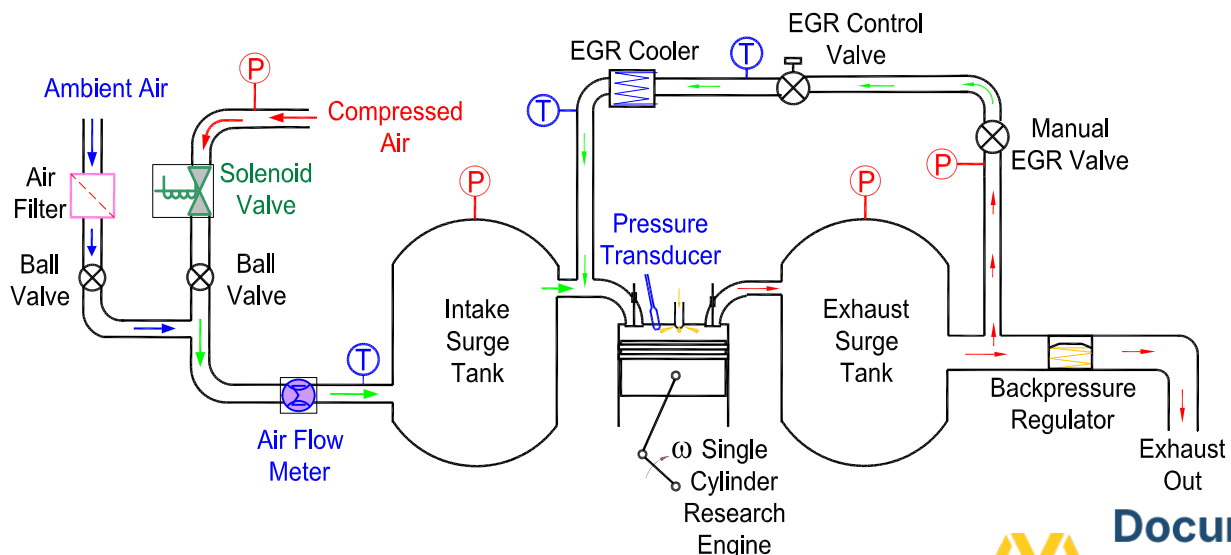


Figure 2: Combustion Test Platform at CDEL, University of Windsor

Table 1: Test Engine Specifications

Engine Type	Diesel 4 Stroke Direct Injection
No of Cylinders	1
Displacement [cm ³]	767
Bore x Stroke [mm]	96 x 106
Compression Ratio	17.5 to 13:1
Maximum Cylinder Pressure [MPa]	18
Injection System	Common-rail
Maximum Injection Pressure [MPa]	180

EGR was cooled with the engine coolant and the EGR amount was controlled with a combination of EGR valve position and exhaust backpressure control. In-house LabVIEW codes were developed to establish CAN communication to the EGR valve and for data acquisition. The engine coolant and lubricating oil conditions were monitored and controlled at a fixed temperature of 80°C with external conditioning systems to minimize discrepancies in the test results.

A dual-bank exhaust analyzer system (NO_x, THC, CO, CO₂, O₂, and soot) was instrumented for the tests; one for the exhaust emissions and the other for the intake gas concentrations. The control platform consisted of a set of embedded real-time (RT) controllers, field programmable gate array (FPGA) devices, and synchronized high-speed signal conditioning, and recording units. The system allowed the injection scheduling to be commanded on a crank angle resolved basis and the injection quantity to be controlled on a time-resolved basis.

In-cylinder pressures were acquired using a Kistler pressure transducer connected through a Kistler 5010B charge amplifier. The pressures were recorded for 200 cycles at 0.1°CA (degree crank angle) resolution and averaged to calculate the indicated mean effective pressure (IMEP), net heat-release rate and the cumulative heat-released. The 0.1°CA resolution was used to provide accurate ignition delay periods and thus phasing of the heat-release rates during the on-line monitoring of the combustion event.

Three pistons with a reentrant bowl shape were used in this study. The compression ratios of these pistons were 17.5, 15 and 13:1.

RESULTS AND DISCUSSION

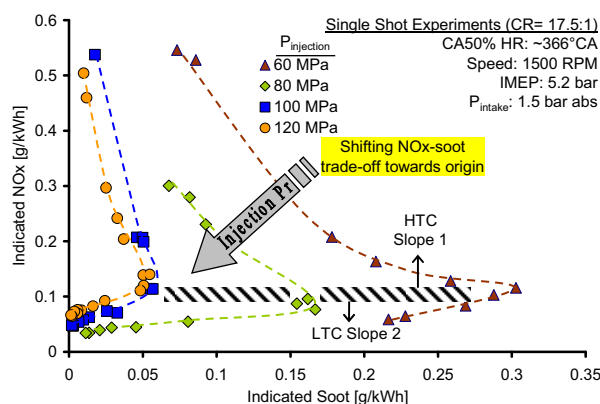
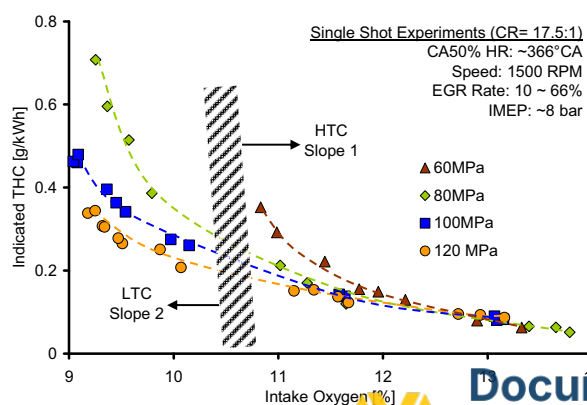
The test matrix for the experimental work is shown in Table 2. The baseline LTC tests were carried out at 17.5:1 CR and 5.2 bar IMEP. The combustion phasing was maintained within a narrow crank angle window of 5–10°CA ATDC. The injection pressure was varied from 60 to 180 MPa and intake boost from 1.45 to 3 bar abs and the effects on LTC performance and emissions were analyzed. To make a fair comparison between the results with variations in the boost pressure, all the test results have been plotted against the intake oxygen concentration. The targeted load was 10–12 bar IMEP for this study.

Table 2: Test Matrix

Parameter	TEST #					
	1	2	3	4	5	6
CR [-]	17.5	17.5	15	15	13	13
IMEP [bar]	5.2	8	8	10	10	12
CA50 [°CA]	366	366	366	365	370	370
Speed [RPM]	1500	1500	1400	1400	1400	1400
P _{injection} [MPa]	60, 80, 100, 120	90, 150	90, 120	120	120	180
P _{intake} [bar abs]	1.5	1.45, 1.75	1.75, 2	2.5	1.5, 2, 2.5	2.5, 3

CR 17.5:1 – RESULTS

EGR sweeps were performed at ~5.2 bar IMEP at 4 different injection pressures to shift the NO_x-soot trade-off towards the origin as shown in Figure 3. A moderate boost of 1.5 bar abs was used since the engine load was low. It can be seen that high injection pressure was quite effective in suppressing the peak soot levels observed with increasing EGR. This is necessary to enable the transition from *slope 1* to *slope 2* as well as to substantially lower the HC emissions shown in Figure 4. *Slope 1* refers to the segment of soot climbing but NO_x declining curve when EGR increases during HTC combustion. It represents the classical NO_x-Soot trade-off, while *slope 2* is the segment of simultaneous soot and NO_x declining curve when EGR increases during EGR-enabled LTC combustion. A similar trend was observed for the CO emissions as well, with CO emissions reduced to <20 g/kWh.

**Figure 3: Improving the NO_x-soot trade-off (Test 1)****Figure 4: HC emission (Test 1)**