

Heat Release Pattern Diagnostics to Improve Diesel Low Temperature Combustion

Ming Zheng, Raj Kumar,
Yuyu Tan and Graham T. Reader
University of Windsor

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ABSTRACT

Empirical results indicated that the engine emission and fuel efficiency of low-temperature combustion (LTC) cycles can be optimized by adjusting the fuel-injection scheduling in order to obtain appropriate combustion energy release or heat-release rate patterns. Based on these empirical results the heat-release characteristics were correlated with the regulated emissions such as soot, hydrocarbon and oxides of nitrogen. The transition from conventional combustion to LTC with the desired set of heat-release rate has been implemented. This transition was facilitated with the simplified heat-release characterization wherein each of the consecutive engine cycles was analyzed with a real-time controller embedded with an FPGA (field programmable gate array) device. The analyzed results served as the primary feedback control signals to adjust fuel injection scheduling. The experimental efforts included the boost/backpressure, exhaust gas recirculation, and load transients in the LTC region. The impact of heat-release phasing, duration, splitting, and shaping on the combustion-efficiency and cylinder pressure-rise rate was also analyzed with an engine cycle simulation to facilitate the model-based control.

INTRODUCTION

Recent empirical and analytical work has indicated that the lowered combustion temperature in diesel engines by the use of exhaust gas recirculation (EGR) or highly premixed lean charge was capable of reducing the soot and nitrogen oxides (NOx) production simultaneously to very low-levels and thereby reduce the reliance on NOx and soot after-treatment [1-22]. However, the fuel-efficiency of low temperature combustion (LTC) engine cycles was commonly compromised by high levels of hydrocarbon (HC) and carbon monoxide (CO) emissions that drain substantial amount of fuel energy from the engine cycle. In addition, for the LTC cycles the scheduling of fuel delivery has lesser leverage on the exact timing of auto-ignition because of the prevailing

prolonged ignition delay and compounded cycle-to-cycle variations. This frequently results in substantial fuel-efficiency penalty due to off-phasing of the combustion process from the phasing of best efficiency.

This work intends to analyze and correlate the above mentioned challenges of LTC cycles via heat-release analyses. The influence of heat-release characteristics on emissions for conventional diesel combustion has been investigated extensively in the past [23-25]. The illustrative cases are shown in Figure 1 and Figure 2. In Figure 1, the heat-release rate for an engine with a typical mechanical fuel-injection system and no emission control is shown. An examination of the heat-release rate showed a significant portion of the fuel undergoing diffusion dominated combustion resulting in high soot. The injection timing was configured at 17° before-top-dead-center (BTDC) to obtain the combustion phasing for best efficiency. The advanced combustion phasing also resulted in high NOx. The heat-release rate such as the one shown in Figure 1 was more common before the advent of stringent emission control measures. Figure 2 shows the heat-release rates with two important NOx emission control techniques; injection timing retard and split injection marked "A" and "B". The additional heat-release rate "C" shows combustion with post-injection for exhaust after-treatment devices.

This discussion highlights the correlation between the heat-release characteristics and combustion in a modern diesel engine. In this paper, the correlation between the heat-release characteristics and emission/efficiency has been extended to LTC combustion. Based on such an analysis the authors have produced the LTC heat-release rate characteristics that meet:

- simultaneous low-NOx and soot emission
- have limited increase in carbon-monoxide and hydrocarbon emissions
- retain diesel like efficiency

Once the criteria of heat-release rate necessary for the LTC combustion was established, the transition from the

conventional to LTC regimes was performed with the assistance of a simplified heat-release based control. The heat-release rates presented in this paper have been presented in a normalized basis and evaluated using in-house engine cycle simulation software [26].

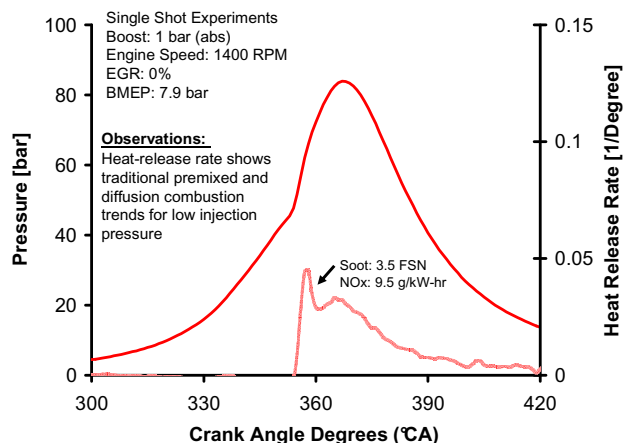


Figure 1: Heat-Release rate characteristics for classical diesel combustion without emission control.

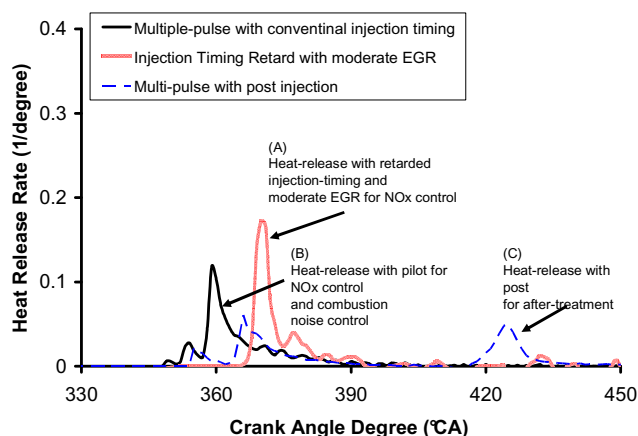


Figure 2: Heat-release rates configured for NOx control and heat-release rate with post injection for diesel after-treatment.

APPROACHES

A modern 4-cylinder Ford Puma common-rail diesel engine was modified to operate in single-cylinder research mode and instrumented for the tests (Table 1, Figure 3). As described by Han et al. [17], the segregation of Cylinder-1 from the rest 3 cylinders when controlled appropriately was an effective technique for conducting exploratory research in unstable combustion

regimes with a non-motoring dynamometer. In these tests the Cylinders 2-3-4 were operated in the conventional combustion mode, while the combustion in Cylinder-1 was pushed into the LTC cycles by independently controlling the EGR, boost, exhaust back pressure and fuel scheduling.

A comprehensive control and measurement system was instrumented for the Ford Puma and the other engine test-benches in the laboratory. A dual-bank exhaust analyzer system (NOx, HC, CO, CO₂, O₂, and soot) was instrumented for the tests; one for the exhaust emissions and the other for the intake gas concentrations. The intake air was supplied from an oil-free dry air compressor. The engine boost, exhaust backpressure, and EGR valve opening were precisely controlled with a set-of PC-based system. The engine coolant and lubricant oil conditions were monitored and controlled closely with external conditioning systems to minimize the discrepancies of the testing results. During the experiments no separate intake air temperature modulation was applied. Therefore, it was primarily decided as a function of the EGR-flow-rates, fresh-intake air temperature and the engine-load level.

In this research, the amount of soot was determined by an AVL 415S smoke meter. The consideration is such made that the particulate matter (PM) largely contains dry soot and soluble organic fractions (SOF) [27]. In the conventional high temperature combustion (HTC) mode, dry soot is a primary component of PM for the state-of-the-art diesel engines, unless extremely high level of EGR or injection timing retard is allied. In LTC mode however, the SOF constituents may be substantial. But the SOF contents are relatively easy to destroy in an oxidation catalytic converter. The research focus on PM has been left to the soot contents that can be estimated by a smoke meter [28], even though SOF is lesser responsive in such measurements. Additionally, the soot measurement with a smoke meter has been a de facto standard practice of industrial research [29,30]

Table 1: Geometric characteristics of the test engine.

Engine Type	4 Cylinder, 4 Stroke Ford DuraTorq "Puma"
Displacement [cm ³]	1998
Bore [mm]	86
Stroke [mm]	86
Compression Ratio	18.2:1
Combustion System	Direct Injection
Injection System	DELPHI Common-rail (up to P _{Rail} ~ 1600bar)

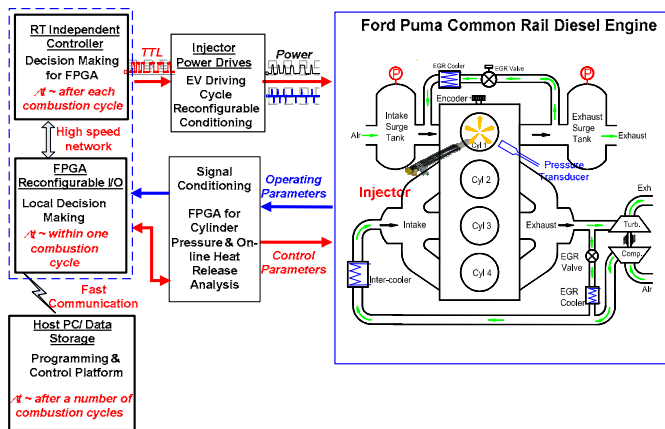


Figure 3: Schematic representation of the test setup with independent control on intake boost and exhaust backpressure at University of Windsor.

The empirical investigations were carried out with the conventional diesel fuel (Cetane Number: ~50). In order to enhance the homogeneity of the cylinder charge with diesel fuels, a variety of fuel delivery strategies have been devised and tested at the authors' laboratory, as shown in Figure 4. The intake port injection strategy was reported previously [31], in which multi-pulse sequential injection and intake charge heating were applied to improve the cylinder charge mixing. The EGR fuel reforming technique, which helped to produce a stream of gaseous fuel from the liquid diesel supply, had been documented separately [32,33]. For the present work only the in-cylinder injection strategies were investigated. The details of the injection strategies are given below:

Single-injection close to TDC with EGR: In this injection strategy, a single injection was configured close to the TDC. The time required to enhance the homogeneity of the cylinder charge was obtained by the selection of appropriate levels of EGR and the injection-timing.

Multi-pulse early injection strategy: In this injection strategy, the fuel was delivered early during the compression stroke in a series of injection events. The criterion for selection of injection strategy, particularly the number of injections, injection timing and the pulse-width of each injection has been discussed in their earlier work by the authors [34]. The sparse and the dense injection strategy refer to the dwell between the injections. A selection of an appropriate injection strategy helped to contain the un-burnt hydrocarbons while maintaining low-NO_x and low-soot.

The last multi-pulse injection strategy discussed in the paper is the multi-pulse-HCCI-injection-strategy or the Early+Post injection strategy. In this strategy, a part of the fuel (HCCI-Injection part) was delivered very early during the compression process and the remainder of the fuel was injected (late-main-injection) towards the end of the heat-release of the HCCI fuel injection. The logic behind such a strategy was that the late main

injection event would have a very short ignition delay period and undergo close to conventional combustion. The split nature of heat-release helped to contain the rapid rate of pressure that is typically associated with HCCI type of combustion.

The precise fuel injection scheduling was implemented using a real-time controller embedded with a field programmable gate array (FPGA) device. The FPGA generates the desired transistor-transistor logic (TTL) pulse patterns corresponding to the on-fly updated injection schedule. This TTL output signal is amplified using the injector power driver to execute the pulse trains, which are programmed to drive the injectors with the suitable voltage and current curves.

Since the tests were performed on the targeted single cylinder of the four-cylinder engine with independent boost and fueling control, efforts were not made to evaluate the effective load at the testing engine speed. Therefore, it was decided to use the IMEP as an indicator of load and %load was not directly used. The hydrocarbon and carbon monoxide emissions in the exhaust were used to evaluate the fuel burning efficiency while the amount of condensed fuel in the lubrication oil dilution was not considered. This paper intends to identify the major heat-release characteristics that may enable simultaneous low-NO_x and low-soot combustion, while maintaining diesel like cycle thermal efficiency.

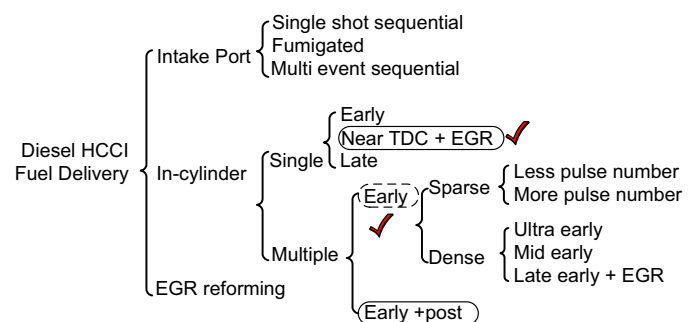


Figure 4: Practical fuel premixing for LTC type of combustion [1].

DETERMINATION OF HEAT RELEASE CHARACTERISTICS

In this section the empirical data was correlated with the emission and the efficiency characteristics. In this way the desired heat-release rate characteristics for each of the parameters could be formulated.

Heat-release pattern for NO_x:

The commonly applied techniques for NO_x reduction are EGR, injection timing retard and pilot-injection. However, to meet the forthcoming stringent emission norms diesel engine manufacturers are increasingly relying on EGR as the primary in-cylinder NO_x control technique [35-36].

The first step was to understand the efficacy of the major techniques such as EGR and pilot-injection for NO_x reduction. An EGR sweep was performed at a fixed combustion phasing for the cases of single injection and 2-injection strategies (Figure 5). At zero EGR the use of pilot injection reduced NO_x in comparison to the single injection strategy; however, after 40% EGR, the NO_x was largely decided by EGR alone (Figure 6-Figure 8). At very high EGR levels (Figure 8) the initiation of the pilot combustion was suppressed and the heat-release rate was similar to the case of single injection.

The fixed combustion phasing was achieved by closed-loop control. The cylinder pressure data and the transient engine angular speed discretized at 0.1 degree crank-angle were used as the primary input for the dynamic fuel injection adjustment. The corrections were applied only to shifting the main and the pilot-injection with the same dwell when the EGR was changed. Also, the ratio of the pilot to the main injection quantity was kept constant for the entire EGR sweep. The mid-heat release rate was kept fixed at 5 degrees after TDC. This value was decided based on the experimental and simulation studies which indicated that the indicated-efficiency peaked between 5~7 degrees after TDC when the heat-release duration was less than 40°C [1,2].

The effect of EGR on combustion in-efficiency in terms of increased CO and HC is shown in Figure 9. It can be readily seen that both the single and the two-shot injection strategies had similar burning efficiencies.

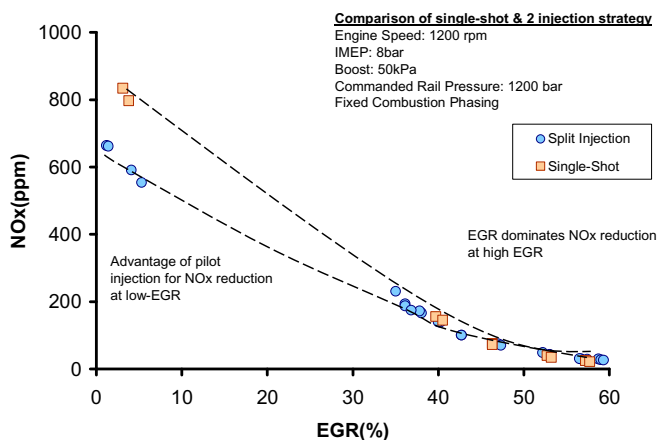


Figure 5: Effect of continuously increasing EGR with a fixed combustion phasing for single injection and 2-injection strategies.

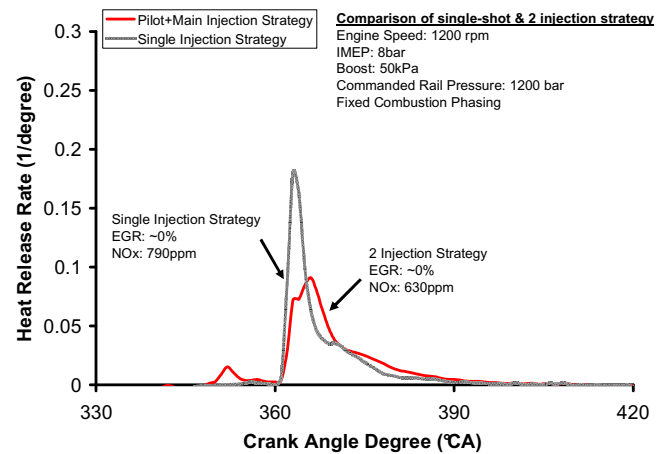


Figure 6: NO_x reduction by the use of pilot injection (no EGR).

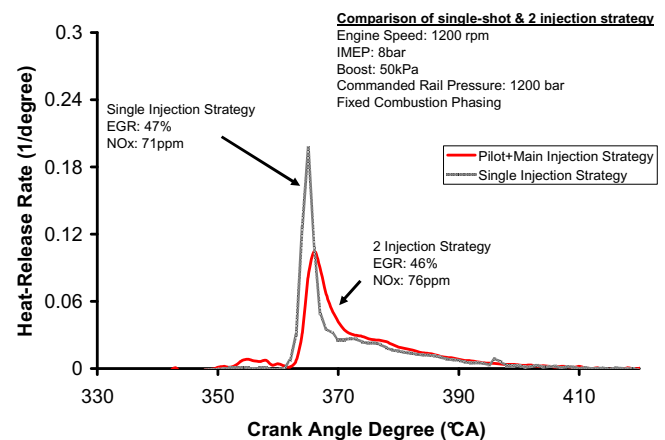


Figure 7: Combined effect of EGR and pilot injection for NO_x reduction at moderate EGR.

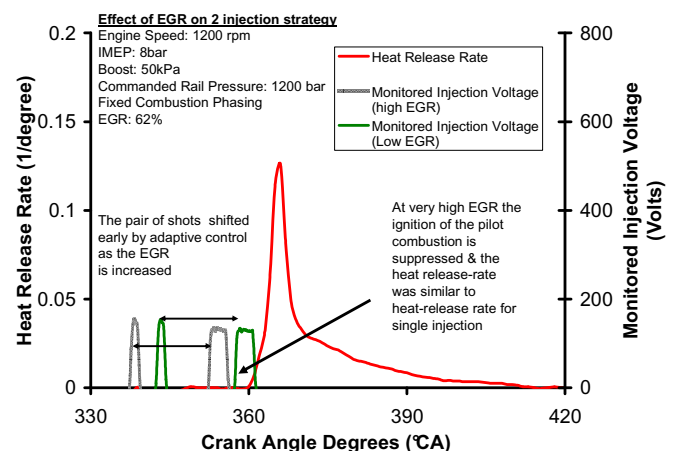


Figure 8: Initiation of pilot-combustion suppressed by the use of heavy EGR.

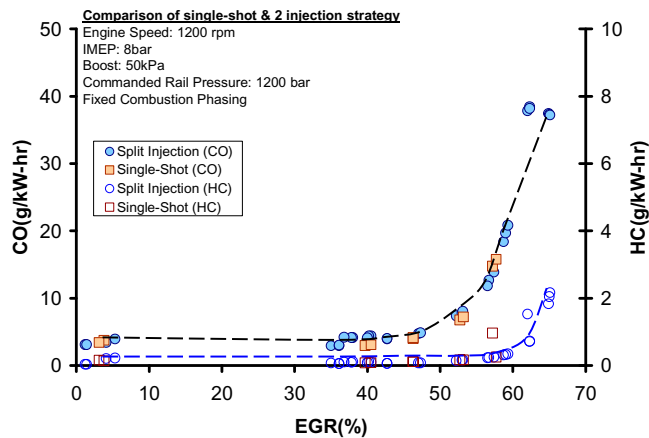


Figure 9: Effect of EGR on CO and HC during different injection strategies.

The NO_x-EGR behavior was also investigated at other injection pressures and loads, it was observed that the NO_x decreases monotonically with EGR for all these conditions (Figure 10). All the experimental data for the NO_x-EGR curve at different loads converged into a single curve when plotted as a function of intake oxygen, suggesting that the dilution effect was strongest for the present experiment conditions (Figure 11). Thus it was observed that for achieving the stringent emission levels the NO_x would have a stronger correlation with EGR/intake oxygen % than with the heat-release rate. The NO_x and intake charge dilution correlation has been observed by other researchers also [37-39].

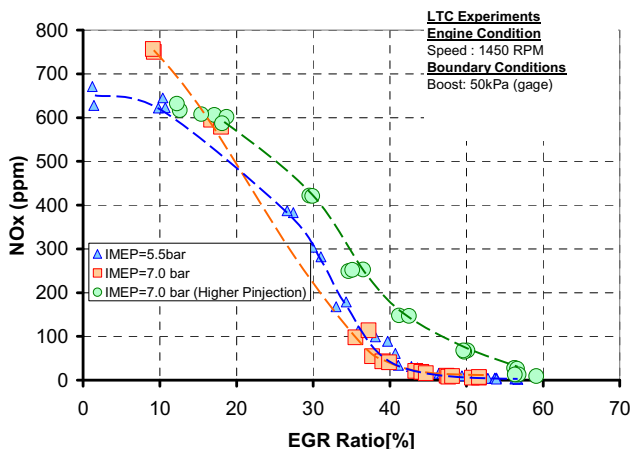


Figure 10: Continuous decrease in NO_x with increasing EGR.

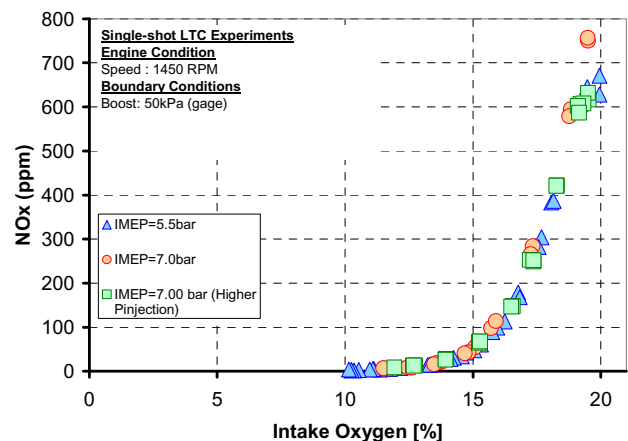


Figure 11: NO_x as a function of intake oxygen for different load conditions.

Heat-release pattern for soot:

Two approaches have been used by the authors to achieve simultaneous low NO_x and low soot. [1,2,8,11,17,21,22]. The first approach was the multiple injection strategy with heavy EGR, called multi-pulse-HCCI-injection-strategy. In this strategy all the fuel was delivered during the compression stroke in a series of precisely controlled injection pulses. Figure 12 shows the implementation of multi-pulse-HCCI-injection-strategy with three progressively increasing levels of EGR for a fixed fueling quantity. For 45% EGR, the combustion was initiated immediately after the end of third injection, therefore very little time was available for preparation of the near homogenous charge for the third injection, resulting in high soot. When higher amounts of EGR were applied the ignition delay for the third injection was also prolonged providing ample time for mixing for the third injection, thereby resulting in lower soot. Therefore, it can be seen that the injection with the shortest ignition delay had a significant bearing on the soot formation and this ignition delay was called the minimum mixing duration (Figure 13).

The second injection strategy employed to reduce soot and NO_x simultaneously was the single-shot close-to-TDC injection strategy with heavy EGR. Such an injection strategy was able to reduce soot when the application of EGR prolonged the ignition delay by 50% compared to the case of no EGR or provided an ignition-delay of 1.5 ms [1-2].

The minimum mixing duration for different injection strategies at various loads is shown in Figure 16 along with the ignition delay of the single-shot LTC combustion. It can be seen that a heat-release rate with an ignition delay of ~1.5ms for the case of single injection or a minimum-mixing duration of 1.5ms for the case of multiple injection strategy was able to produce low-soot (Figure 15).

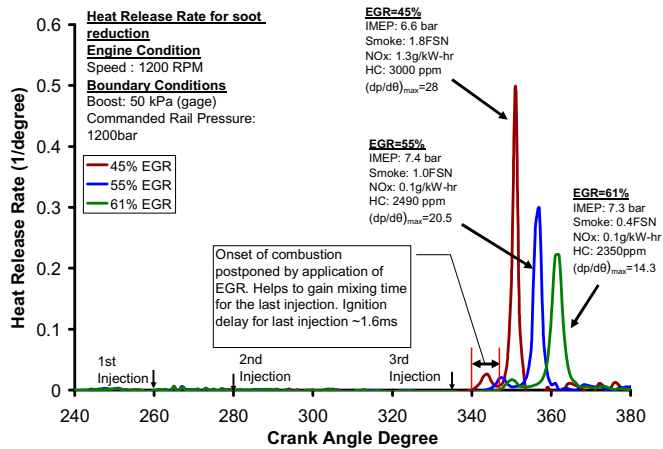


Figure 12: Heat-release rate for soot reduction with multiple-injection and application of EGR.

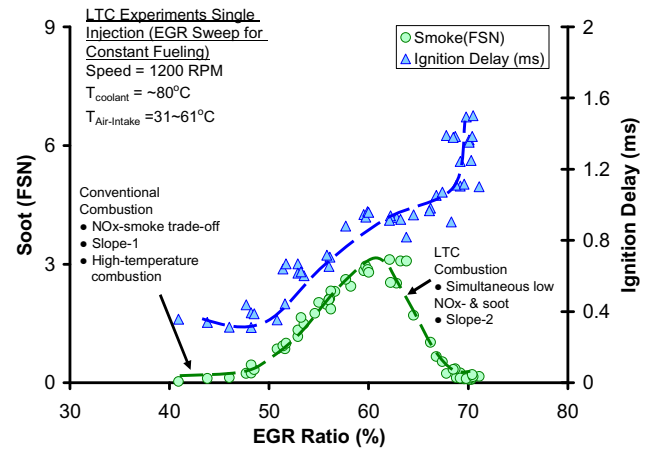


Figure 15: Relationship between ignition-delay and soot for LTC with single-shot injection strategy and a heavy use of EGR.

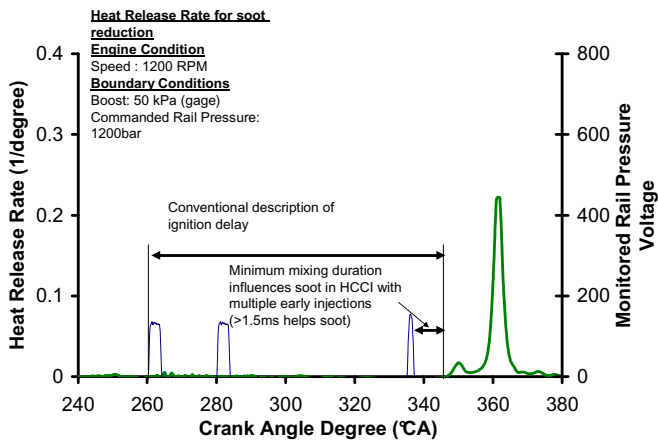


Figure 13: Heat-release rate for soot reduction with multiple-injection and application of EGR.

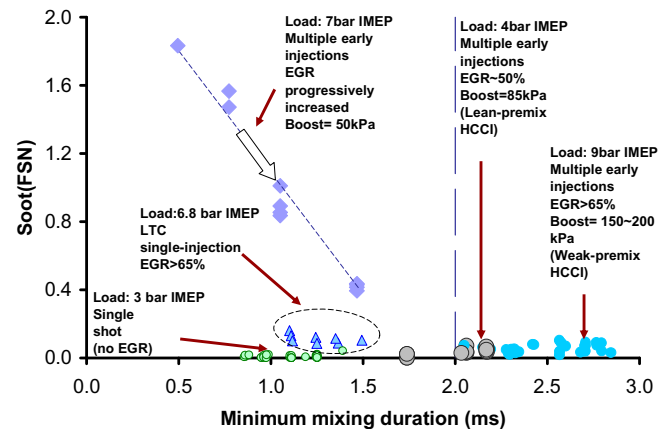


Figure 16: The effect of injection strategy on the soot during LTC.

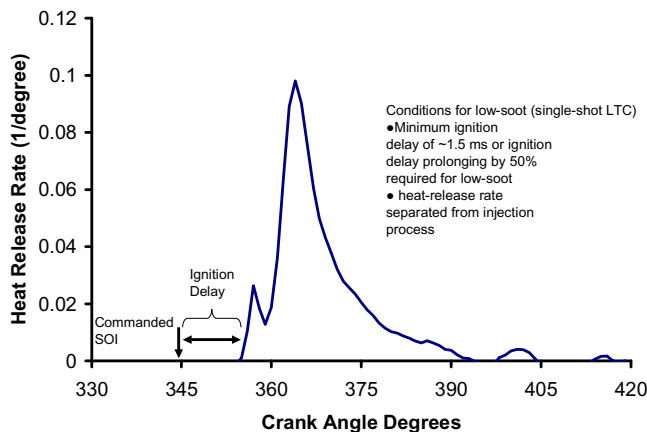


Figure 14: Heat-release rate for soot reduction with single-injection and application of heavy-EGR.

Heat-release pattern for HC:

The heat-release had a stronger relationship with HC for the case of early multiple-pulse injection strategies. For the case of multiple-pulse injection the HC was dependent on the ignition delay process, the injection strategies with longer ignition delay resulted in higher HC (Figure 17). The details for "sparse-injection strategy", "dense-injection strategy" used in the Figure 17 can be found in the previous work of the authors [1,2,8,11,17,21,22].