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Implementation of multiple-pulse injection strategies to enhance the homogeneity for simultaneous low-NOx and -soot diesel combustion

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ABSTRACT

The diesel combustion implemented with the use of a homogeneous lean charge has shown to produce simultaneous reduction of nitrogen oxides (NOx) and soot emissions at low-load conditions. Similarly, at higher load levels, a cylinder charge mixture weakened by the use of exhaust gas recirculation (EGR) and enhanced homogeneity has also shown to result in simultaneous reduction of NOx and soot emissions. In this study multiple-shot injection experiments have been investigated as a means to enhance the homogeneity for simultaneous low-NOx and low-soot combustion at both low- and moderate-load conditions. Up to 8 fuel injection pulses per cylinder per cycle were applied to modulate the homogeneity history. The empirical results were conducted under independently controlled EGR, intake boost, and exhaust backpressure to enhance the flexibility in adapting the engine boundary conditions towards this type of combustion. Test results have been presented in increasing the engine load up to 9 bar IMEP.

1. Introduction

Modern diesel engines have made significant improvements with the advent of the common-rail fuel injection and turbo-charged air-system. This has helped to lower the soot emissions and the combustion noise of the engines, in addition to retain their traditionally high thermal efficiency. However, the emission regulating bodies such as United States Environmental Protection Agency (US EPA) and Environment Canada have mandated increasing stringent emission norms for the diesel engines in the near future. A major challenge for the implementation of these emission norms is the presence of the NOx-soot trade-off, which entails that an in-cylinder measure to reduce NOx emissions leads to soot increase and *vice-versa*. Low-temperature combustion (LTC) strategies, such as homogeneous charge compression ignition (HCCI) and smokeless diesel combustion attempt to overcome the above mentioned NOx-soot trade-off and produce simultaneous low-NOx and low-soot combustion [1–12].

Numerous experimental and modeling studies have been carried out to understand the conditions necessary for the low-emission combustion. Based on these studies the local in-cylinder temperature and the local air–fuel ratio have been identified as the significant parameters and their influence on the NOx and soot formation has been extensively studied [12–23]. The formulations necessary for low-emission combustion have been identified on an $\Phi - T$, or $(1/\Phi) - T$, diagram such as the one indicated in Fig. 1. These formulations are considered to be applicable for a homogeneous cylinder charge or the locally homogeneous regions of a heterogeneous charge. This figure shows 4 primary approaches to simultaneous low-NOx and low-soot combustion during the diesel combustion:

Lean-homogeneous mixture at low-load HCCI: The burning of a diesel fuel in an excessively lean and homogeneous cylinder charge mixture (equivalence ratio $\Phi < 0.3$) results in simultaneous low-NOx and low-soot combustion [24–26]. This type of combustion is considered as a representative for low-load homogeneous charge compression ignition (HCCI).

Weak-homogeneous mixture at high-load HCCI: At higher loads, it is typically difficult to prepare a lean-homogeneous cylinder charge necessary to lower the flame temperature and therefore, at higher loads the cylinder charge is diluted with appropriate amounts of EGR. Even though the application of large amounts of EGR renders the local air–fuel ratio towards the stoichiometric value, the soot formation is suppressed by enhancing the homogeneity. The combustion of such diluted cylinder charge that is closer to stoichiometric but of significantly higher homogeneity, is considered to be a representative of high-load HCCI [7,27,28].

Fuel-reforming: In this method, the EGR-loop of the diesel engine is utilized to produce gaseous fuel, primarily hydrogen (H_2) and carbon monoxide (CO). The recirculation of these gaseous

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Nomenclature

BTDC	Before-Top-Dead-Center
°CA	Crank-Angle in Degrees
CO	Carbon Monoxide
EGR	Exhaust Gas Recirculation
FBP	Final Boiling Point
FPGA	Field Programmable Gate Array
HCCI	Homogeneous Chare Compression Ignition
HC	Hydrocarbons
IMEP	Indicated Mean Effective Pressure
LTC	Low-Temperature Combustion
NOx	Oxides of Nitrogen
ppm	Parts Per Million
TTL	Transistor–Transistor Logic
TDC	Top-Dead-Center

Greek symbols

θ	Crank-Angle
Φ	Equivalence Ratio
μs	Micro-seconds.

species helps to enhance the premixed combustion. If the gaseous fuel follows a lean burn process, it has a potential for simultaneous low-NOx and low-soot combustion [29–31].

Smokeless rich-combustion: The simultaneous low-NOx and low-soot for this combustion mode are approached by the use of a large amount of EGR. The use of EGR to suppress NOx is well established, however when massive amounts of EGR are used, it can suppress the combustion flame temperature to levels below the threshold limits for soot formation and thereby achieve simultaneous low-NOx and low-soot. In addition, the high levels of EGR prolong the ignition delay to an extent that a cylinder charge mixture of enhanced homogeneity is formed before the combustion process [12].

In this paper only HCCI combustion is discussed for achieving simultaneous low-NOx and low-soot combustion and the multiple-pulse injection strategies are examined as a means to enhance the homogeneity of the cylinder charge mixture during various engine operating conditions. Even though HCCI combustion achieves simultaneous low-NOx and low-soot emissions, it is usually associated with higher hydrocarbon (HC) and CO emissions compared to the conventional diesel combustion. A brief discussion has been presented here to understand the primary emissions in HCCI combustion and later the paper provides guidelines for the selection of the multi-pulse injection strategy to minimize the HC and CO emissions associated with HCCI combustion processes.

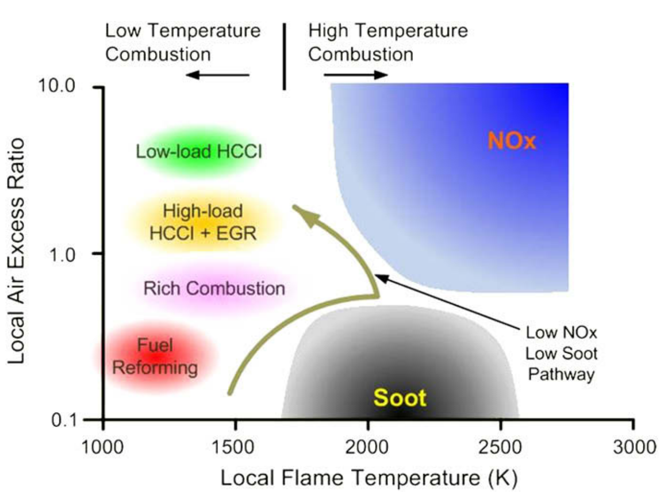

Fig. 1. Pathway for simultaneous NOx and soot reduction [19].

1.1. Emission formation during HCCI combustion

The main motivation for studying HCCI combustion stems from its potential for significant reductions in NOx and soot emissions. The underlying mechanism responsible for the reduction in NOx emissions is considered to be the absence of high-temperature regions within the combustion chamber. The combustion temperatures are lower because either the HCCI combustion reactions occur at the globally lean air–fuel ratios, or with the EGR diluted cylinder charge mixture; both situations lead to a temperature level significantly below the temperatures encountered within the reaction zones for the conventional diesel combustion. The absence of soot is attributed to the absence of the diffusion combustion during an HCCI combustion cycle. During HCCI combustion, typically higher HC and CO emissions are observed. The low in-cylinder temperatures necessary for HCCI operation also lead to decreased post-combustion oxidation rates that contribute to higher level of CO and HC emissions for HCCI combustion. Another factor that results in higher HC emission is the propensity of fuel-impingement on the cylinder walls during in-cylinder injection very early during the compression stroke [10].

2. Experimental set-up

A modern 4-cylinder Ford common-rail diesel engine, running on single-cylinder mode was instrumented for the tests (Table 1, Fig. 2). The original intake and exhaust manifolds were replaced with prototype manifolds so that the tests could be conducted with the independently controlled levels of EGR, intake boost and exhaust backpressure in Cylinder 1. In the exploratory tests, Cylinders 2–4 were operated in the conventional combustion mode under a reconfigurable fuel-injection strategy, while the combustion in Cylinder 1 was then pushed into the HCCI type of combustion. Up to 8 fuel injection pulses per cylinder per cycle were applied to modulate the homogeneity history of the HCCI operations in order to better phasing and completing the combustion process. Since the tests were performed on the single-cylinder of the 4-cylinder engine with independent boost and fueling control, efforts were not made to decide the maximum power or torque at the testing engine speed. Instead, indicated mean effective pressure (IMEP) was used as an indicator of load.

A dual-bank exhaust analyzer system was instrumented for the tests; one for the exhaust emissions and the other for the intake gas

Table 1
Geometric characteristics of the test engine.

Type	4-Cylinder, 4 stroke Ford Dura Torq "Puma" Diesel
Bore	0.086 m
Stroke	0.086 m
Displacement	1.998 l
Compression Ratio	18.2:1
Injection System	Delphi common-rail (up to $P_{Rail} \sim 160$ MPa)
Number of Injector Nozzle Holes and Nozzle Diameter	6 Holes and 0.149 mm diameter

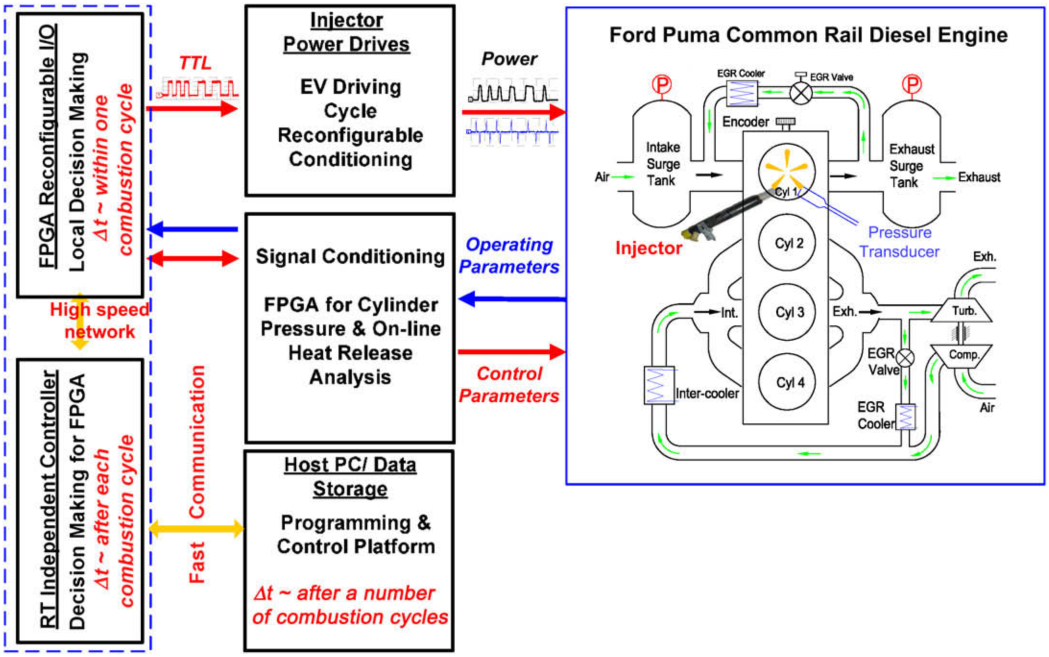

Fig. 2. Experimental set-up details of the engine configuration and control hardware.

Table 2
Intake and exhaust gas sampling analyzer systems.

Analyzers	Species	Measured	Manufacturer and Model Number
Non-Dispersive Infra-Red	CO	ppm	CAI Model 300
Non-Dispersive Infra-Red	CO_2	[%]	CAI Model 200 (Intake) CAI Model 602P (Exhaust)
Paramagnetic	O_2	[%]	CAI Model 200 (Intake) CAI Model 602P (Exhaust)
Chemiluminescence	NOx	ppm	CAI Model 600 HCLD
Heated Flame Ionization Detector	THC	ppm	CAI Model 300M-HFID
Variable Sampling Smoke Meter	Smoke/dry soot	FSN, mg/m^3	AVL Model 415S

CAI: California Analytical Instrument.

concentrations. The details of the emission analyzers used in the tests are shown in Table 2. 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 systems. The engine coolant and lubricant oil conditions were retained closely with commercial external conditioning systems (FEV Coolcon and Lubcon, respectively) to minimize the discrepancies of the testing results. The specifications of the test fuel are provided in Table 3.

The details of the engine-electronics hardware that was set-up for running the modified single-cylinder engine are shown in Fig. 2. The precise fuel injection-scheduling was implemented using a real-time controller embedded with a field programmable gate array (FPGA) device. The FPGA device generated the desired

Table 3
Characteristics of the diesel test fuel.

Characteristic	
Density (kg/m^3) at 15 °C	835.8
Cetane Number	50.2
Kinematic Viscosity (cSt) at 40 °C	1.5
Distillation Temperature (°C) Up to 95% distillation	175–350
LHV (MJ/kg)	42.9
Total Sulfur Fuel (ppm)	<4
Reduced Chemical Formula	$CH_{1.9}$
Stoichiometric A/F (mass)	14.57

Table 4
List of experiments.

Experiment	Test Characteristics	Implementation
1	Prepare a lean-homogeneous charge for simultaneous low-NOx and low-soot before the combustion process.	Load: 3 bar IMEP Injection strategy: Multiple-injection strategy Boundary Conditions: No EGR and no boost
2	Prepare a weak-homogeneous charge for simultaneous low-NOx and low-soot before the combustion process.	Load: 6–7 bar IMEP Injection strategy: Multiple-injection strategy Boundary Conditions: Boost and EGR
2 (a)	Reduce CO by improving oxygen availability.	Load: 6–7 bar IMEP Injection strategy: Multiple-injection strategy Boundary Conditions: Boost and EGR
2 (b)	Reduce CO by performing in-cylinder oxidation.	Load: 6.0–8.0 bar IMEP Injection strategy: Multiple-injection strategy Boundary Conditions: Boost and EGR
2 (c)	Reduction of HC by employing injection-scheduling adjustments.	Load: 6.0–9.0 bar IMEP Injection strategy: Multiple-injection strategy Boundary Conditions: Boost and EGR

transistor–transistor logic (TTL) pulse patterns corresponding to the injection schedule. The timing of the commanded injection pulses was crank-angle resolved at 0.1 °CA intervals and the duration of the injection was time-resolved in micro-seconds deterministically. This TTL output signal was amplified using the injector power driver to execute the pulse trains, which were programmed to drive the injectors with the suitable voltage and current profiles. All the programming required for configuring the FPGA logic gates was done using LabVIEW programming environment and the injection-scheduling was updatable on-the-fly basis [32]. The FPGA device was accommodated in a peripheral component extending the interconnection of the instrumentation chassis (PXI type) that also included a real-time controller used for floating point calculations.

An additional real-time controller was set-up for the fuel-rail pressure regulation. The engine hardware modifications allowed bypassing the original engine-control unit and running independent fuel-injection and air–fuel ratio management strategies.

The in-cylinder pressure was acquired using a flush-mounted AVL pressure transducer at 0.1 °CA resolution. The implementation of on-line heat-release rate analysis using a PC-based system allowed the computation of important combustion parameters such as IMEP, maximum cylinder pressure, crank-angle of maximum pressure, maximum rate-of-pressure rise, crank-angle of maximum rate-of-pressure rise, crank-angle of 50% heat-released, and normalized heat-release rate among others on a cycle basis. The availability of the above combustion parameters on a cycle basis allowed avoiding the engine operations in the vicinity of regions with engine knocking or very high pressure rise rates.

3. Experimental results

The experimental tests were presented at a load ascending scheme as shown in Table 4. The first set of experiments were performed at a load level of 3 bar IMEP. An attempt was made to prepare the lean-homogeneous mixture before the combustion process using a multiple-injection strategy without using EGR. For the next set of experiments at higher loads it was necessary to use EGR to dilute the cylinder charge so that the NOx could be reduced. An appropriate amount of EGR was necessary to reduce the soot at these load levels. The main limitation for the first set of multi-pulse HCCI experiments was the large amounts of un-burnt CO and HC. In the following set of experiments, solutions have been provided to partially overcome these problems of high HC and CO.

In this work, test results have been reported for engine speeds of 1200 rpm and 1450 rpm. Similar results were obtained at other engine speed of 1800 rpm, however for succinctness only results at 1200 rpm and 1450 rpm are reported.

3.1. Low-load HCCI: preparation of lean-homogeneous mixture

The multiple-injection strategy was implemented with the injection events scheduled very early into the compression stroke to enhance the mixing process and achieve a lean-premixed mixture necessary for simultaneous low-NOx and -soot. The injection strategy consisted of 7 early injections, starting at 260 °CA and staggering with a dwell of 5 degrees, and a last injection close to TDC (350 °CA). The type of injection strategy was chosen so that, the early injections would assist in the formation of a lean-homogeneous mixture and the last injection would allow moderate combustion phasing control. This injection strategy was not able to achieve the simultaneous ultra low-NOx and -soot combustion. An examination of the heat-release rate showed that even though a significant part of the fuel was injected early during the compression stroke for forming an early homogeneous mixture, for the last injection there was almost no ignition delay which provided little opportunity for the formation of a late lean-homogeneous mixture (Fig. 3).

Thus, most of the NOx was likely as a result of the near conventional combustion of the last injection. Hence, the last injection was advanced so as to provide extended time for the formation of the lean-homogeneous mixture. The quantity of the last injection was also reduced to minimize the fraction of fuel injection close to TDC. Both the timing advance and the reduction in the fueling quantity helped to reduce the NOx as can be seen at the point B (Figs. 4 and 5). Finally, for the point C, all the injections were advanced further into the compression stroke. The first 7 injections were spaced 5 degrees apart starting at 240 °CA and the last injection was at 330 °CA (Figs. 5 and 6). This time an average NOx level of around 12 ppm was achieved. The soot was at 1 FSN for all the test points for this group of

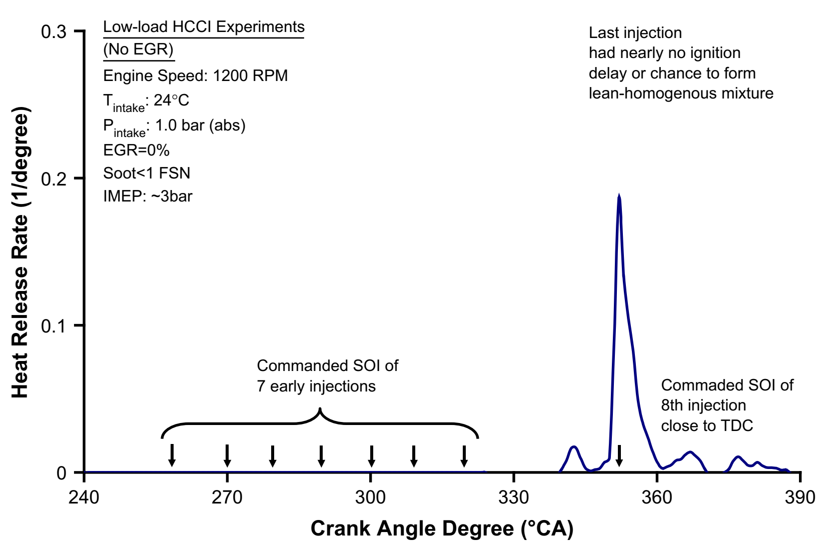

Fig. 3. Heat-release rate when multiple-pulse injection strategy was used to prepare a lean-homogeneous mixture.

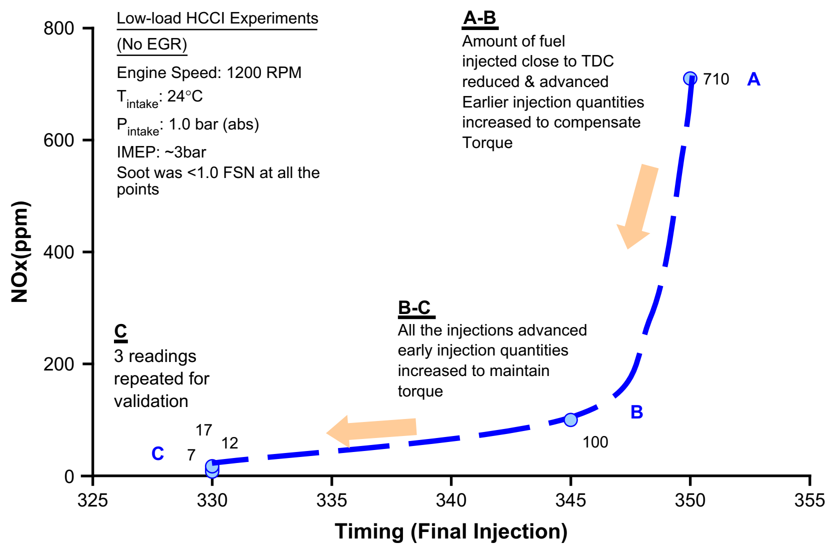

Fig. 4. Injection timing and quantity selection for lean-homogeneous mixture preparation.

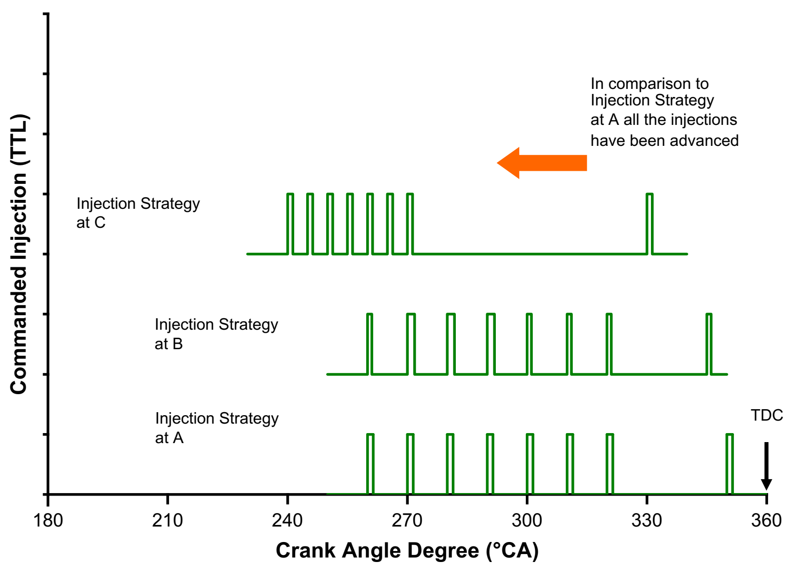

Fig. 5. Injection strategy during the transition from conventional to low-emission combustion.

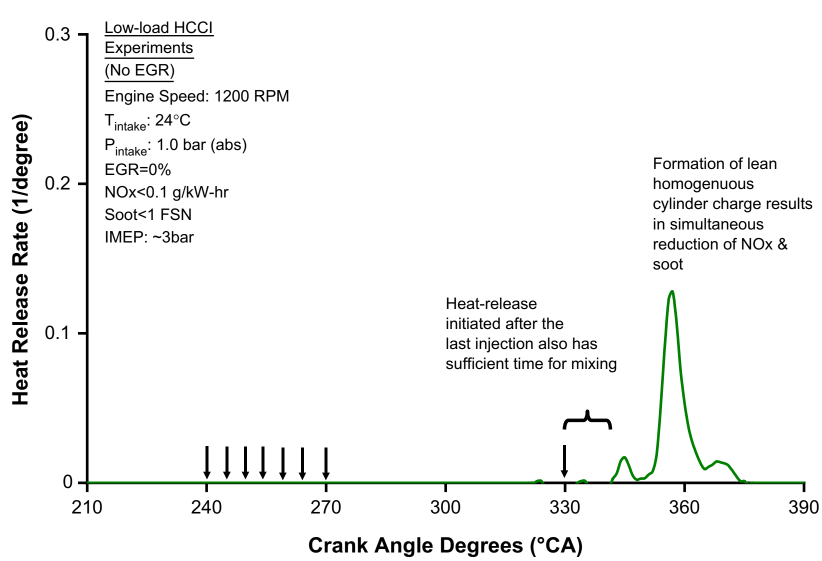

Fig. 6. Heat-release rate at point C.

Table 5
Details of the modifications for final-injection to achieve HCCI type of combustion.

Injection Strategy	Details of 8th Injection	IMEP [bar]	NOx [ppm]	Smoke [FSN]
A	250 µs at 350 CAD	3.3	710	0.4
B	150 µs at 345 CAD	3.1	108	1
C	180 µs at 330 CAD	3	7	1

Table 6
Details of commanded injection timing during transition to HCCI combustion.

Injection Strategy	Commanded Rail Pressure [bar]	Commanded Start of Injection							
		1st	2nd	3rd	4th	5th	6th	7th	8th
A	1200	260	270	280	290	300	310	320	350
B	1200	260	270	280	290	300	310	320	345
C	1200	240	245	250	255	260	265	270	330

Table 7
Details of commanded injection duration for the injection strategies during transition to HCCI combustion.

Injection Strategy	Commanded Rail Pressure [bar]	Commanded Start of Injection							
		1st	2nd	3rd	4th	5th	6th	7th	8th
A	1200	200	200	200	200	200	200	200	250
B	1200	150	250	250	250	150	150	150	150
C	1200	180	180	180	180	180	180	180	180

experiments under low-load and no EGR conditions. The implementation details of the last injection are provided in Tables 5–7. Note that the injection quantity was slightly increased from 150 µs to 180 µs to obtain the load at 3 bar IMEP. Based on this experiment it can be seen that it was possible to prepare a lean-homogeneous mixture for simultaneous low-NOx and low-soot with the multiple-injection strategy and with no EGR at low-load engine operating conditions. However, the fuel combustion efficiency therein may deteriorate the thermal efficiency of the engine [28].

3.2. *Multi-pulse HCCI at moderate load with multiple-injection strategies and EGR*

At higher loads, it was necessary to implement EGR dilution to assist in the NOx reduction. A simplified multiple-injection strategy was implemented with 3 injections. The first 2 injections were again implemented very early during the compression (260 °CA, 288 °CA) while the third injection was at 335 °CA. The reduced number of pulses allows longer dwell between the shots, which is considered effective to retain quality and consistency of each of the multiple-shots. Initially, a moderate amount of EGR was applied (45%) and it was observed that the fuel experienced spontaneous auto-ignition significantly before TDC (Fig. 7). The combustion was initiated at 340 °CA thus only a short mixing duration was available for the last injection, thereby resulting in a high soot level of 1.8 FSN. However, when the EGR was progressively increased to 55%, the onset of the combustion was postponed. This helped to gain additional time for preparation of a homogeneous mixture.

The increase of EGR led to 2 opposing effects on the soot formation; the increased sooting tendency due to reduced oxygen availability and the increased time for mixture preparation. For the present experiment the soot decreased from 1.8 FSN to 1.0 FSN which suggested that the gain in mixture preparation time could compensate for the reduced oxygen availability. An additional benefit of raising EGR was to shift the combustion phasing closer towards the TDC, which reduced the compression work. This was reflected in the increase in IMEP from 6.6 bar to 7.4 bar IMEP for the same fueling quantity. In addition, the shift in phasing closer to TDC resulted in a decrease of rate-of-pressure rise $(dp/d\theta)$max, from 28 bar/°CA to 20 bar/°CA. The increase in EGR also led to a reduction of the NOx emissions from 1.3 g/kW-h to 0.1 g/kW-h. The application of EGR therefore assisted the simultaneous reduction of soot and NOx emissions.

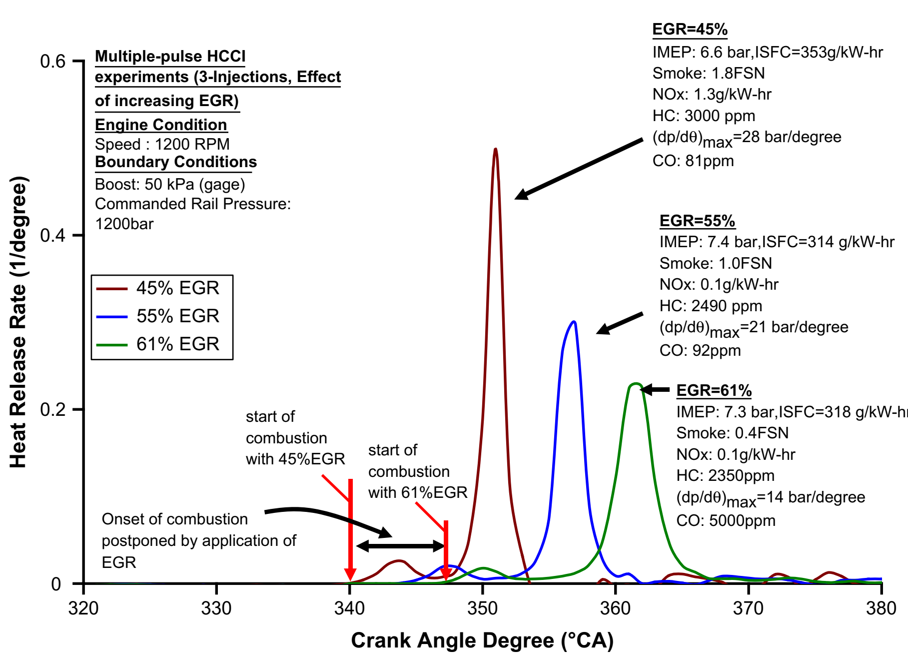

Fig. 7. Effect of EGR during multi-pulse EPC combustion experiments.

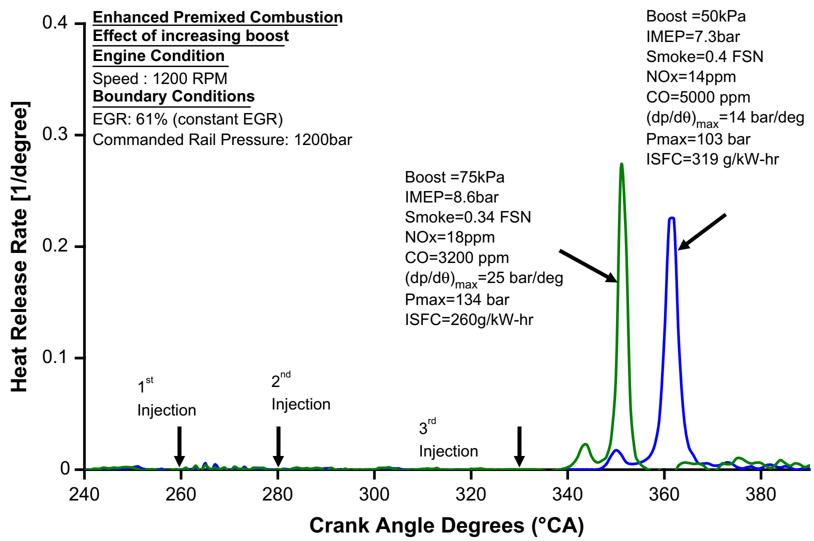

Fig. 8. Effect of boost on to reduce CO.

When the EGR was increased further to 61%, additional improvements in the emission and performance characteristics were obtained. The NOx remained close to 0.1 g/kW-h levels but the soot dropped further to 0.4 FSN. The combustion phasing was postponed further and the peak of heat-release rate was shifted after TDC. The improvement in the combustion phasing reduced the $(dp/d\theta)$max to 14.3 bar/°CA. No change in IMEP was noticed even though the compression work was reduced, this was because when the EGR was increased from 55 to 61% the CO increased from around 100 ppm to 5000 ppm. The increased CO was an indication of incomplete combustion, thus the gain in IMEP by better combustion phasing was offset by a loss in IMEP by incomplete combustion.

Based on the heat-release characteristics shown in Fig. 7 it can be seen that with a multiple-injection strategy and an EGR level of 61% it was possible to achieve simultaneous low-NOx and low-soot combustion. However, the main disadvantages of this combustion strategy were that a significant portion of the fuel was not participating in the combustion process fully as indicated by the large amounts of un-burnt CO and HC in the exhaust. As discussed previously the large amounts of CO and HC were results of low-temperature combustion, lowered oxygen availability in presence of large amounts of EGR and possible fuel-impingement on the cylinder walls. In the next sections solutions have been presented to mitigate high levels of high CO and HC during the HCCI combustion.

3.2.1. Reducing CO for multi-pulse HCCI experiments by increasing oxygen availability

The high levels of CO during HCCI type of combustion were the result of increasingly incomplete combustion that was mainly caused by high levels of EGR being applied. Therefore, it was decided to increase the boost, to increase the availability of oxygen. The boost was increased from 50 kPa to 75 kPa while the EGR ratio was kept constant (Fig. 8). The increase in boost lowered CO, however it lead to the advancement in the combustion phasing. The advancing of the combustion phasing also led to an increase in the rate-of-pressure rise. The experiments were further performed at

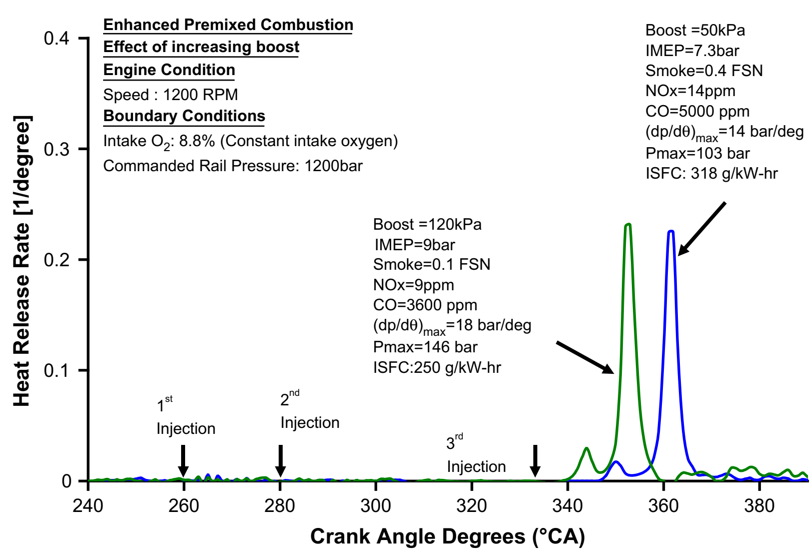

Fig. 9. Effect of boost to reduce CO.

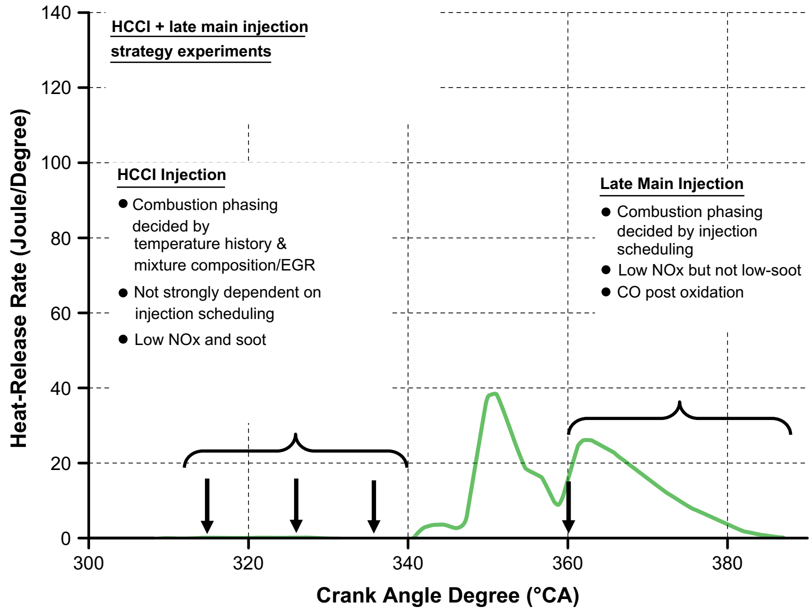

Fig. 10. Reduction in CO by post-oxidation.

a higher boost of 120 kPa while keeping the intake oxygen concentration same as the baseline boost of 50 kPa (Fig. 9). A much higher rate of EGR was needed to reach the same intake oxygen as the baseline case. Despite, the use of higher EGR at the boost of 120 kPa was possible to reduce the CO from 5000 ppm to 3600 ppm. Thus it can be seen that the increase in boost had a beneficial effect in reducing CO and at the same time it was able to retain the benefits of low-NOx and low-soot combustion. The only drawback of this strategy was the advancement of the combustion phasing which also resulted in a higher maximum rate-of-pressure rise.

3.2.2. Reduction of CO by in-cylinder oxidation using an HCCI-plus-late-injection strategy

For a conventional HCCI type of combustion with a multiple-early-injection strategy, all the fuel was injected early during the compression process and the EGR was used to withhold the combustion process and obtain an appropriate combustion phasing. An alternative to this approach noted as HCCI-plus-late-injection strategy has been presented here. In this strategy, only a part of the fuel (HCCI-injection part) was injected very early during the compression process and the remainder of the fuel (late-main-injection) was injected towards the end of the heat-release of the HCCI fuel injection (Fig. 10). 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 and would destroy the CO produced by the incompleteness of the HCCI part of combustion.

A comparison of the engine operations at the HCCI-plus-late-injection strategy (marked A), the HCCI only injection (marked B), and the main only injection (marked C) is shown in Fig. 11. The

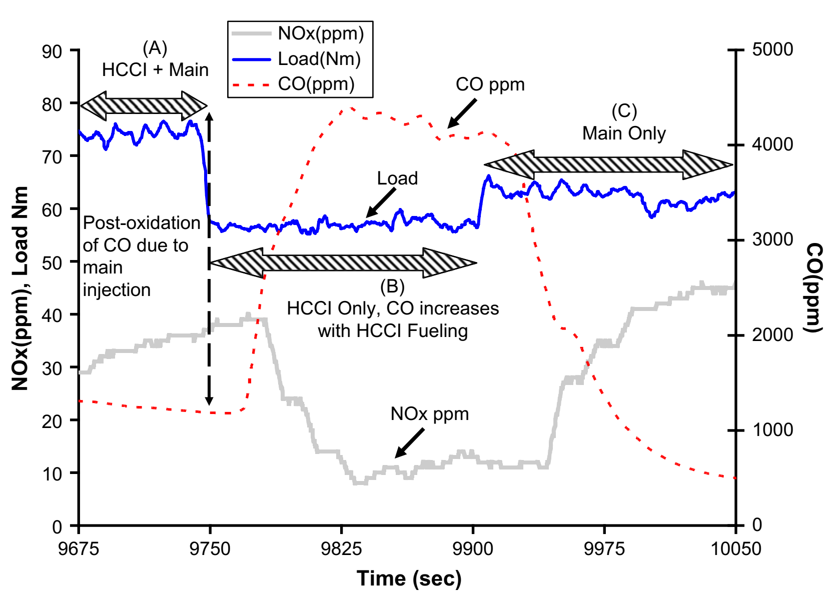

Fig. 11. In-cylinder CO oxidation experiments.

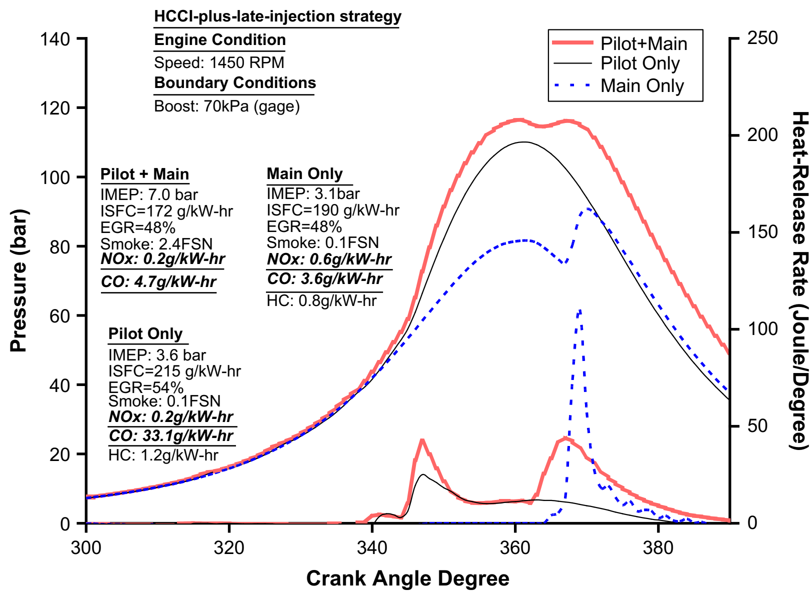

Fig. 12. Typical heat-release characteristics for HCCI-plus-late-injection strategy.

HCCI-plus-late-injection strategy consisted of injections at 315 °CA, 325 °CA, 335 °CA and 360 °CA. The commanded injection quantity for the first 3 injections was 320 µs each and for the last injection it was set at 400 µs. For the HCCI only injection strategy, the last injection at 360 °CA was turned-off while for the main only injection strategy, the first 3 injections were turned-off. The boost at 70 kPa and the EGR at 50% were kept constant during the entire test. The NOx during the HCCI-plus-late-main-injection strategy was almost the same as the main injection only injection strategy, which indicated that the NOx largely did not increase with the increase in engine load. This suggests that there is an additional internal-cycle EGR effect raised by the first stage of HCCI combustion on the late main combustion process. However, during the HCCI-plus-late-main-injection strategy, the CO was lower than the HCCI only injection. This suggests that the late-main-injection aids in the oxidation of the CO. More, investigations are currently underway to identify the load and oxygen concentration conditions that favor the CO oxidation process. This method of in-cylinder CO oxidation was associated with drawback, namely higher soot. For the HCCI experiments in Figs. 7–9 the soot was typically lower than 0.4 FSN whereas for the HCCI-plus-late-injection strategy the soot level was close to 2.5 FSN (Fig. 12).

The authors have thus devised 2 methods to decrease CO. The first method was to increase the boost that in turn increases the oxygen availability. Note that this solution may be difficult to consider when applying to an actual multi-cylinder engine with turbocharging because the increase in boost is usually associated with an increase in the backpressure which may have an adverse impact on the fuel-efficiency. A limitation of this method was that, at higher boosts, the combustion was initiated early during the compression stroke which led to high values for maximum rate-of-pressure rise. The second method that has been discussed for CO reduction was the in-cylinder oxidation of CO by using HCCI-plus-late-injection strategy. This method allowed the in-cylinder oxidation of CO but a significant drawback of this method was that low levels of soot could no longer be maintained. In the next section

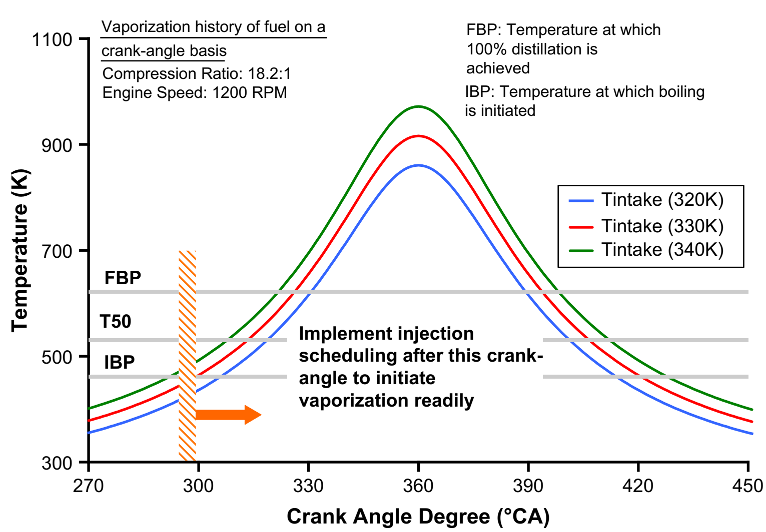

Fig. 13. Vaporization characteristics of diesel fuel used on a crank-angle domain.

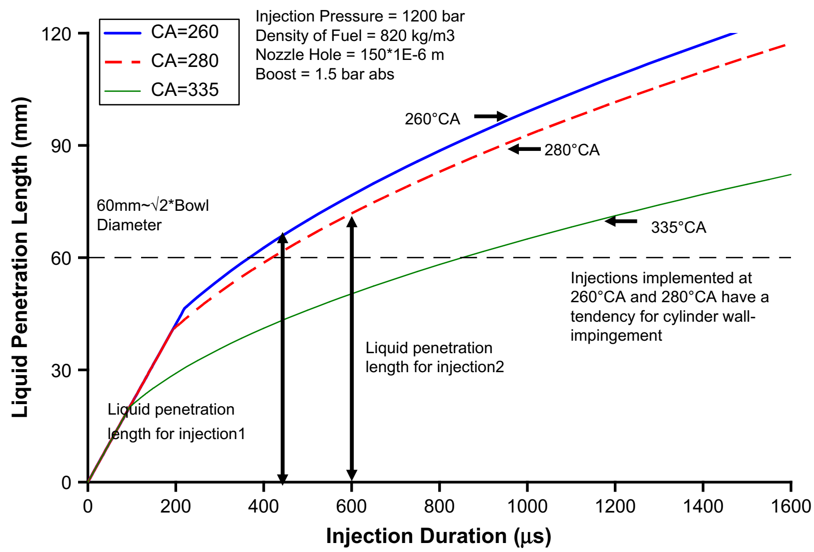

Fig. 14. Increased tendency for fuel-impingement during early injection.

Table 8
High HC injection strategy.

Injection Strategy (High HC)	Injection 1	Injection 2	Injection 3
Timing (CA)	260	280	335
Quantity (µs)	450	600	200

Table 9
Low-HC injection strategy.

Injection Strategy (Low-HC)	Injection 1	Injection 2	Injection 3	Injection 4
Timing (CA)	315	320	325	330
Quantity (µs)	300	300	300	300

the authors have discussed the methods of HC reduction during multiple-pulse injection HCCI at moderate loads.

3.2.3. Reduction of HC

The major achievement of the multiple-early-injection strategy was its ability to attain simultaneous low-NOx and low-soot. However, this method was also associated with high HC emissions. To understand the high HC emissions it was important to understand the properties of diesel fuel. Unlike gasoline, diesel is harder to vaporize. Based on the material safety data sheet for the testing diesel, the vaporization was initiated only at around 460 K and the entire vaporization is to complete up to 620 K. On a crank-angle domain, it meant that the fuel vaporization was readily initiated only for injection timings after 280–290 °CA under moderate boost (Fig. 13). This suggests that the first 2 injections of the multi-pulse injection strategy would have had a strong propensity to condense because of the prevailing low in-cylinder temperatures at the time of injection. Another likelihood of HC is attributed to the wall-impingement of the early injected fuel due to the prevailing low cylinder charge density at the time of early injection. The liquid spray length calculations based on the phenomenological model proposed by Hiroyasu and Arai [33] have also indicated that the

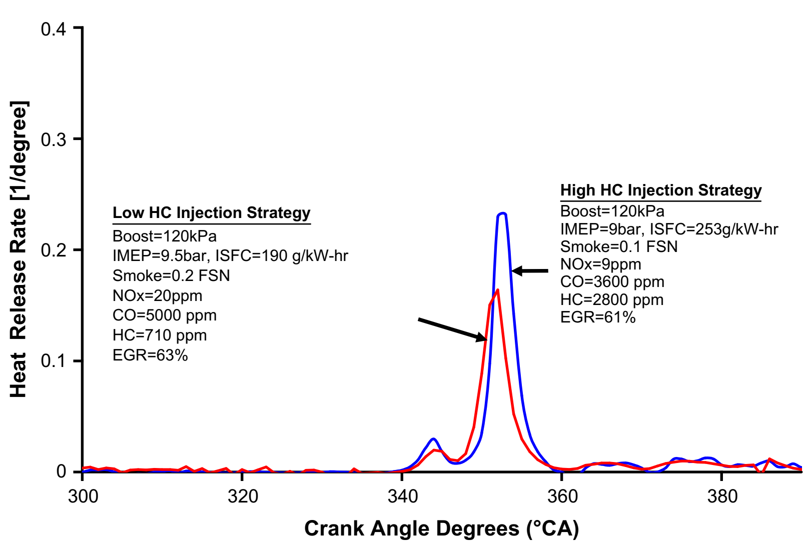

Fig. 15. Reduction of HC by injection strategy modification.

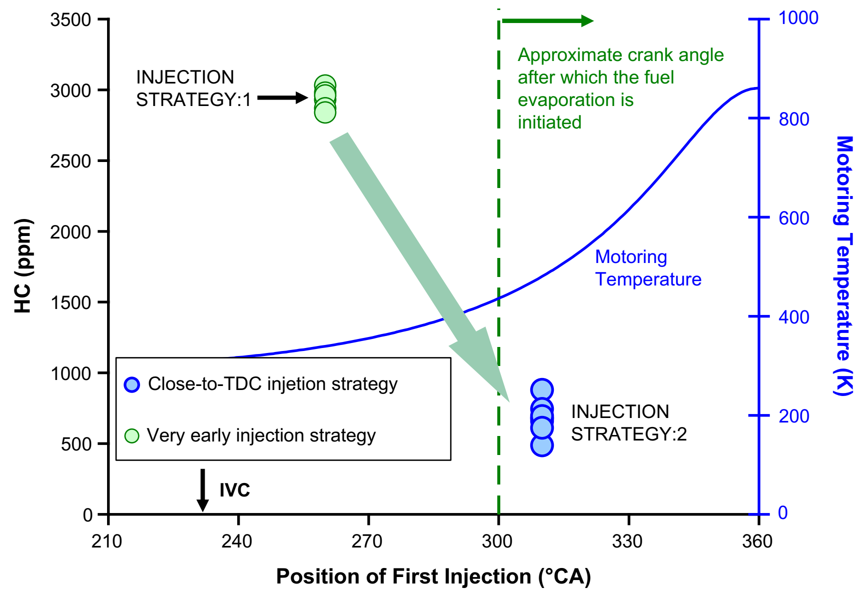

Fig. 16. Effect of injection strategy on HC emissions.

first 2 injections may have a very high tendency for wall-impingement as shown in Fig. 14. Therefore, the original injection-scheduling was modified and the injection timings were shifted closer towards TDC. Also the number of injections was increased to 4 to reduce any likelihood of cylinder wall-impingement. The original injection strategy shown in Table 8 was modified to the injection strategy shown in Table 9. The experiments with the modified injection strategy are shown in Figs. 15 and 16. It can be seen readily from these figures that the closer to TDC injection timings and the 4-injection strategy helped to significantly lower the HC. Fig. 16 shows the results of an EGR sweep for both the injection strategies.

The above experiments showed that the moving of the injection timings closer to TDC produced a significant reduction in HC while retaining the simultaneously low-NOx and -soot benefits. Therefore it was imperative to examine as to how close these injections could be moved closer to TDC while retaining the emission benefits. For this set of experiments a fixed injection-scheduling consisting of 2 injections, one at 20 °CA before-top-dead-center (BTDC) and the other at 8° BTDC were considered. With this injection strategy it was not possible to achieve the simultaneous low-NOx and low-soot whereas the HC emissions were lower than any of the previous multiple-injection strategies discussed. The heat-release rate for a representative case of 100 kPa and 51% EGR is shown in Fig. 17. It can be seen that the combustion started at 345 °CA and thus the first injection at 340 °CA had an ignition delay of merely 5 °CA that was available for mixture preparation. For the second injection at 352 °CA, there was no distinct ignition delay to prepare a homogeneous mixture necessary for low-soot combustion.

Based on the above results, it can be seen that the injection strategy had significant impact on attaining simultaneous low-NOx and -soot combustion. The time required for the mixture preparation was made available by injecting the fuel very early during the compression stroke and having a sufficient ignition delay by using

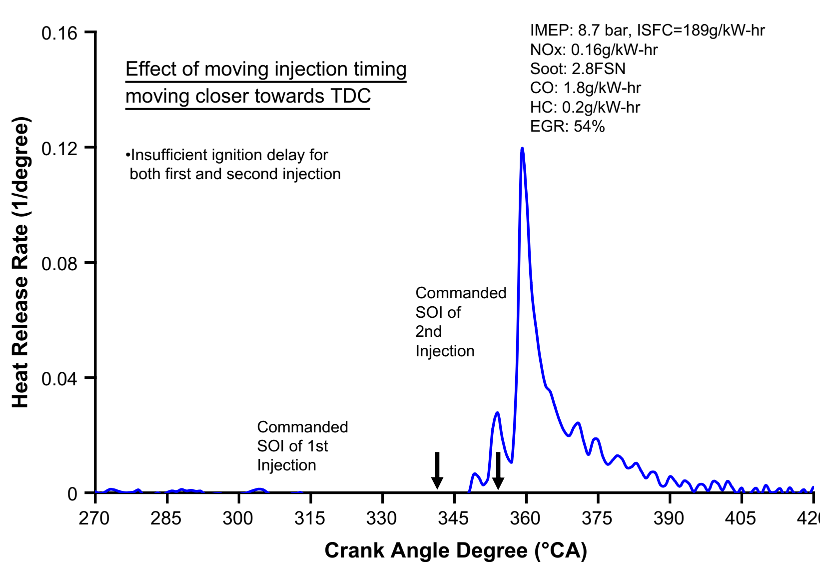

Fig. 17. Effect of injection strategy on HC and soot emissions.

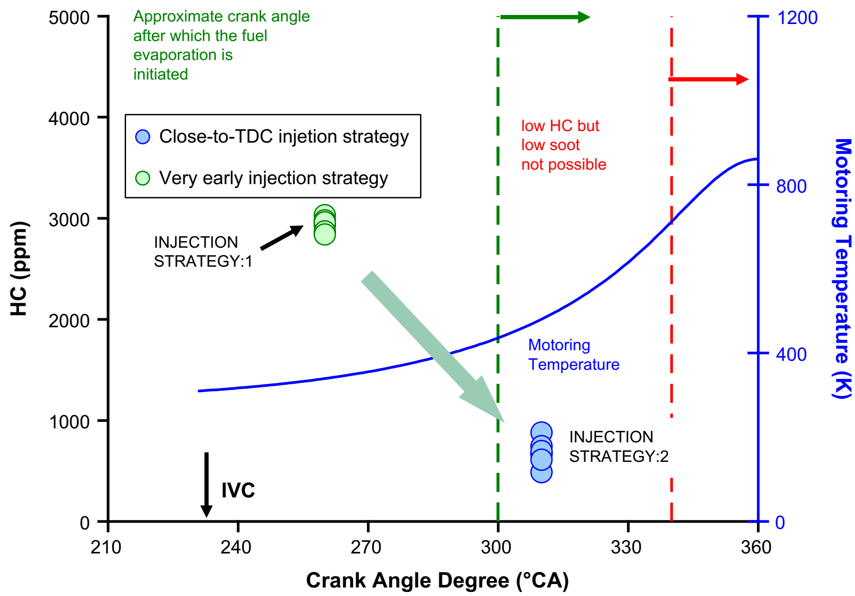

Fig. 18. Effect of injection timing on multiple-pulse EPC experiments.

EGR. Very early injection timings (Fig. 7) were able to produce combustion with low-NOx and -soot but resulted in high HC emissions due to fuel condensation and impingements. Therefore, it was necessary to move the injection timings closer towards TDC to assist in the vaporization process. However, there was a limit to which the injection timing could be moved towards the TDC. For injection timings after 340 °CA it was not possible to attain an ignition delay long enough to form a homogeneous mixture necessary for simultaneous low-NOx and low-soot. The crank-angle window for injection timings that were able to achieve simultaneous low-NOx and -soot is marked in Fig. 18.

4. Conclusion

The application of multi-pulse strategy for high pressure diesel fuel injections has been applied to achieve simultaneous low-NOx and low-soot combustion in diesel engines and the following conclusions can be drawn from this work.

At low-loads the multiple-injection strategy allowed the preparation of a lean near-homogeneous mixture prior to starting the combustion process and thus attained simultaneous low-NOx and low-soot. For the low-load conditions it was possible to reduce NOx without resorting to charge dilution with EGR.

At higher loads it was necessary to use EGR as an enabler along with the multiple-injection strategy. The use of an appropriate level of EGR was found to be necessary to lower the NOx and gain the time necessary for the homogeneous mixture preparation for soot reduction. For the initial multiple-injection strategies considered the main drawbacks observed were the high CO and HC. It was possible to reduce HC by suitably modifying the injection strategy. The modifications consisted of moving the injection timings closer to TDC and avoiding wall-impingement. The timing window for simultaneous low-NOx, low-soot and low-HC control has also been identified.

It was possible to reduce the CO by increasing the boost or by the use of an HCCI-plus-late-injection strategy. Both the CO reduction strategies had effect on other engine parameters as well. For instance, the use of higher boost led to advancement in combustion phasing whereas the use of HCCI-plus-late-injection strategy had a detrimental effect in terms of higher soot.

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