

Development of a Fuel Injection Strategy for Partially Premixed Compression Ignition Combustion

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ABSTRACT

A production version of a V-8 engine was redesigned to run on partially premixed charge compression ignition (PCCI) combustion mode with conventional diesel fuel. The objective of the PCCI combustion experiments was to obtain low engine-out nitrogen oxide (NO_x) and after-treatment tolerant soot emission level. Two fuel injection strategies were used during the PCCI combustion experiments: a) pilot-with-main injection strategy (Pil-M), b) pilot-with-main-and-post (PMP) injection strategy.

In the Pil-M injection strategy, a significant fraction of the fuel was delivered early during the compression stroke. The early pilot helped to prepare a lean-mixture of enhanced homogeneity before the combustion was initiated. The combustion of this pilot injection followed by the main combustion helped to reduce soot for a constant NO_x value. The pilot-injection timing and quantity had to be selected appropriately to retain the fuel-efficiency. Such an injection strategy was successful up to an engine load-level of 10bar BMEP. At higher load levels, it was found that the Pil-M injection strategy was insufficient for a soot reduction. Therefore, the soot reduction was enhanced by using a small quantity of post injection to promote the late-cycle oxidation of soot. The PMP injection strategy helped to expand the load-limits of clean combustion to a load of 16.5 bar BMEP; however this injection strategy had a higher fuel-efficiency penalty as compared to the Pil-M injection strategy.

INTRODUCTION

The temporal and spatial generation of the emissions, particularly NO_x and soot has been analyzed by various methods such as by laser-diagnostics, modeling and in-cylinder sampling studies [1-10]. Based on these studies, the local in-cylinder temperature and local in-cylinder air-fuel ratio distribution are considered the primary factors effecting the in-cylinder NO_x and soot formation. In the past researchers have tried to characterize the emission formation on the Φ -T space and identify the regions where simultaneous low-NO_x and low-soot combustion may be obtained. **Figure 1** shows an illustrative Φ -T diagram with conventional combustion and two commonly used clean-combustion modes, homogenous charge compression ignition (HCCI) and low-temperature combustion (LTC).

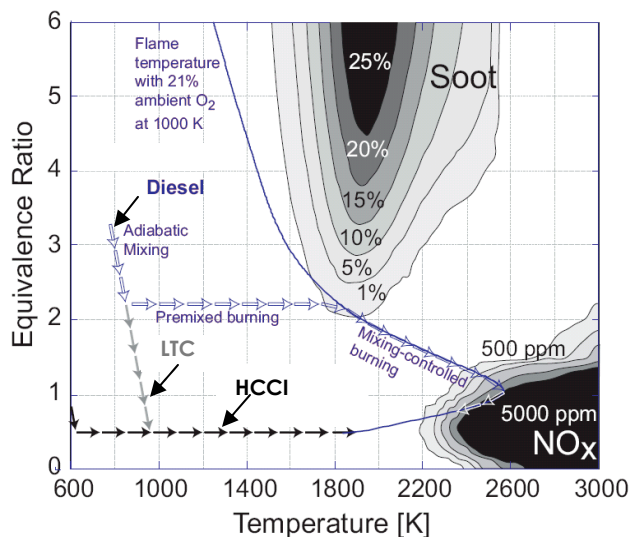


Figure 1 Illustration of conventional combustion and variants of clean diesel combustion on Φ -T map [11]

Conceptually, for the conventional diesel combustion, the fuel-air charge undergoes rich combustion at the end of the adiabatic mixing process during the ignition delay period [11]. This rich combustion may lead to soot-formation depending upon the sooting tendency of the fuel and the Φ -T distribution during the pre-mixed combustion phase. Once the fuel prepared to flammability limits during the ignition delay period is combusted, the rate of combustion proceeds on a mixing-controlled basis. During the course of diesel combustion, the thermal NO_x is generated at times when the local in-cylinder temperatures are in excess on 1800~2000K and there is sufficient oxygen availability [12]. For the traditional diesel combustion, the local- Φ and the local-T stretch into NO_x and the soot islands and as a consequence both engine-out NO_x and soot are observed. The Φ -T map has also been used to formulate pathways for simultaneous low-NO_x and low-soot combustion and these have been called HCCI and LTC pathways as shown in **Figure 1**.

HCCI Combustion: The combustion of a lean or diluted, well-premixed cylinder charge has shown to yield simultaneous low-NO_x and low-soot emissions and this type of combustion has come to be known as HCCI combustion. HCCI combustion does not rely on maintaining a flame front and is instead characterized by spontaneous auto-ignition of cylinder charge at multiple points and this allows for the combustion of very lean or the dilute mixture. The flame temperatures are significantly lower than the diesel combustion given the lean or diluted cylinder charge conditions and thereby result in low engine-out NO_x. At the same time the well-premixed nature of the cylinder charge helps to lower the soot emissions as well [13,14,15,16]. The pathway for HCCI combustion has been shown by solid black arrows in **Figure 1**.

Challenges of HCCI Combustion: The traditional approach to prepare the lean-premixed mixture for conventional diesel fuel is by injecting all the fuel very early during the compression stroke in a single or series of injection events depending on the engine-speed and the load condition [17,18,19,20]. The preparation of the lean-premixed mixture is considered challenging because of the low-volatility and the high cetane number for the conventional diesel fuel. The low-volatility of the diesel fuel necessitates that the in-cylinder injection strategies are initiated after 280~290° which limits the time duration available for mixture preparation for a typical application. Note that these injection windows are dependent on compression-ratio, and intake-temperature as discussed in Reference [21]. Similarly, the high cetane number of the conventional diesel fuel results in a strong propensity for the fuel to auto-ignite during the compression stroke, causing large rates of pressure rise and poor power output. Large amounts of cooled EGR, variable-valve timing (VVA) or variable-compression ratio (VCR) are some of the commonly used techniques for suppressing the auto-ignition of the fuel injected early during the compression and attain the appropriate combustion phasing. Tremendous progress has been made in understanding the HCCI combustion in the recent times, however, implementation of a robust combustion phasing control in a multi-cylinder engine with conventional diesel fuel in a production feasible way is still considered a major challenge [20,21,22].

LTC Combustion: Another alternative combustion mode being actively investigated for achieving clean-diesel combustion is LTC. In this combustion mode, the soot suppression is realized by lowering the combustion temperature below the threshold temperature for soot formation [11,23]. At such low flame-temperatures, the reactions forming soot particles from polycyclic aromatic hydrocarbons (PAH) are inhibited even at air-fuel ratios approaching near stoichiometric conditions.

Challenges of LTC: The low-temperature necessary for smokeless combustion has been traditionally obtained with the application of large amounts of cooled EGR. The high EGR rates necessary of this type of combustion also result in increasingly in-complete combustion as indicated by formation of large amounts of carbon-monoxide (CO) and un-burnt hydrocarbon (UHC), both of which result in a significant impediment to maintain the high fuel economy of the diesel engine cycle. Several LTC experiments, at moderate to high load with conventional diesel fuel have been reported on a single cylinder engine [24]. The application of LTC in a single cylinder engine is facilitated by the decoupled behavior of the boost and the EGR system; however such an air-management is not possible with the turbocharger system commonly present in a production engine. For a production engine, the application of large EGR rates can incur a significant penalty on boost levels

available and the soot may increase with EGR much more rapidly. In addition it may be noted that the single-cylinder LTC experiment results are usually reported for tests performed at constant fueling. This is in direct contrast to a production intent multi-cylinder experiment where the tests are performed on constant load, which necessitates that the fueling be constantly adjusted to maintain a constant load even in the regions where the LTC engine cycle efficiency begins to drop significantly in the presence of high CO and HC.

PCCI as a middle path between conventional and clean-diesel combustion modes: A compromise to avoid the difficulties of HCCI or LTC combustion is the PCCI combustion [25,26]. In the present work the authors have demonstrated that a $\text{NO}_x \sim 0.2 \text{ g/hp-hr}$ and an after-treatment tolerant soot level may be obtained with PCCI combustion to a load 16bar BMEP (brake mean effective pressure). This concept borrows features from both HCCI and LTC combustion modes. **Table 1** and **Table 2** compare the characteristics of the PCCI combustion with the HCCI and LTC respectively.

Comparison of HCCI and PCCI combustion: HCCI combustion suffers from the challenge of combustion-phasing control, limited load range and homogenous mixture preparation for a multiple-cylinder engine. To overcome these challenges, in PCCI combustion, only a part of the fuel undergoes HCCI type of clean combustion, while the remainder of the fuel undergoes conventional combustion. Since the majority of the fuel is undergoing conventional combustion, the combustion-phasing control is still governed by the injection scheduling. Since, only a part of the fuel is used to prepare cylinder-charge of enhanced homogeneity, the mixture preparation for PCCI combustion is less challenging in comparison to HCCI combustion. For the PCCI combustion, the late-cycle “soot-oxidation” may be employed by post-injection to limit the engine-out soot, an aspect significantly different from the HCCI combustion that targets primarily the “soot-formation” process. In the current experiments with PCCI combustion maximum soot level of 2FSN (Filter Smoke Number) is targeted, whereas the HCCI combustion targets a near zero soot level. The low- NO_x emissions are obtained in HCCI combustion by either pre-mixing to very lean equivalence ratios or by diluting the cylinder charge with EGR. However, for the PCCI combustion, retarded combustion phasing and a moderate amount of EGR are the primary enablers for NO_x reduction.

Table 1 Comparison of HCCI and PCCI

	Diesel HCCI	Diesel PCCI
Injection strategy	Lean homogenous mixture for simultaneous NO_x and soot reduction	- Lean homogenous mixture prepared by part of the fuel - Rest of fuel undergoes conventional combustion
NO_x	NO_x reduction due to lean homogenous charge or EGR dilution	EGR for NO_x reduction.
Soot	Homogenous mixture (near zero)	Engine-out target soot <2FSN.

Comparison of LTC and PCCI combustion: From a mechanism point of view, the simultaneous low- NO_x and low-soot combustion is realized during LTC by lowering the combustion temperature below the threshold for NO_x and soot formation on the $-T$ map. The use of large amounts of cooled EGR along with lowered compression ratio is one of the principle strategies to limit the flame temperatures. The injection strategies for the LTC combustion primarily consist of a single injection close to the TDC. The lowered in-cylinder temperature and the use of large amounts of EGR help to prolong the ignition delay and thereby, enhance the homogeneity of the fuel-air mixture in comparison to the conventional diesel combustion and lower the in-cylinder soot formation. Note the short times between the fuel injection event and the start of combustion still preclude thorough pre-mixing during LTC.

For PCCI combustion, the use of EGR is limited to reduce the combustion flame temperature below the threshold limit for NO_x alone and no attempt is made to approach the temperature threshold limit for soot formation. For the PCCI combustion, a retarded combustion-phasing (described by the crank-angle of 50% mass fraction burnt, CA-50) and an appropriate level of EGR was applied to limit the NO_x levels to less than 0.2 g/hp-hr . If the soot level was more than 2FSN, then the appropriate PCCI injection strategy was applied to limit the engine-out soot. For soot reduction, two injection strategies were used; pilot-with-main (Pil-M), and pilot-with-main-and-post (PMP). In the Pil-M injection strategy, the pilot fuel was delivered very early during the compression stroke; while the main fuel was delivered at close to top-dead-center (TDC). The pilot fuel typically had an ignition delay of more than 2milliseconds (ms) which helped to enhance the homogeneity of the pilot fuel and air mixture before the combustion process. The enhanced homogeneity of the pilot fuel helped to reduce the soot-level by up to 1FSN depending on the quantity of fuel injected, as shown later in the experiments. On an energy basis, the pilot fuel was kept to less than 25% of the total energy. This

injection strategy was valid up to a load of ~10bar BMEP, while at higher loads the Pil-M injection strategy alone was insufficient for lowering the soot levels to less than 2FSN. Therefore, at higher loads late cycle soot oxidation was implemented using PMP injection strategy.

Table 2 Comparison between LTC and PCCI

	Diesel LTC	Diesel PCCI
Injection strategy	Primarily single-shot	Primarily multiple-shot
NOx	EGR for NOx reduction.	EGR for NOx reduction.
Soot	Uses large amounts of EGR to suppress soot formation.	Multiple injection to target soot < 2FSN.

SETUP

The base engine was the International 6.4L V8 engine used in medium duty trucks and school buses. The details of the hardware configuration selection are described in Reference [27], and only the salient features are highlighted below.

Engine Design - The engine layout was accomplished by a procedure illustrated in **Figure 2** encompassing (1) defining the engine torque curve, (2) defining the boundary conditions to sustain PCCI combustion, (3) selection of engine hardware, (4) optimized fuel injection equipment, and (5) set up of control supervisor. The modified air management system consisted of a dual-stage turbocharger with a by-pass system. It allowed implementation of boundary conditions that target equivalence ratio () between 0.6 to 0.9 and EGR levels of 40% to 50%. A combination of modified EGR-coolers and the intake charger cooler let engine operation at lower intake manifold temperatures compared to the baseline engine. Various compression ratios were examined and for the present work results are reported for the compression ratio of 14.3:1.

The engine operation was enhanced by a cylinder-pressure based control system that was able to balance all engine cylinders for torque and combustion-phasing with the aide of in-cylinder pressure transducers. A family of injectors encompassing the base injector and multi-row multi-hole injectors were examined both numerically and experimentally as part of this study. This paper reports results from a 7-hole injector-nozzle with an included spray-angle of 158°. Further details about the engine design procedure and hardware selection may be found in Reference [27]. Comparison of the base engine data with the present build is presented in **Table 3**.

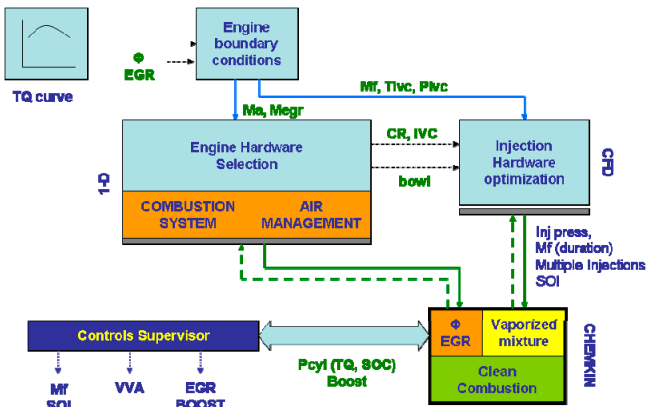


Figure 2 System Optimization

Table 3 Test Engine Specification

	Base Engine	Test Engine
Displacement	6.4L	6.4L
Bore	98.5mm	98.5mm
Stroke	105mm	105mm
FIE	DI Common Rail	DI Common Rail
CR	16.5	14.3
Turbo Charger	Single Stage VNT	Dual Stage VNT with by-pass
EGR system	HP loop Single Cooler	HP loop Dual Cooler
IVC EVO	-133 BTDC 132 ATDC	-133 BTDC 132 ATDC
Bowl Geometry	Re-entrant	Wide (non re-entrant)

Experimental Layout - The engine layout and experimental setup is shown in **Figure 3**. The engine air system incorporated a heater system in parallel to the charge air cooler and the two circuits together allowed intake manifold temperature regulation by using a set of two bypass valves. The present results correspond to a fuel with cetane index (ASTM D4737) of 43.1.

The total hydrocarbons were measured via a heated flame ionized detector, CO and CO₂ via a non-dispersive infrared analyzer, and oxides of nitrogen with a heated chemiluminescence detector. The smoke was measured by means of a classical filter paper method with resolution of 0.01FSN or soot concentrations of 0.1mg/m³. The cylinder pressure was measured with a piezo type transducer and was used to calculate cycle indicated torque and the heat release trace. The EGR ratio was expressed as the ratio of the intake to the exhaust CO₂ concentration.

The coolant temperature has a significant effect on the fuel efficiency and the emissions and therefore was tightly controlled during the experiments by a heat-exchanger system. For instance, during the high-load experiments at 16bar BMEP the coolant temperature was maintained within a window of 100~103°C.

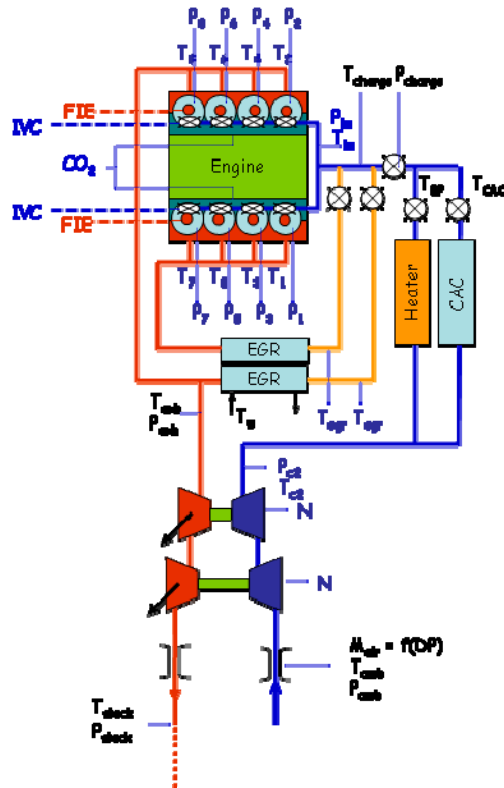


Figure 3 Experimental Layout

The engine is equipped with a variable valve actuation (VVA) system but this feature is not used in this present work. The fuel injection equipment (FIE) is controlled with a rapid prototype system controller.

RESULTS AND DISCUSSION

This project work is supported by the U.S Department of Energy and the objective of the work is to achieve the US 2010 emission norms without NOx after-treatment. The engine mapping with low-NOx was performed up to 7bar BMEP in the past [21] and in the present work the authors have extended the low-NOx map to the higher load regions.

PRELUDE TO PCCI COMBUSTION TESTS

Pilot-with-Main (Pil-M) Injection Strategy: The Pil-M injection strategy will be first discussed at an engine speed of 1750 rpm and a load of 10bar BMEP. At this condition, it was not possible to achieve $\text{NO}_x \sim 0.2\text{g/hp-hr}$ and $\text{soot} \leq 2\text{FSN}$ with the baseline single-injection

strategy. The use of PCCI combustion allowed meeting the desired NOx and soot emission levels at this condition. For this test, the effect of pilot-injection timing and quantity on soot emissions was the primary consideration. Computational fluid dynamic analysis was also performed to better understand the combustion process in the presence of pilot injection.

Pilot-with-Main-and-Post (PMP) Injection Strategy: The impact of PMP injection strategy was investigated at 8, 10 and 16.5bar BMEP. The tests at 8bar BMEP were done to identify the effective range of post-injection timings and quantities. The tests at 10bar BMEP were done to compare the relative merits of Pil-M and PMP injection strategies, since it was possible to meet the target $\text{soot} \leq 2\text{FSN}$ by both Pil-M and PMP injection strategies. At 16.5bar BMEP results showed that it was possible to meet the desired soot emissions only with PMP injection strategy.

In the remainder of this section details of the Pil-Main and the PMP injection strategy are provided.

PCCI COMBUSTION WITH PILOT-MAIN INJECTION

The baseline experiment with no pilot was performed with a single injection strategy configured to provide a CA-50 timing of 7.5° after-top-dead-center (ATDC). The EGR rate was selected so that a NOx emission of 0.18g/hp-hr was obtained. At this baseline operating condition, the soot was observed to be 3.3FSN.

The PCCI combustion with the Pil-M injection strategy was implemented to enhance the homogeneity of the pilot fuel and thereby reduce the engine-out soot. A part of the fuel was delivered early during the compression stroke at appropriate injection timing, so that this fuel had a chance to vaporize and form a lean homogenous mixture before the initiation of the combustion process. This increased homogeneity was expected to assist in the soot reduction. The first step was to identifying the crank-angle and the quantity of fuel that may be implemented as the pilot injection.

Effect of pilot timing and quantity: A sweep of the pilot injection timing showed no soot improvements for close to TDC injection timings. However as the pilot injection timings were advanced soot decrease was more apparent. If the pilot timing was advanced ahead of 50°BTDC, the HC emissions began to increase slowly, while there was no significant advantage for soot emissions (Figure 4). The CO also increased from 15.5 to 22g/hp-hr as the pilot injection timing was advanced to 70°BTDC from 50°BTDC. Based on emission considerations a pilot timing of 50~60°BTDC was used for the tests.