

Fuel Injection Strategies to Improve Emissions and Efficiency of High Compression Ratio Diesel Engines

Usman Asad, Ming Zheng, Xiaoye Han,
Graham T. Reader and Meiping Wang
University of Windsor

Copyright © 2008 SAE International

ABSTRACT

Simultaneous low NO_x (< 0.15 g/kWh) & soot (< 0.01 g/kWh) are attainable for enhanced premixed combustion that may lead to higher levels of hydrocarbons and carbon monoxide emissions as the engine cycles move to low temperature combustion, which is a departure from the ultra low hydrocarbon and carbon monoxide emissions, typical of the high compression ratio diesel engines. As a result, the fuel efficiency of such modes of combustion is also compromised (up to 5%). In this paper, advanced strategies for fuel injection are devised on a modern 4-cylinder common rail diesel engine modified for single cylinder research. Thermal efficiency comparisons are made between the low temperature combustion and the conventional diesel cycles. The fuel injection strategies include single injection with heavy EGR, and early multi-pulse fuel injection under low or medium engine loads respectively. The empirical studies have been conducted under independently controlled exhaust gas recirculation, intake boost, and exhaust backpressure. Multiple fuel injection pulses per cycle and heavy EGR have been applied to modulate the homogeneity history in order to improve the phasing and efficiency of the combustion process. The new low temperature combustion trade-off, that is, CO & THC vs. NO_x & soot is presented in the context of the different fuel injection strategies.

INTRODUCTION

Conventional diesel engines are overall lean-burn systems; however, the classical heterogeneous nature of the high-temperature combustion (HTC) presents numerous challenges regarding nitrogen oxides (NO_x) and particulate matter (PM) emissions. In such diesel engines, the flames tend to initialize in and propagate to regions where the air/fuel ratios are near-stoichiometric [1–4], thus presenting an inherent NO_x-PM trade-off.

To enable compliance with the diesel emission norms, the modern diesel engines utilize a multitude of advanced combustion strategies. The current trend has been to split the heat release into multi-events or even to

shift the heat release away from the top dead centre (TDC) in order to lower the combustion temperature when low emissions of oxides of nitrogen (NO_x) or low noise are targeted [5,6]. In this aspect, the use of exhaust gas re-circulation (EGR) or injection-timing retard has been effective in reducing in-cylinder NO_x formation [5] mainly because the thermal, dilution and chemical effects of EGR lower the flame temperature as well as oxygen concentration of the working fluid [2,6–10]. However, the application of EGR usually increases PM formation because of the predominant diffusion-controlled combustion where the lack of oxygen would lead to soot formation on the rich side of the reaction zone especially at high load conditions [11]. Furthermore, retarding the injection timing also tends to increase the soot formation attributed to the decreasing temperatures during the expansion stroke [10,12]. When the injection occurs near or after the TDC, the decreased fuel-air mixing time caused by the shorter ignition delay leads to lower combustion temperatures. This reduction in the combustion temperatures tends to inhibit the soot destruction rates, thereby increasing the engine-out soot. The hydrocarbon (THC) and carbon monoxide (CO) emissions also tend to depart from the ultra low values, typical of the HTC process. However, the penalty on the fuel efficiency is typically very low [12,13].

Additionally, low-temperature combustion (LTC) strategies, such as homogeneous charge compression ignition (HCCI) and smokeless diesel combustion entail the burning of a homogenous charge that is lean and/or EGR diluted and are therefore prone to produce much higher CO and THC emissions. This can drain a substantial amount of fuel energy from the LTC cycles and presents a major challenge for LTC implementation. Nonetheless, these combustion modes offer the potential of simultaneously reducing NO_x and soot emissions [8,14–24]. Simultaneous low NO_x and low soot are attainable for homogeneous LTC by either pre-mixing to very lean equivalence ratios or by employing EGR to reduce the combustion temperatures of mixtures with high equivalence ratios. For a thoroughly mixed cylinder charge, the tendency for soot formation is low largely regardless of the mixture strength.

The load level of the LTC cycles is limited by the peak cylinder pressure, the maximum rate of pressure rise and the peak combustion temperature. A fuel-lean charge of high homogeneity commonly precedes the LTC mode in diesel engines from low to medium loads. The high homogeneity is 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. Any non-homogeneity will therefore increase the local flame temperature in regions close to stoichiometric air/fuel ratio.

EGR is the commonly applied technique to further withhold the cylinder charge from ignition, which gains time for fuel-air mixing. Additionally, EGR weakens the strength of the spontaneous homogeneous LTC that needs to be contained to limit the maximum cylinder pressure and pressure rise rate. However, incomplete combustion occurs as the abundance of oxygen depletes even with high homogeneity [25]. A higher intake pressure, boost, is therefore beneficial to reduce the incomplete combustion in addition to lowering the fuel strength of the homogeneous cylinder charge.

The possible pathways for enabling LTC are shown in Figure 1. At low loads, LTC may be realized with a single late injection and the use of heavy EGR. As the load level increases, multiple early injections can be utilized to prepare a lean/weak homogenous charge what would result in low NOx and soot emissions. A combination of advanced fuel scheduling strategies and EGR may help to realize LTC cycles on high compression ratio (CR) diesel engines. The implementation of these strategies is one aim of this research work. Moreover, as the load requirements change, there is a need to switch between diesel and LTC combustion modes for maintaining emissions below the desired levels which can be implemented with different EGR strategies. For example, idle and full load operations can be done with conventional diesel operation and high amounts of EGR. For low to high loads, LTC cycles can be employed using the strategies outlined.

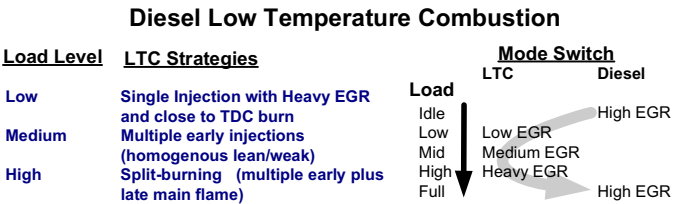


Figure 1: Diesel Low Temperature Combustion

A number of other strategies have been recently reported in the literature to withhold the cylinder charge from ignition in combination with EGR, the common ones being lower CR and variable valve timing (VVT). Mendez et al. [26] achieved an indicated mean effective pressure (IMEP) of 7 bar and low indicated NOx emission of 0.06 g/kWh with a CR 14:1 engine using 2 injections per cycle and 45% EGR. Dronniou et al. [6] used a CR 14:1 engine, single injection per cycle, EGR rate of 47% to

achieve a brake mean effective pressure (BMEP) of 10 bar while maintaining low NOx and soot emissions.

Kodama et al. [19] used a combination of different CRs, VVT, intake temperatures and EGR rates to achieve simultaneous low NOx and low soot emissions at different engine loads. With a CR of 16.8:1, they were able to achieve a BMEP of 5 bar; CR 13:1 for 8 bar; CR 10:1 + VVT for 18.3 bar. The implementation of the LTC cycles is generally in low compression ratio engines such as 16:1, 14:1 or even lower. In all the above cases, the CO and THC emissions were very high.

Engines with a CR of 17:1 or above are generally considered not suitable or are commonly restricted to low load operation only while operating under LTC or HCCI type of combustion. Agrell et al. [27] have reported attainment of IMEP up to 5.6 bar with VVT and CR 18:1 under HCCI operation. Neely et al. [28] reported an IMEP of 8.2 bar with CR 18:1 utilizing a dual loop EGR system. The high pressure EGR loop was fitted with a diesel oxidation catalyst (DOC) and the low pressure EGR loop was after the DOC-DPF in the exhaust system. The removal of soot and oxidation of the THC and CO improved the stability of the engine and therefore, helped to achieve a relatively higher load.

The research presented above has employed an additional technology to improve the load range of HCCI/LTC cycles in high CR diesel engines. However, a strict control on the engine operating parameters like EGR, boost and management of the fuel injection scheduling may help to extend the load range of LTC cycles on conventional high CR engines and therefore, overcome the challenges of operating through the narrower LTC combustion mode corridors.

In this work, a modern diesel engine with a CR of 18.2:1 has been used to investigate the attainment of simultaneous low NOx and low soot in mixed mode combustion. Comparisons are made with conventional single- and two-injections combustion modes for efficiency, noise and emissions.

EXPERIMENTAL SETUP

A modern 4-cylinder Ford common-rail diesel engine, running in single-cylinder mode was instrumented for the tests as shown in Figure 2. The 3 cylinders-to-1 cylinder configuration is a new exploration strategy that enables investigation of unstable combustion regimes with a non-motoring dynamometer. The 3 cylinders are operated in the conventional HTC mode at low load for stable engine operation. The combustion in Cylinder 1 is then pushed into the LTC cycles by independently controlling the EGR, boost, exhaust backpressure and fuel scheduling. The geometric specifications of the test engine are given in Table 1.

Table 1: Test Engine Specifications

Engine Type	4 Cylinder, 4 Stroke Ford DuraTorq "Puma"
Displacement [cm ³]	1998
Bore x Stroke [mm]	86 x 86
Compression Ratio	18.2:1
Combustion System	Direct Injection
Maximum Cylinder Pressure	~180 bar
Injection System	Common-rail (up to P _{Rail} ~ 160 MPa)

A dual-bank exhaust analyzer system (NO_x, THC, CO, CO₂, O₂, and soot) has been instrumented for the tests; one for the exhaust emissions and the other for the intake gas concentrations. The engine boost, exhaust backpressure, and EGR valve opening are precisely controlled with a set of PC-based systems. The engine coolant and lubricant oil conditions are monitored and controlled closely with external conditioning systems to minimize the discrepancies of the testing results.

The control platform consists of a set of embedded real-time (RT) controllers, field programmable gate array (FPGA) devices, and synchronized high-speed signal conditioning, and recording units. Up to 6 fuel injection pulses per cylinder per cycle can be configured and applied to modulate the homogeneity history of the cylinder charge in mixed mode combustion in order to improve the phasing and completeness of combustion.

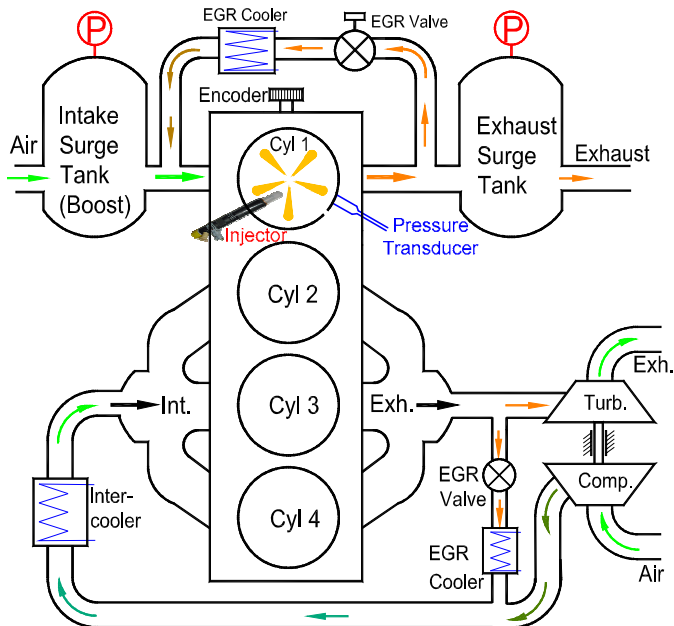


Figure 2: Schematic Representation of the Test Setup with independent control on intake boost and exhaust backpressure at University of Windsor.

In-cylinder pressures were acquired using a flush-mounted AVL G13P pressure transducer in Cylinder 1 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. The net heat-release rate was calculated from a simplified approach, shown in Equation 1, which was derived from the first law of thermodynamics [29].

$$\frac{dQ_{app}}{d\theta} = \frac{dQ_{gr}}{d\theta} - \frac{dQ_{ht}}{d\theta} = \frac{1}{\gamma-1} \left[\gamma p \frac{dV}{d\theta} + V \frac{dp}{d\theta} \right] \quad (1)$$

where $dQ_{gr}/d\theta$ is the heat release rate by combustion, $dQ_{ht}/d\theta$ is the cylinder charge-to-wall heat transfer rate, $dQ_{app}/d\theta$ is the apparent or net heat released, θ is the engine crank angle, γ is the ratio of specific heats (1.37 was used), and p and V the instantaneous cylinder pressure and volume, respectively. The normalised heat-release rate obtained from Equation 1 was compared with that obtained by other techniques [29]. The phasing was found to be within $\pm 1^\circ\text{CA}$ and the results were in reasonable agreement. The heat-release rates presented in the present study are, therefore, normalised by the total cumulative energy.

To precisely regulate the amount of EGR, an exhaust backpressure valve was actuated by an in-house developed PC-control system, to control the pressure differential between the exhaust and the intake. The amount of EGR was then regulated with a combination of the EGR valve opening and the backpressure, independent of the engine operating conditions. The amount of EGR could be estimated from Equation (2), where $\dot{m}_{EGR}$ is the mass flow rate of the recycled gases, $\dot{m}_a$ is the mass flow rate of the fresh air and $\dot{m}_f$, the mass flow rate of the fuel.

$$\text{EGR Fraction} = \frac{\dot{m}_{EGR}}{\dot{m}_a + \dot{m}_f + \dot{m}_{EGR}} \quad (2)$$

Empirically, the amount of EGR could be evaluated with sufficient accuracy by measuring the carbon dioxide (CO₂) concentration in the intake and exhaust [2,30,31]. Alternatively, under steady operating conditions, the EGR rate could be evaluated from Equation (3) where $MAF_{current}$ and $MAF_{initial(w/o EGR)}$ are the intake mass air flow rates with and without EGR application, respectively.

$$\text{EGR Fraction} = 1 - \frac{MAF_{current}}{MAF_{initial(w/o EGR)}} \approx \frac{\text{Intake CO}_2}{\text{Exhaust CO}_2} \quad (3)$$

In this work, the EGR has been calculated based on the intake and exhaust CO₂ concentrations.

DEFINITIONS

The following terms have been used in the paper and are therefore defined here.

SOC – refers to the ‘*Start of Combustion*’ and is defined as the crank angle at which the value of the normalized cumulative heat release curve is 0.05.

CA50 – is the crank angle at which the value of the normalized cumulative heat release curve is 0.5. This is taken as a measure of the combustion phasing.

Combustion Duration – is the duration from the SOC to the crank angle at which the value of the normalized cumulative heat release curve becomes 1.

Slope 1– the segment of soot climbing but NOx declining curve when EGR increases during HTC combustion. It represents the classical NOx-Soot trade-off.

Slope 2 – the segment of simultaneous soot and NOx declining curve when EGR increases (during LTC combustion). It represents the reduction in NOx and soot enabled with a single injection using heavy EGR.

Heavy EGR – refers to large amounts of recycled exhaust gases that result in nearly halved oxygen and high carbon dioxide contents in the engine intake. This indicates EGR levels (typically 50~70%) beyond those commonly applied in production diesel engines.

LTC – refers to any combustion mode that results in ultra low emissions of in-cylinder NOx and PM in conventional diesel engines.

For the single injection, the SOI is designated as SOI_{Main}. For multiple injections (2 or more), the SOI is marked with a subscript indicating the number of the injection.

RESULTS AND DISCUSSION

The aim of this work was to experimentally determine the influence of different injection strategies on the emission and fuel efficiency performance of high CR diesel engines. Tests have been run for both conventional HTC and LTC cycles using 1, 2 and 3 injections for low-load to mid-load range of operation. All the tests have been performed at 1500 RPM.

SINGLE-SHOT VS. 2-SHOT STRATEGY

The use of a pilot injection primarily reduces combustion noise which is a consequence of the high rate of pressure rise (pressure gradient or $dp/d\theta$) due to the rapid combustion of the premixed fuel-air mixture. The amount of fuel that takes part in the premixed phase of diesel combustion is strongly related to the time available for mixing and the cylinder temperature history between the SOI and the SOC – the ignition delay period. The pilot injection can help to reduce the ignition delay duration by elevating the temperature and the pressure before the commencement of the main injection. As a result, the ignition delay of the main injection can be significantly shortened so that the premixed portion of the heat release is reduced, along with a significant decrease in the maximum pressure gradient [32].

The test matrix for the single and two-injection tests is given in Table 2. An EGR sweep was performed to assess the effect of these injection strategies on the noise and NOx and soot emissions. EGR was regulated by changing the opening of the EGR valve while keeping the backpressure constant (~4 kPa). This ensures that the NOx emissions in particular will be minimally affected by the amount of residuals in the cylinder. To maintain the same combustion phasing for both the single- and 2-injection tests during the EGR sweep, the SOI_{Main} (commanded pulse width (PW): 615 μ s) and SOI₂ (commanded PW: 550 μ s) were progressively advanced for the single- and 2-injection strategies respectively. The pilot SOI₁ and pulse width (commanded PW: 280 μ s) were fixed and not changed during the tests.

Table 2: Single and 2 Injection Test Matrix

	No of Injections	
	1	2
SOI ₁ [°CA ATDC]	–	-25
SOI ₂ [°CA ATDC]	–	-10*
SOI _{Main} [°CA ATDC]	-11.4*	–
P _{inj} [MPa]	80	80
P _{intake} [bar abs]	1.45	1.45
T _{intake} [°C]	29~32	
IMEP [bar]	7	7
EGR	Sweep	Sweep
CA50% HR [°CA]	361, 366	

* at baseline EGR of 10%

For the case of combustion phasing (CA50) locked at 361°CA, the results are shown from Figure 3 to Figure 6. The SOC was also fixed at 354°CA.

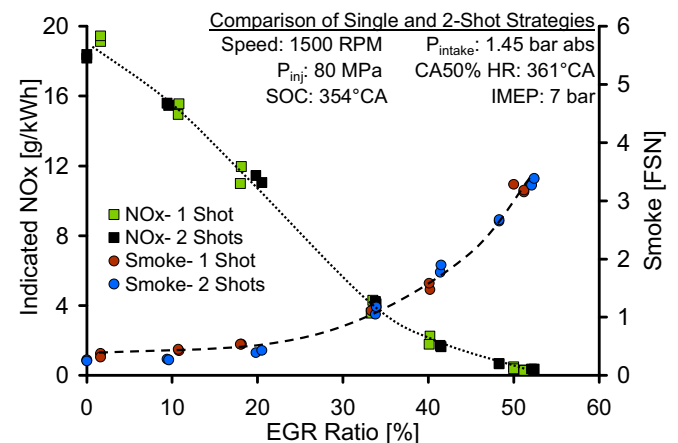


Figure 3: NOx and Soot Emissions for Single- and 2-Injection Strategies with CA50 at 361°CA

The variation of NOx and soot emissions with EGR, shown in Figure 3 indicates that there is virtually no difference in the emission performance between the two injection strategies. However, the 2-injection strategy

showed a significant drop in the combustion noise (Figure 5) up to 40% EGR.

The commanded SOI for the two strategies is shown in Figure 4. During the EGR sweep, the SOI_{Main} and SOI_2 were progressively advanced to maintain the same combustion phasing for both the single- and 2-injection strategies respectively. It is noted that at higher EGR levels (>40%), the ignition delay increases rapidly, causing a sharp increase in the maximum rate of pressure rise (combustion noise) as shown in Figure 5.

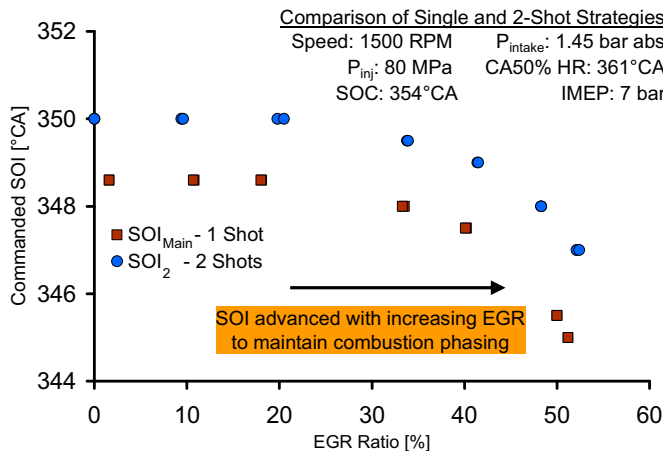


Figure 4: Variation of Commanded Start of Injection for Single- and 2-Injection Strategies with CA50 at 361°C

The use of 2-injection strategy has been reported to reduce NOx emissions and increase soot emissions compared to the single injection strategy [26,32]. To investigate the reasons for the emissions results of Figure 3, the combustion duration was plotted in Figure 5. It can be seen that although the combustion duration increased with increasing EGR, it was the same for the both the injection strategies. To further analyze this aspect, the heat release rates for 3 different levels of EGR are shown in Figure 6.

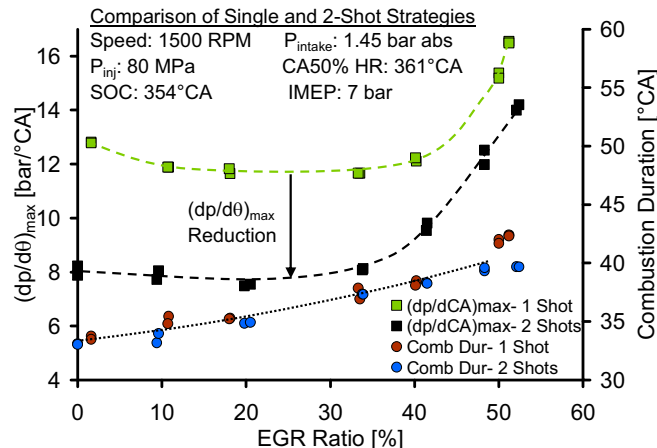


Figure 5: $(dp/d\theta)_{max}$ and Combustion Duration for Single- and 2-Injection Strategies with CA50 at 361°C

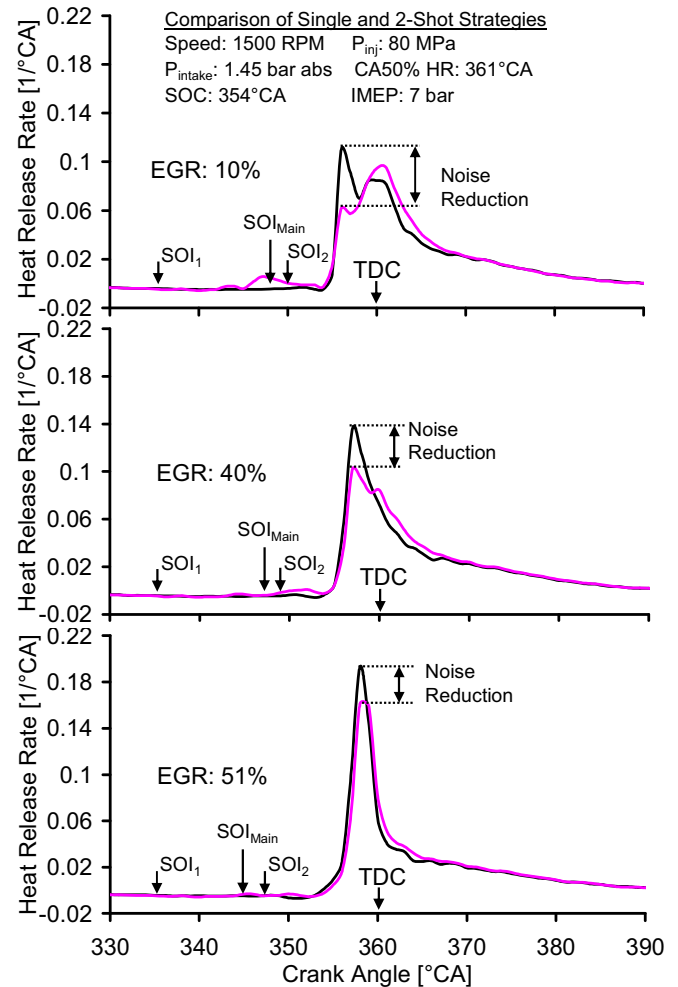


Figure 6: Heat Release Rate Comparison between Single- and 2-Injection Strategies (CA50: 361°C)

For all the 3 cases of 10%, 40% and 51% EGR, the SOC, the CA50 and the combustion duration are the same. Moreover, the pilot injection suppresses the premixed combustion so that a significant noise reduction is achieved. Although reducing the premixed phase may help to reduce NOx [9,33], the phasing of the combustion also is critical to the production of NOx and soot. Previous results show a retarded phasing beyond TDC for the 2-injection strategy [26]. The off-phasing of the combustion after TDC reduces the combustion temperature which may reduce the NOx and increase soot (soot destruction is inhibited). Since the combustion phasing was maintained nearly at TDC during the current work, the diffusion-controlled combustion occurred around TDC. Also, the tail of the combustion matches for both the injection strategies. Therefore, the effect of the 2-injection strategy on the NOx and soot is negligible in this particular case.

As EGR increases, the dilution effects of EGR increase the ignition delay and the diffusion-controlled combustion is observed to reduce. However, the 2-injection strategy still benefits from lower pressure gradients compared to the single-injection combustion. The summary of the above results along with the fuel efficiency is given in Table 3.