

Using Multiple Injection Strategies in Diesel Combustion: Potential to Improve Emissions, Noise and Fuel Economy Trade-Off in Low CR Engines

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ABSTRACT

In former high compression ratio Diesel engines a single injection was used to introduce the fuel into the combustion chamber. With actual direct injection engines which exhibit a compression ratio between 17:1 and 18:1 single or multiple early injections called "pilot injections" are also added in order to reduce the combustion noise. For after-treatment reasons a late injection during the expansion stroke named "post injection" may also be used in some operating conditions.

Investigations have been conducted on lower compression ratio Diesel engine and in high EGR rate operating conditions to evaluate the benefits of multiple injection strategies to improve the trade off between engine emissions, noise and fuel economy. These experiments have highlighted that in the thermodynamic conditions specific to low CR engines and high EGR rate interesting effects on the combustion process could be achieved via multiple injections strategies involving the following phenomena:

1. Fuel introduction and heat release splitting
2. Control of the fuel distribution in the combustion chamber
3. Cooling effect of the vaporizing fuel

Decreasing the peak heat release by splitting the heat release process appears to be adequate for controlling the combustion noise. It is achieved by using several injections in the appropriate thermodynamic and auto-ignition delay conditions in order to reduce the instantaneous fuel burning rate. Thanks to this resulting noise reduction, the engine settings can be re-optimized toward a new trade off.

Multiple injection strategies can also be used to better control the spatial fuel distribution to enhance the air use in the combustion chamber. Generally, this effect can lead to a reduction in particulate emissions at intermediate engine loads, allowing for potentially higher EGR rate.

The cooling effect associated with fuel vaporization lowers locally and globally the temperature of the gases contained in the combustion chamber. If well-understood, these phenomena can be applied to increase the ignition delay, allowing for a longer mixing period and thus a more homogeneous fuel/air mixture, and/or to modify the rate of heat release in the early stage of combustion. Appropriate use of the cooling effect provides a valuable degree of freedom in the optimization of the noise / emission / fuel economy trade off.

INTRODUCTION

To meet next emissions regulation which include low NO_x and low soot levels, homogenous or partially homogeneous Diesel combustion is a promising approach [1-3]. So called Homogeneous Charge Compression Ignition (HCCI) [1], Highly Premixed Combustion (HPC) [5-6] or Low Temperature Combustion (LTC) [7-8] all refer to combustion systems based on enhanced air/fuel mixing and/or high dilution (Figure 1) [2].

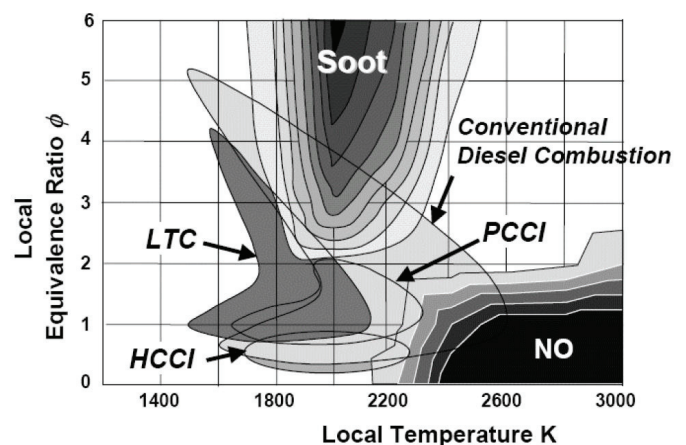


Figure 1: Conventional and other combustion process zones in the NO_x and Soot areas – Figure from Neely, et al, SAE Paper 2005-01-1091.



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These combustion modes can be implemented using low CR engines such as 14:1, 16:1 or lower and high EGR rates in order to increase ignition delay. By increasing ignition delay, the homogeneity of the air and fuel mixture is enhanced and consequently local equivalence ratios are reduced, preventing soot formation [3]. The use of high EGR rates also allows to significantly reduce temperature in the combustion chamber and O_2 concentration. Both effects lead to a NO_x emissions reduction [11-12]. Nevertheless, the implementation of these combustion modes in production engines still faces significant limitations [6]. In particular, the operating range where these specific combustion modes can be applied is limited to a small area of the engine map [13-14], as represented in figure 2.

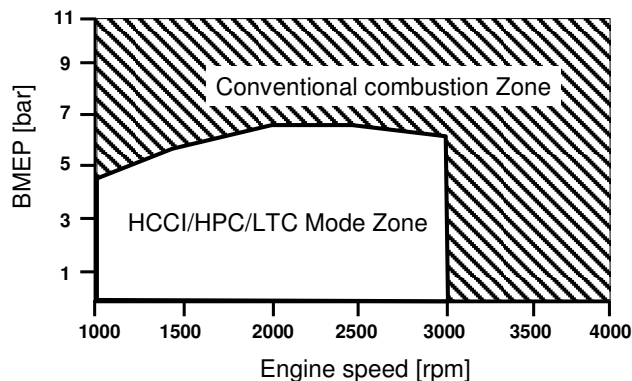


Figure 2: Operating range

Moreover, controlling the combustion noise, maintaining efficiency comparable to today's direct injection Diesel engines and limiting the CO and UHC emissions when using these non conventional combustion modes still represent a difficult challenge [1, 15-17]

For each operating point, trade offs between engine emissions, combustion noise and fuel economy are necessary. In this work, investigations have been conducted on low compression ratio Diesel engine at high EGR rate operating conditions to evaluate the potential of multiple injections. These experiments have highlighted that in the thermodynamic conditions specific to low CR engines and high EGR rate interesting effects on the combustion process could be obtained via multiple injections. In most cases these effects significantly differ from the ones that are observed and used in higher CR diesel engines.

EXPERIMENTAL PROCEDURES

ENGINE SPECIFICATIONS

The results presented in this paper are a compilation of several studies conducted at IFP with several different engines with their own characteristics, including prototype single cylinder engine and multi cylinder engines from commercial vehicles. The following table describes all the engines which were used for this study.

Table 1: Engines specifications

Engine number	#1	#2	#3	#4	#5
Type	Small Bore Light-Duty engine				
# cylinder	4	1	4	1	1
CR	14, 15, 16:1	14:1	16:1	14:1	15:1
Bowl shape	Toroidal	Nadi	Toroidal	Toroidal	Nadi
Valves/cylinder	4	4	4	4	4
FIS	Advanced common rail system				

The fuel used for all the tests is a Diesel fuel that meets European Norm EN 590 (max sulfur level of 50 ppm).

HEAT RELEASE COMPUTATION

The apparent heat release has been calculated by applying the first thermodynamical law and the Woschni heat transfers [24]:

The in-cylinder pressure is measured by a combustion chamber pressure sensor mounted in the glow plug location.

IN-CYLINDER TEMPERATURE COMPUTATION

In-cylinder temperature was estimated using the in-cylinder gas mass trapped at IVC, which was determined with intake air flow rate and EGR rate measurements. The internal residual gas (IGR) rate was assumed to be 5%. Using ideal gas law ($P.V = m.r.T$) the in-cylinder temperature was computed for each crank angle.

SPECIFICITY OF LOW COMPRESSION RATIO ENGINES AND HIGH EGR RATE

Direct injection Diesel engines that meet Euro III emissions standards used to have a high compression ratio and only a single injection was necessary to introduce the fuel into the combustion chamber thanks to less restrictive emissions specifications and noise limits. With actual direct injection engines which exhibit a compression ratio between 17:1 and 18:1 single or multiple early injections called "pilot injections" [18-19] are added in order to reduce the combustion noise. With the development of new after-treatment systems such as particulate filter or to reduce soot, UHC and CO a late injection during the expansion stroke named "post injection" may also be used in some operating conditions [20-21].

It is well-known that decreasing the compression ratio for example from 18:1 to 14:1 induces longer ignition delay, mostly due to the reduction of the in-cylinder temperature [22]. Moreover, using high EGR rates also results in an increased ignition delay due to in-cylinder gas dilution.

However, it is rarely reported that low CR engines and high EGR rates can lead to misfire of small injected fuel quantities such as those which are used for pilot injection.

In fact, when the CR is reduced ignition delay increases and the peak heat release associated with the combustion of the pilot injection is greatly reduced. For CR 14:1 the distinct initial heat release associated with the fuel injected during pilot injection is very often close to be null unless the fuel amount injected during the pilot injection is greatly increased. No distinct combustion of the pilot injection can be identified from the heat release analysis. Figure 3 shows an illustration of pilot injection that does not burn before main injection. This is due to a low CR engine (14:1) and a high EGR rate (46%) that lead to a so long ignition delay that the fuel of the pilot injection is over dispersed and that the resulting very lean mixture never reaches auto-ignition condition before the main combustion phase. As a consequence, for identical EGR rates, single and double injection strategies exhibit similar heat release profile. This is due to the fact that the fuel from the first and second injection burns at the same time.

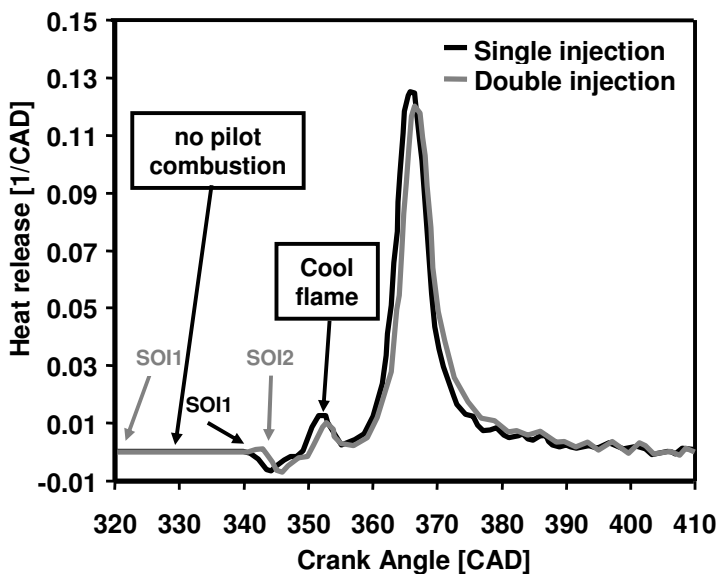


Figure 3: Effect of low CR and high EGR rate on ignition of pilot injection - 1500 rpm – IMEP 4 bar – Engine #2

Pilot + main type injection strategy is typical for these operating conditions in high CR Diesel engines associated with a moderated EGR rate. Of course, in this later case, pilot injection burns and modifies in-cylinder temperature so that ignition delay of the main injection is reduced and conventional diffusion-type diesel combustion is quickly achieved.

Table 2: Single and double injection settings

	SOI 1 [CAD]	SOI 2 [CAD]	Prail [bar]	EGR rate [%]
1 injection		20	1800	46
2 injections	37	18	1800	46

Tests have been run for different compression ratio (16:1, 15:1 and 14:1) and EGR rate (from 0% to 45%), for several engine loads and speeds. All tests have been performed with the same engine (engine #1) and CR variation has been achieved by using different piston bowls. All injection settings (SOI, injection duration and fuel pressure) were kept constant for each EGR rate to easily compare combustion behavior. Injection strategies contain one pilot injection. Injection settings were initially tuned for the highest CR (16:1). For each running condition a heat release analysis was conducted to check if the first injection could be associated with a positive heat release. The objective was to characterize the zone of operating conditions outside which pilot injection does not burn and thus should not be used for combustion noise control. To account for the effect of the intake temperature variations regarding to the engine operating load and speed and the compression ratio effect on in-cylinder temperature evolution, we have chosen to characterize the behavior of the pilot injection as a function of the in-cylinder temperature 20 CAD before TDC.

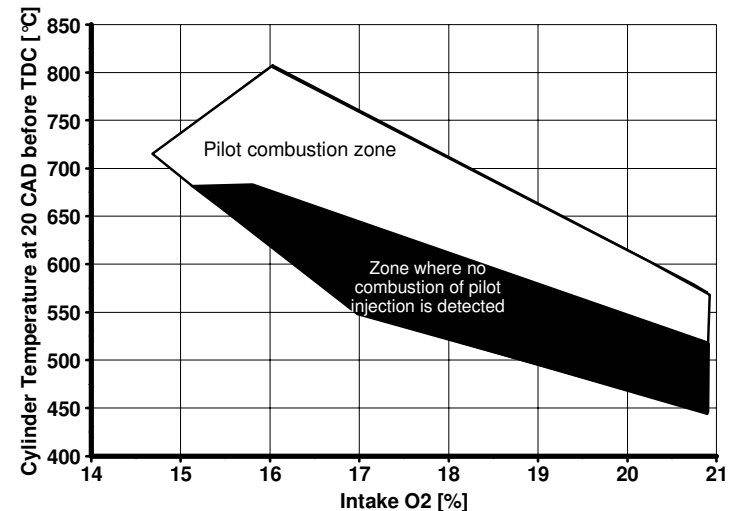


Figure 4: Effect of CR and EGR rate on ignition of pilot injection – Engine #1

The other considered parameter was the EGR rate (dilution gas). The presence of EGR induces a reduction of O_2 concentration which is responsible for lengthening auto-ignition delay [23]. Accordingly, the intake O_2 concentration was chosen rather than the EGR rate along with temperature to draw the 2D plot of figure 4. Results from all the tested running conditions were integrated in figure 4.

Figure 4 shows two different zones where the pilot injection burns or not. Each zone depends on the EGR rate represented by intake CO₂ percentage and the in-cylinder temperature before start of pilot injection represented by in-cylinder temperature at 20 CAD before TDC. This temperature is the result of the intake temperature and the volumetric compression defined by the compression ratio. It appears that low in-cylinder temperature and high intake CO₂ concentration prevent ignition of early-injected small fuel quantities. This corresponds to high EGR rate and low CR. As a consequence, it is not possible to transpose conventional injection strategies to a low CR engine in addition to high rate EGR. Injections settings must be adjusted and in particular it must take into account lower in-cylinder temperature, higher ignition delay and higher fuel dilution. Moreover, the specific in-cylinder thermodynamic conditions and the high EGR rates prevent using the pilot + main injection strategy, unless pilot fuel quantity becomes is greatly increased. In this case, we can consider that the strategy is no longer a conventional pilot + main strategy.

Nevertheless, some other types of multi injection strategies could be used. Those deal with different mechanisms of heat release control.

FUEL INTRODUCTION AND HEAT RELEASE SPLITTING

APPROACH

It is usually admitted that combustion noise measured with an AVL noisemeter and maximum heat release are in most case well correlated. So to decrease combustion noise it is advisable to limit the level of maximum heat release.

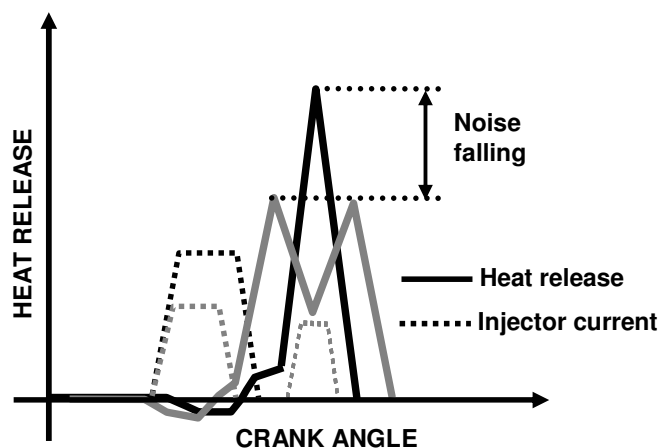


Figure 5: Conceptual diagram of heat release splitting

A promising approach is to split the fuel combustion process into two parts in order to get two separate heat release peaks triggered by two or more injections. The maximum amplitude of the split heat release is lower

than the peak heat release obtained with a single injection and this leads to a lower combustion noise. Depending on the auto-ignition delay of the second injection this specific heat release shape may correspond to two different combustion processes:

1. two premixed-type combustion phases or
2. one premixed-type combustion followed by a diffusion combustion of the second injection (see figure 5).

Thanks to this noise reduction, engine settings can be re-optimized toward a new trade off, in particular EGR rate may be reduced or the combustion phasing may be advanced toward an increased efficiency [15].

EXAMPLE OF HEAT RELEASE SPLITTING

This paragraph describes an illustration of the heat release splitting potential. We consider a 1750 rpm – BMEP 3 bar operating point realized both in single and double injections (Figure 6). The engine tested has a 16:1 CR, with a very high EGR rate (50%) (Engine #3).

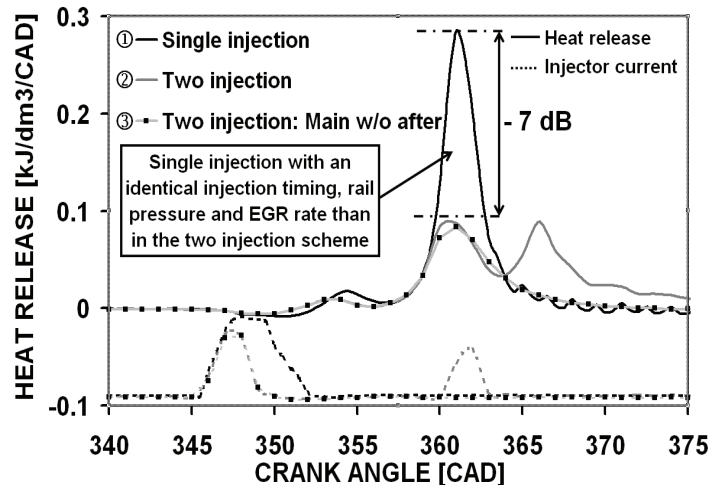


Figure 6: Single and double injections heat release 1750 rpm – BMEP 3 bar – Engine #3

Three injection strategies were tested with EGR rate set at 50% for all cases.

- ① A single injection strategy (EGR rate = 50%) optimized to achieve Euro V equivalent emission levels and a noise target determined by current production cars level.
- ② A double injection strategy: main + after with same start of injection for the main of the single injection scheme and EGR rate = 50%
- ③ A single injection strategy with only the main injection part of the double injection scheme (same SOI and injected quantity than the main injection of the double injection strategy). This test has been run by suddenly cutting off the second (after) injection while running the engine with the double injection strategy. We have only analyzed the first cycle after the second injection was cut