

Low temperature combustion(LTC) strategies employed in a Diesel Engine

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Abstract

Diesel engines are subject to strict emission control regulations and these rules are getting stricter by the decade. Emissions that are strictly monitored are NO_x, UHC and soot. It has been experimentally verified that NO_x reduces when temperature of the combustion chamber is decreased. However, this increases PM and UHC emissions. Strategies applied to reduce temperature and hence emissions in a diesel engine are known as LTC strategies. In this report two different LTC strategies are discussed. Experimental procedures used to determine the variables which affect temperature in each are also discussed. It has been experimentally verified that Injection pressure, Ignition delay and EGR are most important factors on which emissions from a diesel engine depends upon.

Introduction

Recent decades have witnessed huge reductions in the limits of emissions from diesel engines. Pollutants that are usually monitored are NO_x, particulate matter (PM), unburned hydrocarbons (UHC) and CO (emissions). When compared 1990s, NO_x, PM and UHC levels that are permitted are only 3-12%, 2% and 6-12% respectively. The Euro IV standards, followed by Europe and Asian countries, have stricter limits compared to the US limits on emissions. Pollutant emissions from a diesel engine mentioned previously is a function of temperature. NO_x formation occurs at temperatures above 2000K and rises exponentially with increasing temperature. Therefore, in order to reduce the in-cylinder combustion temperature, several techniques

are used and are collectively called LTC strategies. Almost all LTC strategies reduce combustion temperature by using varying levels of EGR for dilution of fuel-air mixture. PM emissions are also a function of temperature; however, reducing combustion temperature alone will not ensure lower PM emissions. High EGR rates do result in lower in PM emissions, but this reduces the combustion efficiency and results in UHC. The other after-effect of high EGR is CO emissions. As the dilution results in a fuel-lean mixture, it becomes imperative that fuel is mixed thoroughly before ignition. LTC strategies broadly describe techniques for optimum fuel injection, for in-cylinder mixing and EGR levels for dilution. Homogeneous-charge compression ignition, which is often described as one of the LTCs is not discussed in this work as HCCI relies heavily on mixing of the fuel such that there are no fuel-rich pockets in the mixture – this is because of very early injection of fuel into the chamber. PPCI-partially premixed compression ignition – which is the topic of discussion of this work – operates closer to conventional diesel engines, but do involve same levels of pre-mixing and has a positive ignition dwell. PPCI strategies usually inject the fuel into a cooler and less dense charge which can be achieved by early or late injection with respect to the TDC. Pre-ignition chemistry is further slowed down due to the ignition delaying effects of EGR. PPCI strategies are subdivided into two categories. First category is developed by Nissan and is called ‘Modulated Kinetics’ where fuel is injected near TDC or in expansion stroke. Other category investigates early injection PPCI, where the fuel is injected early in the compression

stroke, before piston reaches TDC[3]. LTC strategies are also gaining importance because they do not require after treatment devices to reduce emissions.

Modular Kinetics (MK)

This is a late PPCI where fuel is injected close to TDC, very early into the expansion stroke. It has been experimentally observed that NO_x reduces with reduction in O_2 concentration which is achieved in MK by incorporating EGR into the intake. However, this results in smoke due to lack of homogeneity in the mixture. To reduce smoke, premixed combustion is desired. Fuel injected into the combustion chamber needs some time to mix homogeneously with the charge gas. Fuel injection timing is retarded to ensure that mixture is sufficiently mixed. Combustion chamber design is also changed so that the swirl ratio is higher. An experiment has been setup to compare the heat release profiles of engine running on MK, with a conventional diesel engine. From figure 1, it is evident that high EGR heat release in case of MK combustion occurs at a later point

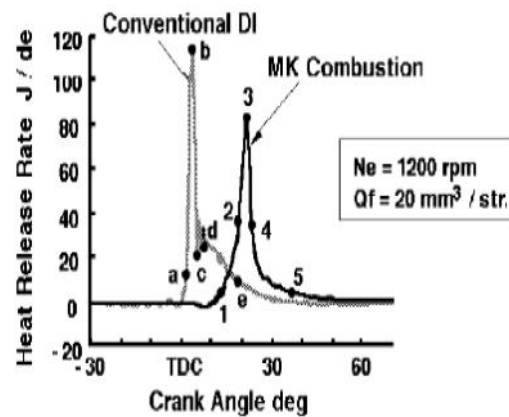


Figure 1 Comparison of heat release characteristics of MK combustion when compared to conventional DI

when compared to conventional DI. This is because heat release for DI occurs exactly at TDC where the fuel is ignited almost instantaneously. It can also be noticed that heat release rate, per degree, is lower. Normal diesel engine combustion has a two-staged profile with maximum heat dumped during the ignition phase but combustion proceeds to have a diffusion phase. MK combustion has a single staged profile and the amount of maximum heat dumped is lower. Photographs of normal diesel combustion are compared to MK combustion where MK combustion displays high transparency. It is concluded that high flame transparency results in lesser soot formation and lesser combustion temperatures. These hypotheses are not substantiated with numbers in reference [1]. Reference [1] also discusses two generations of MK with second generation being improvement over the first generation in terms of engine-load. Second generation MK runs the engine at higher loads and exhibits higher compression temperatures at TDC. This interferes with the basic functionality of MK combustion system for

which injection duration, in terms of CA degrees must be lesser than ignition delay. Injection duration of the fuel is lowered by increasing the injection pressure and also by increasing the nozzle diameter. Table 1 presents experimental results on emission parameters of a first generation MK

Table 1 Emission performance characteristics of a first generation MK

	O ₂ concentration reduction	IT retard	High swirl rate
UHC-Nox	inc-dec	inc-dec	dec-inc
Smoke-Nox	inc-dec	dec-dec	dec-inc
Thermal Efficiency-Nox	inc-dec	dec-dec	inc-inc

From table 1, it is clear that O₂ concentration reduction reduces NO_x by about 90% (experimental result) and injection timing (IT) retard reduces smoke. Thermal efficiency is hampered by retarded injection timing but it recovers the lost efficiency by increasing swirl rate.

For running second generation MK, the parameters that are changed to obtain an ignition delay longer than injection duration are injection pressure, compression ratio and an EGR cooler is included in the intake

system. It has been experimentally verified that, at an injection pressure of 1600 bar, a compression ratio of 16 and a running EGR cooler, required ignition delay is obtained. Figure 2 denotes reduction in PM and BSFC as a function of NO_x for conventional DI engine and MK combustion process.

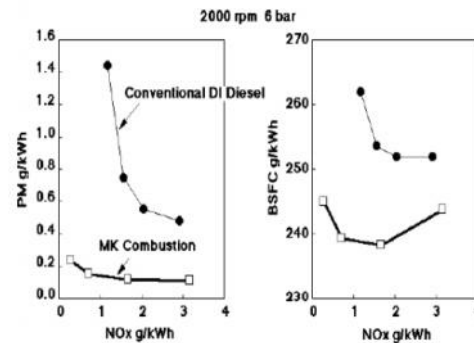


Figure 2 Comparison of NO_x, PM and BSFC between conventional and MK combustion

Following can be concluded from reference [1]

- Compression ratio, EGR and injection are optimizing parameters which regulate injection duration and ignition delay to obtain low temperatures in the cylinder
- Engine can be operated near stoichiometric ratios and the smoke concentrations can be reduced to less than 1 FSU
- MK concept can be used to achieve NO_x reduction rates of 98%

Early injection PPCI

Parameters that are controlled for employing this strategy are EGR and injection pressure. Two challenges that are to be dealt with, during experimentation, are hypothesized. One is the increased UHC emission due to

long mixing times, reduced in-cylinder temperature and locally lean stoichiometric ratios. The other challenge is ignition timing which is kinetically controlled. Diesel mixture has a tendency to ignite abruptly at a low temperature. This is controlled by varying the amount of EGR, Variable Valve Actuation (VVA) or Variable Compression Ratio (VCR). An experimental setup was developed by Ojeda et al [2] to change these parameters. Injection time for the late premixed injection for this experiment is 60 BTDC. Following observations are made from the experimental results

- Fuel vaporization is affected by fuel impingement and injection timing. As injection timing is closer to TDC fuel vaporization is enhanced and UHC rate decreases
- Injection pressures and EGR are varied to get the following plot

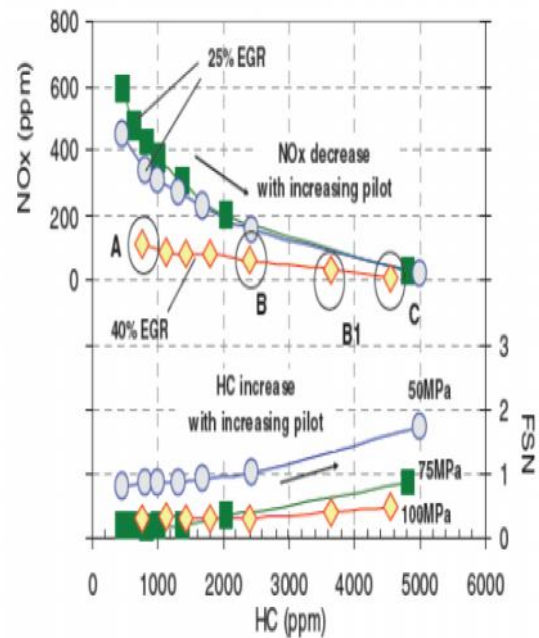


Figure 3 Fuel distribution impact on emission performance N=1000rpm, IMEP=4.5-4.7bar

- It is evident from the figure that NOx decreases with increasing EGR and soot decreases with increasing injection pressure.
- Reduction in NOx is due to reduced temperatures in the combustion chamber because of dilution while soot reduction is attributed to penetration of fuel and homogeneous equivalence ratio at higher injection pressure
- % EGR was maintained at 55% and SOI(Start of injection) was changed to see the effect on UHC and NOx and measured values are presented in table 2. As SOI approaches TDC, clearly UHC decreases
- It has been experimentally verified that an Ignition Delay(ID) of 10^0 - 7^0 is required for mixing

- Increase in injection pressure by 15 kPa reduces FSN by a unit of 1. Also, FSN reduces by 1 unit for every 5° delay

Table 2 Experimental values of UHC and NOx when SOI is varied with constant EGR

SOI (BTDC)	UHC (ppm)	NOx(ppm)
11	5000	Below 15
6	1800	Below 15

Following can be concluded from reference 2

- EGR percentages have a huge impact on NOx but it has a negative impact in terms of increasing UHC
- As injection timing is closer to TDC, UHC decreases as vaporization of fuel increases
- Increase in injection pressure decreases soot because of greater penetration of fuel into the combustion chamber which leads to homogeneous equivalence ratios

Summary and conclusions

Important variables that play an important role in reducing in-cylinder temperatures for promoting LTC are EGR percentage, injection pressure and ignition delay. All these parameters promote lower in-cylinder temperatures and hence lower NOx, but, increase UHC and soot if not used strategically. The experimental results

obtained through literature survey provide evidence that optimization of these parameters helps improve the performance emissions of an engine when compared to conventional CI engine. But these tests have not been performed on entire load range on an engine. It has also been mentioned in these references that it is difficult to implement these strategies at higher and varying loads, typical in an automobile application.

References

1. Shuji Kimura, Osam Aoki, Yasuhisa Kitahara, Eiji Aiyoshizawa, "Ultra-Clean Combustion Technology Combining a Low-Temperature and Premixed Combustion Concept for Meeting Future Emission Standards", SAE Technical Paper, 2001-01-0200, 2001
2. William de Ojeda, Phil Zoldak, Raul Espinosa, Raj Kumar, SAE, 2008-01-0057, 2008
3. Mark P.B. Musculus, Paul C. Miles, Lyle M. Pickett, Conceptual models for partially premixed low-temperature diesel combustion, Science-direct, 39 (2013) 246-283, 2013