INVESTIGATIONS OF EFFECTS OF PILOT INJECTION WITH CHANGE IN LEVEL OF COMPRESSION RATIO IN A COMMON RAIL DIESEL ENGINE

by

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These day diesel engines are gaining lots of attention as prime movers for various source of transportation. It offers better drive ability, very good low end torque and importantly CO_2 emission. Diesel engines are bridging the gap between gasoline and diesel engines. Better noise vibration and harshness levels of gasoline engine are realized to great extent in diesel engine, thanks to common rail direct injection system. Common rail injection system is now well known entity. Its unique advantage is flexible in operation. In common rail injection system, number of injection prior and after main injection at different injection pressure is possible. Due to multiple injections, gain in emission reduction as well as noise has been already experienced and demonstrated by researcher in the past. However, stringent emission norms for diesel engine equipped vehicle demands for further lower emission of oxides of nitrogen and particulate matter.

In the present paper, authors attempted to study the effect of multiple injections in combination with two level of compression ratio. The aim was to study the combustion behavior with the reduced compression ratio which is going to be tried out as low temperature combustion concept in near future. The results were compared with the current level of compression ratio. Experiments were carried out in 2.2 L cubic capacity engine with two levels of compression ratios. Pilot injection separation and quantities were varied keeping the main injection, rail pressure, boost pressure, and exhaust gas recirculation rate constant. Cylinder pressure traces and gross heat release rates were measured and analyzed to understand the combustion behavior.

Key words: *compression ratio, common rail, pilot injection, pilot quantity*

Introduction

Diesel engines are lean burn engine and posses advantage of being more fuel efficient than its counterpart gasoline. Oxides of nitrogen (NO_x) and particulate matter (PM) is of prime concern in case of diesel engine and needs cost effective solution in order to be competitive in the market. In order to address the stringent emission norms worldwide, the solution for their control is classified into two broader ways [1]:
(1) in cylinder combustion technologies, and
(2) after-treatment technologies.

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The after-treatment technologies such as NO_x storage catalyst (NSC), selective catalytic reduction (SCR), diesel particulate filter (DPF) *etc*. though very effective in reducing the pollutant but are expensive and takes out the competitive edge of diesel engines. They also involve complex calibration and hence increased cost of development and validation. Therefore, it becomes very essential to explore the alternate combustion techniques such as homogeneous charged compression ignition (HCCI) and partially charged compression ignition (PCCI). The NO_x and PM formation is more predominant in conventional high temperature combustion (HTC). In HCCI, the early multiple injections help the mixture to burn lean in premixed part [1, 2]. The simultaneous reduction of NO_x and PM can be achieved by reduction in the combustion flame temperature and PM due to lean burn and sufficient mixing time [3, 4]. However, the HCCI is restricted to typically low and medium load due to combustion instability at higher loads [1, 2].

In the PCCI, part of the fuel is premixed and rest of the fuel burns with conventional HTC. The partial premixing is done with the help of pilot injection coupled with the main injection at the top dead center (TDC) with exhaust gas recirculation (EGR). PCCI can be used over wide range of speed load and reduces the NO_x and PM thus providing lesser work for the after-treatment devices while meeting stringent norms. In the current research, the premixed combustion achieved with help of pilot injection was studied along with reduced compression ratio (CR).

The reduced CR helps to achieve the goal of low temperature combustion. The lower CR helps to reduce the cylinder pressure levels and mechanical friction levels with lower emissions. This enhances the higher power output [5, 6]. The effect of compression ratio is similar when using alternative fuels instead of conventional fuels [7].

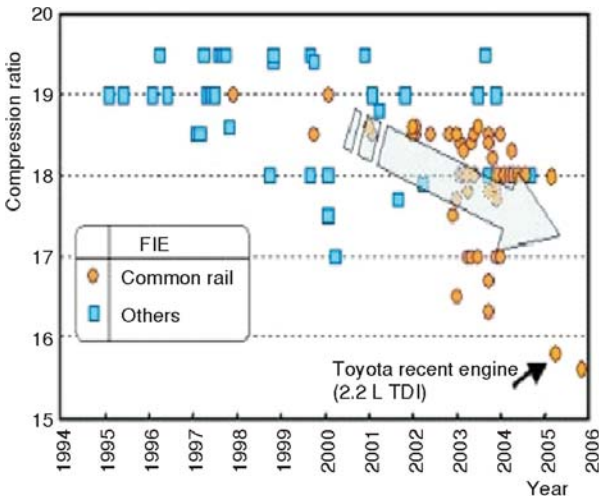

Figure 1. Trend of CR [8]

The shown fig. 1 gives the trends of CR in Europe [8] up to year 2006. It is seen that the CR reduced to a level of less than 16. This trend continues till date with CR in the range of 16~16.5. It is not practical to go lower than these values for start ability and increased HC/CO emission reason. With the introduction of common rail, the trend to go with lower CR is inevitable. This is due to the fact that with common rail, injection can be made suitable for the lower compression. Dakata *et al*. [8] conducted a simulation run with two different CR. It is seen from their work that the lower CR moves out the highest temperature zone from NO_x formation zone (as seen in φ-T diagram in fig. 2). This leads to the reduced NO_x emission. Hence, the need to investigate a combination of lower CR and multiple injections can be effective strategy for future NO_x-PM trade off.

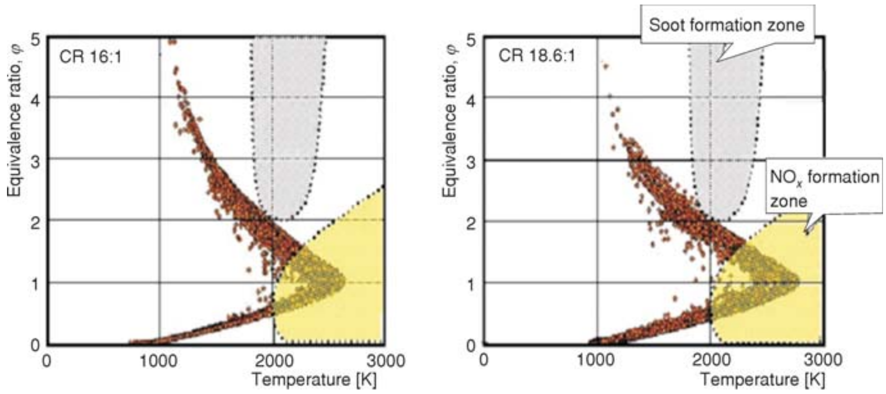

Figure. 2 Comparison of operating range in *φ-T* diagram given by computational fluid dynamics simulation; engine capacity 2.2 L, 2000 rpm, Pme = 0.86 MPa, 15° aTDC, IT = TDC) [8]

In fig. 2, equivalence ratio means ratio of actual air fuel ratio (AFR) to stoichiometric AFR for a given mixture.

Experimental set-up and test description

A 2.2 L, 4-cylinder, direct injection, and common rail diesel engine was used for performing the subject study. The engine specifications are given in tab.1.

Table1. Engine specifications

Engine parameter	Specification
Engine capacity [L]	2.2
Bore [mm]	85
Stroke [mm]	96
Compression ratio [–]	18:5:1 and 16.5:1
Rated power [kW at rpm]	88 at 4000
Max. torque [Nm at rpm]	290 at 1800-2600
Firing order	1-3-4-2
Aspiration	Turbocharged (VGT) with inter cooling
EGR and EGR cooling	Yes, without by-pass

From the base CR of 18.5:1, reduction to a ratio of 16.5:1 was made by changing the combustion bowl volume. The combustion bowl was widened and the injector nozzle spray angle was reduced by 4° from its base value to match the changed bowl. The combustion pressure was measured with the help of Piezo-electric non-cooled cylinder pressure sensor from AVL. The sensor was mounted in place of a glow plug position. The heat release rate w. r. to crank angle (CA) was calculated with the help of measured cylinder pressure histories by a device called INDICOM supplied by AVL. The cylinder pressure measured was used for the calculation of heat release. The same was derived from first law of thermodynamics concept. This is explained in detail in [9, p. 510] and [10].

In addition to the measurement, the raw emission measurements were performed by the commercially available analyzer. NO_x was measured with the help of chemiluminescent analyzer (CLA) while CO and un-burnt HC were measured with non-dispersive infra red (NDIR) and flame ionization detector (FID) analyzer, respectively. Smoke measurement was performed with the help of AVL opacimeter. The principal of the operation of these equipments is explained in detail in [9] .The value obtained in filter smoke number (FSN) was converted to g/h of soot with the help of formula by AVL calculation. The measurement was performed at an engine speed load point of 2600 rpm and 84 Nm loads. The pilot separation was varied from 1000 μs to 3000 μs with pilot injection quantity variation from 1 mg per stroke to 4 mg per stroke, keeping the EGR rate, common rail pressure, main injection timing, boost pressure ratio, and intake gas temperature.

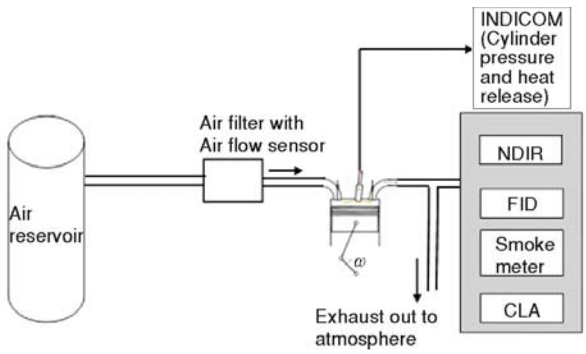

Figure 3. Experimental set-up during the trials

Figure 3 shows the complete measurement layout used during the experiment. The engine was mounted on an engine dynamometer running on eddy current principle. The condition air was supplied in both the case. Cylinder pressure was measured during the experiment. The raw exhaust gas was analyzed with the help of above mentioned analyzers and reported. The engine was kept in the speed-torque mode and pilot separation and quantities were varied. The various emissions were measured and plotted in the form of contour graphs.

Discussion of results

Effect of compression ratio on NO_x

Figure 4 shows the comparison of the NO_x emission for both CR.

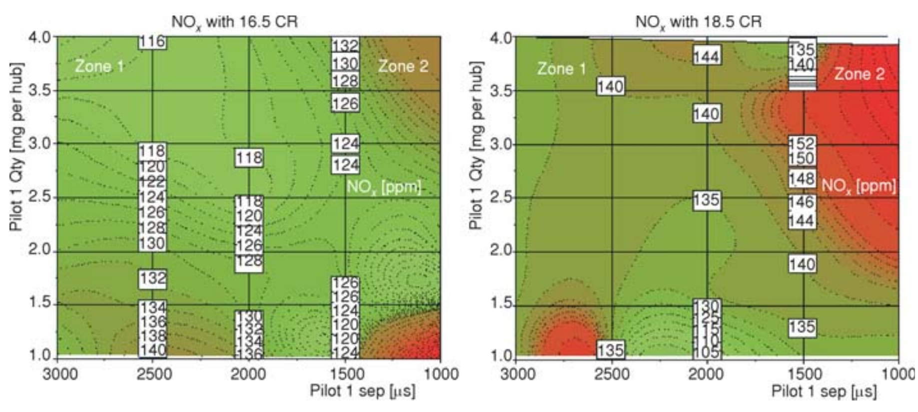

Figure 4. Comparison of NO_x emission with varying pilot injection/separation for two levels of CR

The contour graph of NO_x is divided into different zones for better understanding. Zone 1, with higher pilot injection quantity and higher separation, shows the lower emission of NO_x in both the cases. The reason could be the reduction of the ignition delay due to the pilot injection which lowers the combustion flame temperature to rise quickly when the main injection combustion occurs. This implies a partially homogeneous compression ignition concept and found to be reducing NO_x as against the normal HTC. (which are normally 1 to 2 mg per stroke of pilot quantity with pilot separation ranging from 1000-2500 µs). The lower CR *i. e*. 16.5:1, the NO_x was found to be lower than 18.5 CR in zone 1 as well as zone 2. Figure 5 shows the zone 1 point with pilot separation of 2500 µs and pilot quantity of 3.5 mg per stroke. The higher cylinder pressure in case of 18.5 is reason of having more NO_x. This can be justified as below. As shown in fig. 5, in the insect, the heat release rate (HRR) comparison between two cases of CR. In case of 18.5 CR, the compression pressure is going to be always higher than the case with 16.5 CR. Thus, the constant pilot injection fuel of 3.5 mg per stroke gets evaporates and there appears a small pilot heat release followed by a main injection heat release in case of 18.5 CR. However, with 16.5 CR, the compression pressure may not be sufficient to generate similar pilot heat release and as a result, this gets merged to main injection heat release. This reduces the ignition delay. This reduction in ignition delay is major contributor for the NO_x reduction as reported by many researchers [1, 2, 4]. Also, the peak of main injection heat release was also high in case of 18.5 CR than in the case of 16.5CR. In fig. 6, the similar phenomena was tried to understand. In this case, the pilot injection HRR was separated from the main injection HRR. In case of 1000 µs injection separation from the main injection event, injection happens relatively late as the case in zone 1. In zone 1 (corresponding to 1000 µs), the injection happens when the cylinder pressure is close to 40 bar (16.5 CR) and 50 bar (18.5 CR) in case of zone 2 as compared to 30 bar (16.5 CR) and 40 bar (18.5 CR). The same can be seen from figs. 5 and 6. Thus, zone 2 allows better condition inside the cylinder to start the pilot injection combustion than in case of zone 1. This can be explained with the help of increased heat release for fig. 5 than in case of fig. 6. However, the higher overall cylinder pressure and hence the temperature and the more fuel of main injection burning in premixed part of the combustion cause more NO_x for 18.5 CR.

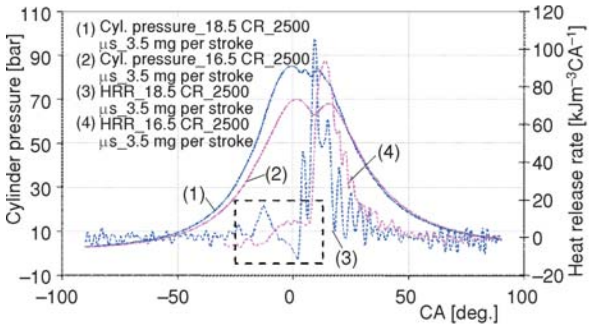

Figure 5. Cylinder pressure and HRR comparison for pilot separation of 2500 µs and 3.5 mg per stroke (zone 1)

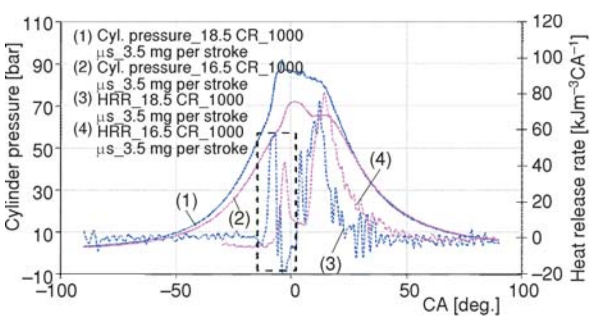

Figure 6. Cylinder pressure and HRR comparison for pilot separation of 1000 µs and 3.5 mg per stroke (zone 2)

Effect of CR on smoke number

Smoke emission generally increases as the pilot injection quantity is retarded keeping the main injection constant [2]. From fig. 7, it is seen that smoke number is higher in the region of zone 2 than zone1 irrespective of CR though the NO_x emission is also higher. This can be explained as follows: As the pilot injection is getting delayed from 2500 μs to 1000 μs, it comes closer to the main injection. In our experiment, the main injection remains fixed. Thus, this retarded pilot injection once burned (as seen in fig. 6), main injection occurs.

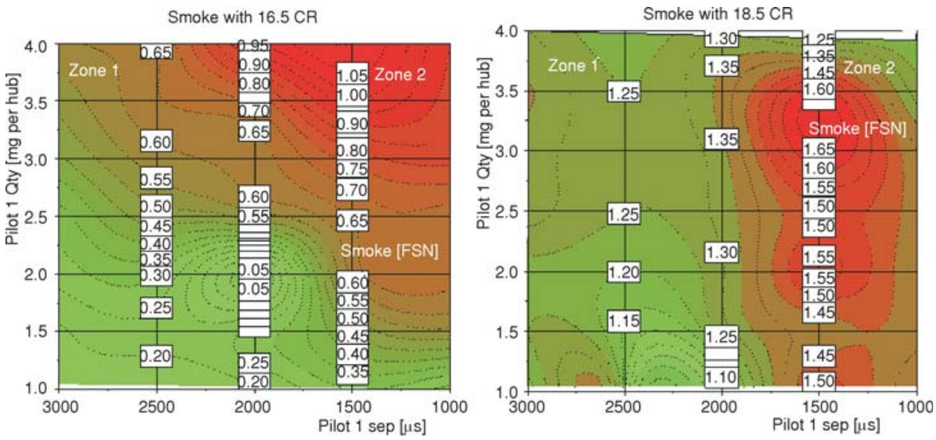

Figure 7. Comparison of smoke number with varying pilot injection and compression ratio

Higher cylinder pressure and temperature in case of 18.5, the rate of burning was higher for pilot than with 16.5 CR. Thus, 18.5 CR helps to make the relatively warm condition and then main injection occurs. The main injection quantity gets injected into the pilot conditioned cylinder and makes the mixture locally rich. The combination of higher pilot quantity with a short dwell period emitting a higher smoke level was due to shorter reaction time for the fuel to mix with air that leads to less complete combustion. The poor mixing process resulting from a larger pilot quantity results in the reduction of soot oxidation Thus, the combustion during this event causes smoke. The Local richness in case of 18.5 CR was more than the case with 16.5 CR due to the reason explained above and hence more smoke can be seen with 18.5 CR in zone2 than with 16.5 CR. This can be seen in fig. 7. For the increase in the smoke emission near the area of 240 CRA, due to the interference of main injection with the rich mixture was valid for our experiment too. In our case the engine speed was kept at 2600 rpm and the included angle between pilot and main injection is 23.40 CRA. The included angle for injection nozzle is 51.40 due to seven hole nozzle configuration. The swirl ratio was approximately 2.2. This condition confirms the introduction of main injection in a rich pilot flame. However, the Okude *et al.* [2] investigated the effect of swirl by conducting the experiment and found that the swirl was not an only cause of increase in smoke emission at this pilot separation. It is explained that the fuel injected at retarded pilot injection enters into the squish area. The squish volume in such case was very small and hence very less air is available since piston was very near to TDC. The fuel mixes very poorly and hence leads to increase in smoke. As the pilot separation increases, the fuel which was entering inside the squish gets more air since in this case; the piston was relatively away from the TDC. Thus, increase air in squish reduces smoke .This can be seen from fig. 7 from zone 2 to zone 1 in case of both CR.

Effect of compression ratio on CO and HC emission

Figures 8 and 9 shows the CO and HC contours, respectively, for the varying pilot separation and pilot quantity during the experiment. Both CO and HC exhibit the similar behaviors as reported by Okude *et al.* [2], Usman Asad *et al.* [5], Dober *et al.* [6] , the CO and HC increases dramatically when the pilot separation increase and away from the main injection. This was mainly due to the fact that early injection during early or middle of compression stroke enters into the combustion bowl as well as the squish volume. This forms a mixture too lean to burn and doesn't allow the fuel to oxides. Some of the fuel also impinges on the wall of the cylinder liner. This causes the fuel efficiency to deteriorate in such condition. A very early injection times like 60° or 80° bTDC the pressure, temperature and density in the combustion chamber were very lower and therefore the spray penetration was longer. This concept using early injection reduces

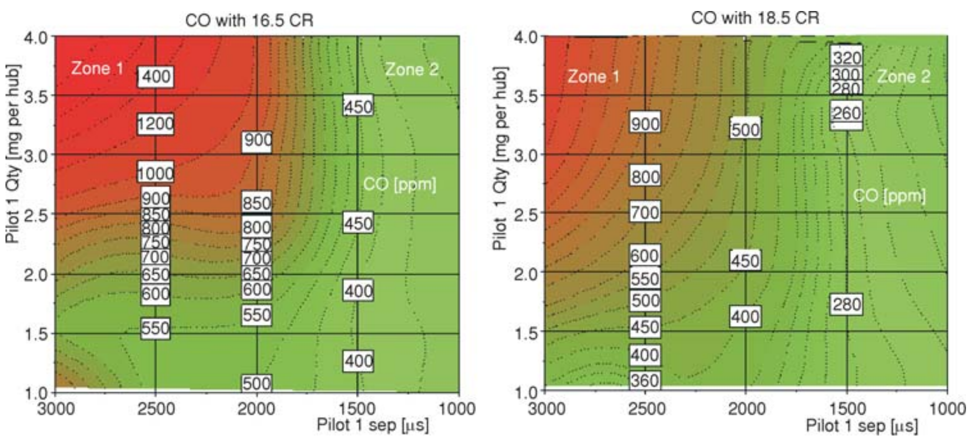

Figure 8. Comparison of CO emission with varying pilot injection and CR

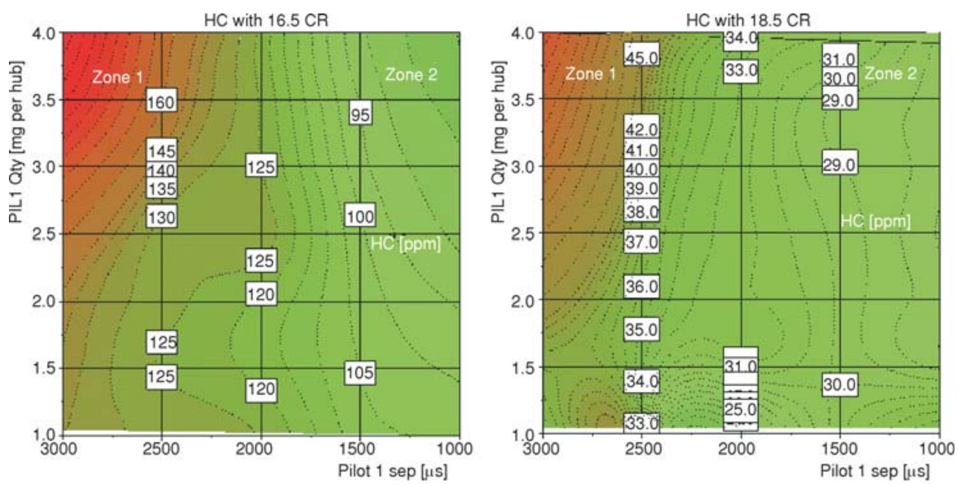

Figure 9. Comparison of HC emission with varying pilot injection and CR

both particulate and NO_x, however CO and HC increases. It also tends to increase the noise due to the fact that it increases the ignition delay than the case with pilot injection with retarded pilot injection. In order to study the effect with the two different CR, the increase of cylinder pressure during compression stroke was more with 18.5 CR than 16.5 CR. This reduces the CO and HC formation than the case with 16.5 CR. Thus, the lower CR engine demands for a higher after treatment loading than with higher compression. Thus, with lower CR engine, too early pilot injection with the higher pilot quantity is detrimental for CO and HC emission. The solution is to divide this high pilot quantity into multiple shots to reduce the dilution of fuel with the engine oil. This reduces the combustion noise also.

Figure 10 shows the comparison of the breake specific fuel consumption (BSFC) measured with two CR. It was very clear that with the higher CR, the BSFC was found to be better. The variation in BSFC from zone 1 to zone 2 was not much or constant in case of 18.5 CR. But, 16.5 CR exhibit more deterioration in zone 1. This could be mainly due to the overall lower temperature in case of 16.5 CR.

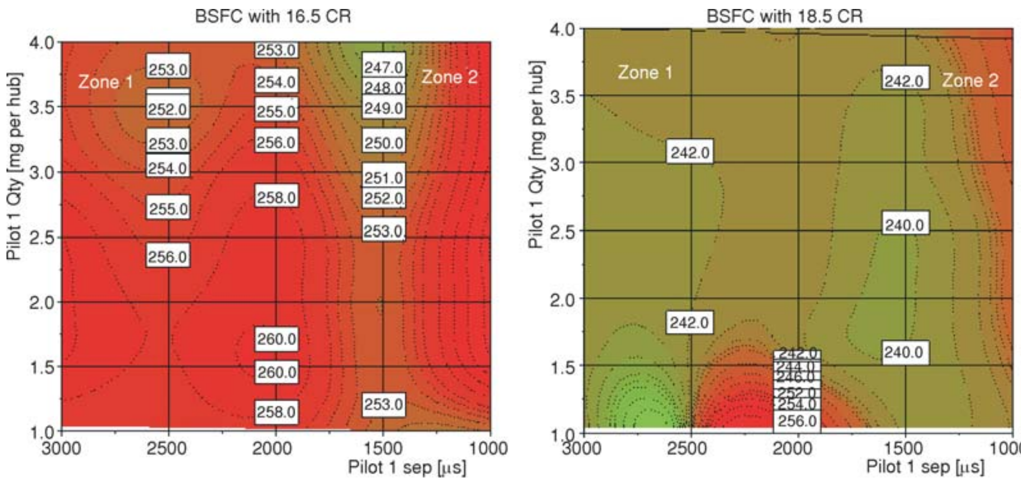

Figure10. Comparison of BSFC with varying pilot injection and CR

Conclusions

- The effect of varying CR has similar emission formation behaviors except the magnitude of pollutant formed.
- The reduction of NO_x with 16.5 CR than 18.5 CR mainly due to the lower combustion temperature. Also, the zone of highest combustion temperature might have shifted from NO_x formation zone considerably.
- The HC and CO formation behavior was similar irrespective of the compression ratio, however, the 16.5 CR exhibit dramatic increase in the HC and CO with higher pilot separation and higher pilot quantity. This was due to the too lean mixture in the carly phase of the compression stroke with lower temperature. This situation does not oxides the fuel.
- Reduced CR has better potential of reducing the NO_x and smoke. However, higher CO and HC with 16.5 CR can demands for increased oxidation catalyst performance to meet the emission level.
- The smoke formation was found to be higher in zone 2 (1500 μs and 3.5 mg). Both the CR shows similar phenomena. However, the 18.5 CR has relatively higher smoke number. This

is mainly contribution from the main injection fuel entry into the pilot injected conditioned event and creating locally rich mixture.

- Smoke emission in zone 2 was also anticipated to increase due to some of the fuel getting trapped in squish volume which has deficient air. Thus, smoke emission found to be increased.
- Overall lower smoke emission in case of 16.5 CR allows the more EGR to introduce for the same NO_x level. Thus, further lower NO_x can be achieved for the same level of particulates in 16.5 CR. Alternatively, the introduction of double pilot for the same level of smoke (as in 18.5 CR) can reduce noise drastically.
- BSFC with 16.5 compression ratio was higher than with compression ratio *i. e*. 18.5. This was mainly because of the non availability of higher temperature to burn the mixture effectively.

The work presented was limited to the higher speed and medium load (2600 rpm and 84 Nm). The same can be extended to the low speed high load and other points to explore the possibilities to reduce the NO_x-PM simultaneously with lower CR. With the trend to go with lower CR engine and implementation of multiple injection strategies coupled with advanced after treatment in-cylinder NO_x and soot can be reduced. The work can be extended to understand the effects of post injection coupled with the pilot injection with late partially premixed combustion on emission behavior.

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Nomenclature

BSFC – brake specific fuel consumption, [$gkW^{-1}h^{-1}$]
CA – crank angle, [deg.]
CR – compression ratio, [–]
HRR – heat release rate [$kJm^{-3}CA^{-1}$]
Pme – mean effective pressure, [MPa]

Acronyms

BDC – bottom dead center
EGR – exhaust gas recirculation
FSN – filter smoke number
IT – ignition timing
Pilot Qty – pilot injection 1 quantity
Pilot Sep – pilot injection 1 separation
PM – particulate mater
SCR – selective catalitic reduction
TDC – top dead center

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