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Mitigation of Emissions through Injection Strategies for C I Engine

Jayashri N. Nair

Abstract

Fuel conversion efficiency is high with diesel engines compared to petrol engines. However high emissions from diesel is a matter of concern and its mitigation paves way for scope of research. Exhaust gas recirculation is one of the method widely accepted to curb NO_x emissions. Recently, split or multiple-injection strategy has been explored by researchers to precisely control the fuel injected per cycle and also to mitigate emissions. Present work reflects technical review of effect of injection strategies on performance, emissions and combustion on C.I. engine with diesel and biodiesel as fuel. Injection strategies like duration of injection, number of injections, the dwell period between two injections, quantity of injection, and multiple injections are analyzed for their influence on engine output and brake specific fuel consumption. Also their effect on emissions especially soot and NO_x emission are reviewed. First the effect of injection strategies with diesel fuel is discussed followed by biodiesel.

Keywords: split injection, pilot injection, NO_x emissions, Soot emissions, multiple injections

1. Introduction

The emissions from diesel engine are hazardous for human health as it causes respiratory problem in human beings. NO_x emissions in combination with water and oxygen forms acid rain and is also responsible for the global warming. To improve the air quality in cities, regulations and control measures are taken to lower exhaust emissions from heavy vehicles. However, there are no much improvements mostly because of the difficulties in eliminating NO_x and PM emissions. The need of an hour is simultaneous reduction of NO_x and PM emissions from diesel engines. However it is challenging to control NO_x and PM emission simultaneously. Optimizing injection timing through split injection can be a prominent solution to curb these emissions from engine. In split injection, the injection is divided into two or more pulses thus reducing the delay time. Major fraction of the combustion takes place during expansion stroke. NO_x released from the engine is reduced as NO_x is mostly formed in the premixed combustion. Investigations are done by many researchers to optimize the injection scheme and analyze the effect of split injections on combustion process and emissions.

Fuel injection timings influence the performance, emissions and the combustion part of the engine to a great extent. With the variation in the injection timings the state of air changes which effects the ignition delay. Occurrence of injection when the piston is far away from TDC reduces the temperature and pressure of the air

increasing the ignition delay. If injection starts when piston is nearer to TDC then temperature and pressure of the air will be higher which will decrease the ignition delay.

2. Multiple injections

Multiple fuel injections are employed, instead of single injection as in the conventional fuel injection system. The main injection provides maximum quantity of fuel per engine cycle. Pre injections can be one or more injections before the main injection. In many cases pre injections are termed as pilot injection. Pre injections can be employed when the compression stroke starts or can also be employed just before the main injection.

Multiple injections strategies involve following phenomena

1. Introducing fuel and dividing heat release rate (HRR).
2. Spatial distribution of fuel in combustion chamber.
3. Cooling effect of vaporizing fuel.

Linearity of the heat release rate is desirable for minimizing combustion noise. Pre injections helps in dividing the heat release process which eventually controls the combustion noise. Triple and quadruple injections also assists in minimizing combustion noise. Furthermore spatial fuel distribution is improved due to multiple injection strategies for effective usage of air for combustion in combustion chamber. Generally, this effect can lead to a reduction in particulate emissions at intermediate engine loads. The cooling effect associated with fuel vaporization lowers locally and globally the temperature of the gases contained in the combustion chamber. These phenomena can be applied to modify the rate of heat release in the early period of combustion by increasing the ignition there by allowing for a longer duration of mixing period and thus a more homogeneous fuel/air mixture. Correct use of cooling effect provides a valuable degree of freedom in the optimization of the noise, emission and fuel economy trade off. Multiple injections can be used for lower compression ratio engines with high EGR rates to mitigate the noise, emission and fuel economy trade off.

Post injections are injections after the main injection. It can occur immediately after the main injection or long time after the main injection and are also referred as after injections or late injections. Post injections are used to mitigate unburned hydrocarbons, particulate matter and for managing exhaust after treatment. Post injections can also be used with various EGR rates with single or double post injections to improve trade off relationship between NO_x and HC, CO emissions.

3. Effect of multiple injections on CI engine with diesel fuel

3.1 Effect of varying injection timing and multiple injections with diesel fuel

In the fullness of time, clean, cheap and high torque diesel engines will be in demand. Controlled combustion is an essential part for an economic and clean diesel engine. Homogeneous air- fuel mixture plays a key role in effective combustion. Homogeneity of air-fuel mixture is affected by spatial fuel distribution in combustion chamber. Higher injection pressure, longer dwell time and increased

pilot fuel quantities can contribute to better mixing quality resulting in increased homogeneity of air-fuel mixture and optimum engine performance with low fuel consumption and soot emissions. However trade off does exist between NO_x and soot emissions with more quantity of fuel in pilot injection. With changing quantity of fuel in first injection, reduction in both particulate emissions and BSFC was observed with single injection at fast rate [1]. Also optimizing the rate of injection for the lowest BSFC did not affect the pressure rise with single injection. However, it was evident that the quantity of fuel in the first injection effected the rate of in-cylinder pressure rise and NO_x emissions also. Peak pressure reduced by more than 45% with split injection. The NO_x emissions increased with more quantity of fuel in the first injection, whereas the particulate emissions decreased. High homogeneity of air fuel mixture leads to early burning of fuel in premixed combustion zone, increasing the in-cylinder combustion temperature resulting in high NO_x emissions. Furthermore, split injection allows combustion to continue in the power stroke without any increase in soot emissions and thus utilizing the maximum charge. This indicates that pulsed injection may provide a means to reduce particulate emissions, and allow for reduced NO_x from controlled pressure rise.

In another investigation, the injection pressure and the total quantity of fuel injected was kept constant but the ratio of amounts of fuel injected between two injection pulses were varied and also the time intervals between the two injections were varied [2]. With longer time interval between two injections and less quantity of fuel in the first injection, the in-line cylinder pressure decreased. Mixing of in-cylinder gas was enhanced by the second injection and the injection interval, which eliminated local high temperature areas resulting in reduced NO_x emissions. Shorter time interval between two injections resulted in increased NO_x emissions. The smoke emissions were high with less fuel quantity in the first injection due to the fact that large amount of oxygen was consumed during the first injection. More fuel was injected in the second injection which led to decreased combustion duration and resulted in increased smoke. However the smoke emission reduced with increased fuel quantity in the first injection. BSFC improved with less fuel quantity in second injection and shorter injection interval resulting in delayed crank angle at 50% heat release.

Slight modification in the engine can assist in optimizing and treating the trade-off between NO_x and other emissions in combination with split injections. Design of double lobe cam with optimum split and dwell can influence reduction in engine emissions [3]. Use of double lobed cam showed reduction in NO_x emission but showed reverse trend on CO and CO_2 emissions. Split injection with 10° crank angle dwell using double lobed cam was optimum in effectively reducing the NO_x emission by 14.1% and unburned hydro carbon by 11.8% without penalizing the soot and power. There was no considerable variation observed with SFC and brake thermal efficiency for the modified engine with split injection. In a similar study the amount of fuel injected was divided equally for pilot injection and main injection and was compared with the single injection [4]. Injection duration and injection rates were reduced. In case of split injection it was observed that the heat release rate reduced compared to the single injections resulting in lower NO_x emissions. On retarding the split injection timing, soot emissions decreased compared to single injection. As the split injection timing was retarded, the larger size particles which forms the total particle volume and weight decreased, but HC and CO emissions were higher for split injections.

Factors influencing emissions namely, ignition delay, adhered fuel, and squish are affected with the changes in the injection timings. Changes in injection timings affects the position of the piston, cylinder pressure and temperature at injection. Advancement of first stage injection timing to 80°C BTDC, reduced BSFC to 20% [5].

The NO_x and smoke emissions were improved with less quantity of fuel in the first injection and advancement of the injection from 80 °C BTDC to 100 °C BTDC. The CO emissions decreased when the first injection was advanced to 100 °C BTDC and the second injection was retarded over TDC.

3.2 Effect of varying fuel injection pressure with diesel fuel

Increasing fuel injection pressure is one of the best control techniques for optimizing combustion in diesel engines. High injection pressure promotes fine atomization of fuel, and uniform mixing of fuel and air thus, decreasing the combustion duration. Split injections coupled with higher pressure injection strategy tend to improve performance and emissions of engine. However combination of this strategy results in high NO_x emissions. Also increased spray tip penetration due to high injection pressure results in spray impingement on wall and piston, leading to high HC emissions. In an investigation, conventional diesel fuel (Navy NATO F76) was compared with the new Navy hydro processed renewable diesel (HRD) fuel from algal sources, as well as the high cetane reference fuel nC16 (n-hexadecane $\text{CN}_{14}100$) [6]. It was observed that increasing fuel injection pressure shortened the ignition delay for all fuels. The combustion duration was longer for higher cetane number fuels for the same fuel pressure. This may be attributed to less premixing of fuel before the start of combustion. The author tried to study the relation between physical and chemical delay times with HRD and nC16. As injection pressure increases, the importance of chemical delay increases especially with lower cetane number. Split injections combined with exhaust gas recirculation (EGR) and higher injection pressure has the potential for diminishing NO_x emissions and elevating the engine performance. The test was carried out on a V6 common rail direct injection engine [7]. The engine was turbocharged with variable turbine geometry turbochargers. The experiments were carried out at two different speeds 1500 rpm (35.1, 70.2 and 140 Nm) and 2000 rpm (43.3, 86.6 and 120 Nm) with injection pressure of 300, 430, 500, 600, 700 bar. The increase in injection pressure from 300 bar to 700 bar resulted in improved engine performance and emissions for all engine conditions. Increase in peak cylinder was observed for both EGR ON and EGR off conditions. In all engine test conditions the BSFC decreases as the injection pressure increases due to an improved fuel mixture and rapid combustion rate. However, these values were slightly increased when the engine operates with cooled EGR ON (1500 rpm, 35.1 Nm EGR OFF) at 600–700 bar injection pressure. This is strongly believed to be due to decreased combustion temperature and reduced oxygen availability for EGR ON. This results in higher fuel consumption. The reduced oxygen, higher inert in-cylinder gas and low boost pressure contributed to the poor combustion with cooled EGR ON. The specific fuel consumptions also decreased at both speeds. Reduction in CO emissions were observed with EGR off by 80% at 1500 rpm and 60% at 2000 rpm. The THC emissions also showed reduction with EGR OFF by approximately 70% at 1500 rpm and approximately 90% at 2000 rpm. However the NO_x emissions increased 4 times at 1500 rpm especially at 70.2 Nm and by approximately 3 times at 2000 rpm especially at 43.4 Nm. The rate that NO_x emissions increased as injection pressure rise was lower for EGR ON than for EGR OFF. Several factors that contribute to the fast combustion process in diesel engines are; fuel droplet size, penetration length, turbulence intensity, fuel evaporation, rate of combustion and ignition delay. However, all of these can contribute to the higher NO_x formation. As expected, the EGR ON produces improved NO_x reduction even at higher injection pressure for all engine test conditions. The use of cooled EGR produces lower peak in-cylinder pressure compared to cooled EGR OFF. This is due to a retarded combustion, a result of the reduced oxygen density and high heat

capacity of the gas mixture. In addition, the reduction of fuel burnt in the premixed combustion phase can be considered as a strong factor in lowering in-cylinder peak pressure.

4. Effect of multiple injections on CI engine with biodiesel fuel

4.1 Effect of varying injection timing and multiple injections with biodiesel fuel

The formation of NO_x with biodiesel fuel blends, depend upon bulk modulus of biodiesel, oxygen content of biodiesel, cetane number, saturated fatty acid content and engine operating conditions. Varying injection timing has proved to be a potential technique in curbing NO_x emissions in case of biodiesel. During the premixed combustion phase, NO_x is formed in lean flame region. Optimization of combustion timing and regulating the quantity of fuel burned in premixed phase can significantly reduce the NO_x emissions.

Coconut biodiesel with 20% and 50% proportions by volume in diesel were tested with single, double and triple injections [8]. In double injection the fuel mass was distributed equally for both injections while in triple injection 33.33% of mass was distributed in each injections with a dwell time of 1.3 ms in both double and triple injection case. Injection timing was varied from 12°BTDC to 2°ATDC . Advanced start of injection timings increased brake thermal efficiency for all fuels. This may be due to longer ignition delay which promotes better mixing of fuel and air resulting in efficient combustion. Also in case of advanced injections the peak pressure was attained at TDC. With single injection at 12°BTDC brake thermal efficiency decreased with the increase in the biodiesel blends. For all injection timings and schemes the BSFC was higher for biodiesel blends in comparison to diesel. Due to the lower heating value of the biodiesel more mass is needed to produce the same power output. Also it is noted that with increase in split injections the BSFC increases for all the fuels. This may be due to the longer duration of combustion process with the higher number of split injections which increases the heat loss and reduces the peak pressure which reduces the work output. NO_x is increased with increase in the advancement of injections due to occurrence of peak pressure around TDC which results in higher temperature. Biodiesel blends showed less NO_x emissions than diesel for all split injections and single injection. This may be due to higher cetane number and lower calorific values of the blends which helps in reducing the rate of heat release. With B50 blend simultaneous reduction of NO_x and smoke emission is possible with retardation in injection timing with triple injection scheme.

In another investigation effect of injection timing on NO_x emissions with ultra-low sulfur diesel fuel and biodiesel blends (name not specified) were studied [9]. At low load conditions biodiesel blends were found to produce slightly lower NO_x emissions than the neat diesel fuel. However at higher loads the NO_x emissions were higher for both single and double injection conditions. Overall, biodiesel diesel blends and the baseline diesel fuel had very similar heat release rate profiles. When the injection timing was retarded it proved effective for single injection conditions than using pilot injection with retarded main injection in reducing the NO_x emissions. Under the low load condition, the pilot injection strategy led to substantially reduced NO_x emissions. Similar effect of retardation on NO_x emission is reported using Pongamia methyl ester [10]. The injection timing was retarded by 4° for the blends. All the blends (B20, B40, B60, and B80) showed lower NO_x emissions and HC emissions with retarded injection timing. The smoke emissions also reduced for all the blends with retarded injection timing.

4.2 Effect of varying quantity of fuel in the injections with biodiesel fuel

Varying quantity of fuel in multiple injections affects the performance and emission of the engine [11]. For single injection the quantity of fuel discharged was 10 mg whereas for multiple injections the fuel quantity was divided in equal proportion for both injections in first test (5 mg + 5 mg) and 3 mg in first injection and 7 mg in second injection for second test. With single injection start of energizing was arranged at TDC, 10°BTDC, 20°BTDC whereas for multiple injections it was arranged at TDC, 10°BTDC, 20°BTDC, 30 ° BTDC. In case of single injection test, injection pressures varied to 60 MPa and 120 MPa. For single injection as the advancement increased the peak combustion pressure and peak heat release rate increased. However at 30 ° BTDC these values dropped. This can be attributed to the inline cylinder pressure and temperature which were lower during the spray and resulted in long ignition delay. Also the fuel injected dispersed in the squish and crevice regions. Soot emissions were lower with higher injection pressure. Peak NO_x emission was reported at 20°BTDC for 60 MPa and 15°BTDC for 120 MPa. For injection timings below these values, the NO_x emissions continuously decreased. The increase in NO_x emission was attributed to the proper mixing of the spray with air. The decrease in the NO_x emission at less injection timings was attributed to the incomplete combustion. CO and HC emissions increased with the advancement of the injection timings. In case of multiple injection at 120 MPa with 20°BTDC pilot injection and main injection at TDC showed lower heat release rates than single injection. Due to shorter ignition delay the second combustion resumed quickly than the first combustion consequently the temperature of combustion chamber increased for first combustion. During the first injection the consumption of oxygen will be maximum and so the rate of heat release was higher for the first injection as compared to second injection. It was observed that with shorter ignition timings supported less soot, HC and CO emissions but NO_x increased.

4.3 Effect of varying fuel injection pressure with biodiesel fuel

Proportion of biodiesel in diesel influences the injection spray pattern [12]. Due to the increased fuel line pressure, with increase of biodiesel in the blends the penetration distance of the spray also increases. Simulation results reports that the probability of wall impingement is more with higher blends. The ignition delay period decreased with all biodiesel blends resulting in less rate of pressure rise. This may attributed to higher cetane number of the biodiesel. Reduction in torque is noted with B100 at rated load. However for rest of the blends there was no significant change in the torque. HC, CO and smoke emissions decreased with all blends while NO_x emissions increased in the range of 1.4–22.8% with all biodiesel. This may be attributed to the oxygenated fuel and automatic advance in dynamic injection timing. It was concluded that B15 was the optimum blend with respect to no wall impingement and NO_x emissions.

Tests were conducted to evaluate best injection timing and injection pressure with Honge methyl ester and cotton seed oil methyl ester [13]. A toroidal re-entrant combustion chamber of the engine was selected. The injection pressure was varied from 220 to 260 bar and the injection timing of 19°, 23° and 27° BTDC was executed at compression ratio of 17.5. At injection timing of 19° BTDC and injection pressure of 240 bar biodiesel showed best BTE. Honge methyl ester showed better performance compared to cotton seed methyl ester. Further the injector of six holes with 0.2 mm orifice diameter yielded better results compared to 0.25 mm and 0.3 mm orifice diameter. It showed lower brake thermal efficiency for the biodiesel fuel. Smaller orifices have shorter ignition delay which reduces heat loss and time loss

resulting in higher brake thermal efficiency. The NO_x emissions were lower whereas the HC and CO emissions were higher with 0.2 mm orifice diameter for the bio-diesel fuel.

Tests were conducted for three injection pressures 180, 200, 220 bar for four different loads at 2200 rpm with methanol blended diesel from 0–15% with an increment of 5% [14]. The original pressure of the engine was 200 bar. It was reported that at decreased pressure of 180 bar the heat release rate, combustion efficiency, NO_x emissions, CO_2 emissions and peak cylinder pressure decreased whereas CO, HC and smoke number increased. On the other hand, smoke number, unburned hydrocarbon, and carbon monoxide emissions reduced with 220 bar, and peak cylinder pressure, heat release rate, combustion efficiency, nitrogen oxides and carbon dioxide emissions increased at all loads.

Exhaust emissions and BSFC with biodiesel blends (Name not specified) on diesel engine with different injection pressures at four different loads were studied [15]. All the biodiesel blends showed less CO emissions at lighter loads and high emissions at full loads. It was also noted that the CO emissions and HC emissions decreased with the increase in the biodiesel percentage. At 50 kPa constant load the CO emissions, HC emissions and smoke opacity decreased with the increasing injection pressure. As the engine load increased the NO_x emissions increased for all the blends. There was a rise in the NO_x emissions with the increase in the percentage of the biodiesel. With the increase in injection pressures, blends with high percentage of biodiesel showed less BSFC.

Optimization of injection pressure and compression ratio can improve engine performance [16]. The pressures selected were (150 bar, 200 bar, 250 bar) and compression ratios selected for the test were 16, 17, and 18. On comparing all the combination of pressures and compression ratio it was found that at 250 bar injection pressure and 18 compression ratio gave the highest brake thermal efficiency and lowest brake specific fuel consumption for the Jatropha methyl ester. However the HC and exhaust temperature increased with this combination whereas the smoke and CO emissions reduced. No change was observed with the NO_x emissions at higher pressures. For all the combination of pressure and compression ratio the Jatropha methyl ester showed better results than neat diesel both in case of performance as well as emissions.

In a similar study higher BSFC with linolenic linseed oil methyl ester at higher pressure of 240 bar was reported [17]. Moreover the thermal efficiency improved at 240 bar with some increased emission in NO_x . This may due to the changes in the shape of fuel spray which results in shortening of the length of the spray resulting in higher dispersion and higher spray tip penetration. This ultimately lead to better combustion. The ignition delay was reported to be lower at higher injection pressures as compared to diesel and at full load the peak pressure was the highest. The combustion analysis shows that, the ignition delay is lower at higher injection pressures compared to diesel. Peak pressures increased with the increase in the load for all injection pressures for the biodiesel as well as diesel. Smoke was lower than diesel at all loads for the biodiesel.

5. Conclusion

Fuel reactivity influenced simultaneous reduction in NO_x and soot emissions and increased dwell period, reduced particulate matter for diesel fuel. Multiple injection strategies are effective only with certain adjustment with injection rate as well as the duration of dwell period. Quantity of fuel in the first and second injection also greatly influences brake thermal efficiency and smoke emissions.

Split injections with biodiesel has mitigated NO_x emissions but at the cost of engine performances. Split injections with higher injection pressure reduced soot, HC and CO emissions at the cost of NO_x emissions. Higher injection pressures with biodiesel did not show consistent results with NO_x emissions however when coupled with EGR strategies, it has depicted significant reduction in NO_x emissions.

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Author details

Jayashri N. Nair

VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad, India

*Address all correspondence to: jayashri@vnrvjiet.in

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