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Low Temperature Combustion with Multiple Injection Strategies in Single Cylinder Diesel Engine

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Abstract: ***Low-temperature combustion(LTC) with multiple injection strategies is a recent trend for NO_x and soot reduction in single-cylinder diesel engines. This paper presents a technical study of past research carried out on multiple injections, which are pilot I and pilot II injection before main injection, to decrease engine soot to meet emission legislation while upholding efficiency and decrease or eliminate exhaust after treatment. Previous research indicates that extending ignition lag to enhance the proper premixing, and controlling temperature of combustion to optimal level using Exhaust Gas Recirculation, have been accepted as an important aspect to attain low temperature combustion. In this paper, we first discuss the effect pilot I injection and pilot II injection strategy through varied injection quantity and time range. Thereafter, we briefly review how pilot II injection provides better results compared with the pilot I injection, which is by reason of better premixing, improves the turbulent effect and lowers the emission. Next, we provide a broad overview of the collected works on the effect of injection pressure, temperature and rate of exhaust gas recirculation on engine emissions. We conclude by identifying a few dependencies of engine parameters in low-temperature combustion by multiple injections so as to reduce the engine emissions.***

Keywords: ***Low-temperature Combustion, Multiple injections, Engine-out emission, Ignition delay, Exhaust Gas Recirculation.***

I. INTRODUCTION

Toxic gas emissions need to be reduced to have better competence in the energy system. Mainly the transport sector is focused a lot on the energy system. Hybrid engines, thermal management systems of an engine, biofuels, battery operated cars, and fuel-cells technology are now using to increase the effectiveness of the transport sector. To dodge NO_x plus soot creation zones, there should be proper control on the inner temperature of a cylinder which is the leading constraint for both formations of contaminants and thermal energy[1]. To achieve this, research has led to new combustion technologies such as LTC. It uses various features such as EGR, lean mixtures, high CR, fuel stratification, VVT and diminutive ignition intervals which would provide the best combustion process but it has restrictions caused by HC emissions and high burning sound[2]. Several approaches have been endeavored such as multiple injections, high cetane number, and high volatility fuel and high intake pressure to diminish the combustion noise and the CO and HC emissions[3][4]. In recent periods there are more difficulties to meet the strict rules and regulations without extensive use of after treatment and this can be achieved using HCCI, PCCI, and RCCI. This less amount of engine exhaust emissions are achieved by adequate partial premixing and the great quantity of EGR drops the temperature of combustion.

PPC is a concept where low combustion temperature could be attained by monitoring the injection of fuel and chemical kinetics. This low-temperature combustion concept often used where the ignition delay period is extended in order to improve fuel-air premixing. An increase in ignition lag makes available additional time intended for fuel to penetrate gas blend before the starting of combustion which reduces both the creation of PM and NO_x due to lesser combustion temperatures. It has been observed earlier that PPC with single injection gives rise to the very high amount of pressure upsurge rate as of extended ignition lag, which leads to high audible noise and vibrations and causes mechanical engine damage, therefore it has to be kept minimum as much possible in order to have a smooth operation of an engine. A remedy to the problem is to divide the fuel injection into numerous injection events i.e. multiple injection. In this paper, the main objective is to study multiple injection strategies in LTC and its effects on engine exhaust emissions.

II. METHODOLOGY

Low combustion temperature can be carried out using HCCI, PCCI, and RCCI. Mechanical damages to the engine, less combustion controllability, and high-temperature compassion could occur in the HCCI engine due to the high rate of pressure rise. As shown in Fig. 1 widely accepted strategy is PCCI, which is carried out using multiple injections, EGR, high intake Pressure and high intake temperature. The strategies of multiple injections like the pilot, main and post-injections are being used for lowering the engine-out emissions and smooth operation of diesel engines. This paper highlights the comparative study between both on engine-out emissions.

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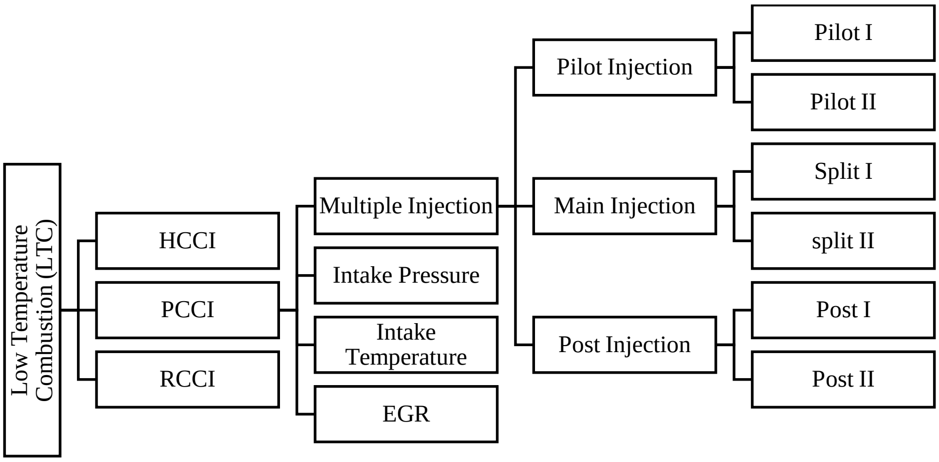

Fig. 1: Methodology of present work

III. LITERATURE REVIEW:

An experiment performed by Lianhao et.al.[5] on the metal engine using PPC with multiple injection and they have identified that the metal engine gives high efficiency using multiple injections in both low and high EGR rates. An investigation of LTC strategies like HCCI and RCCI had been performed by Divekar et al.[6] and they determined the influence occurred due to the high rate of intake pressure, high rate of EGR, change in engine speed, the timing of injection and it's pressure on operating confines. They even investigated and identified the factors affecting LTC for early pilot injection to the main injection. Brijesh et.al. [7] performed optimization on the timing of injections, compression ratio (CR), amount of EGR for the VCR engine. To perform the least possible turns they used Taguchi analysis and studied the effect of key parameters on the performance of engine and exhaust emissions with single to noise (SN) ratio study. Their outcomes showed that retarding the timing of injection and adding adequate EGR provides improved efficiency even with less injection pressure (200bar). Lee et.al.[8] performed an experiment to study the effect on LTC using diesel and biodiesel by intake pressure in CI engine. They evaluated and compared the overall performance and emission characteristics for which they employed a modulated kinetics (MK) approach. Their experimental results showed that due to obstruction of fuel injection in LTC lowers smoke, THC and CO emissions but upsurge NOx productions. Oluwasujibomi et. al.[9] executed a study where initial strategies are not matching to achieve LTC for less HC and CO production and better efficiency. Later they examined the effect of dwell, quantity, and timing of fuel injection, using the Design of experiments (DOE) method. Soloiu et. al. [10] investigated lowering NOx and soot formation in CI engine by the implementation of PCCI which is also known as PPC which was coupled with LTC with regimes 1-3 bar IMEP. They developed single-cylinder engine where multi-fuel like n-butanol by port injection and biodiesel supplied by direct injection this results revealed decrement of in-cylinder pressure by 25%, heat losses by 10-50% and soot emission by about 98%, but also showed a high increment in CO, HC, and non-methane hydrocarbons (NMHC) emissions. Bonsack et.al.[1] performed an experiment to lower down the soot and NOx by high-level dilution of EGR and multiple injection strategies. They used various types of fuels and formulated a cetane number, aromatic content in fuel and distillation temperature by means FACE. They investigated the impact of varying the timing of injection and quantity of fuel during a split injection strategy. Their results showed that using single and split injection strategies with the fuel of high CN shows an increment in the diameter of the particle. To find the character of each pulse in order to lower the engine exhaust emissions and combustion noise Park et.al [11] performed an experiment using triple injection strategies. They found that the first pulse and the second pulse of split injection are important to define the ignition delay, results showed that unburned emission reduced with increment in the mass of the first pulse and engine noise reduced with an increment of third pulse fuel amount. Two experiments accomplished by Yang et.al.[12] on LTC at 18.2:1 compression ration, one is a diesel with EGR up to 60% and second direct injection of ethanol with moderate EGR up to 30-45%. Their results showed that due to engine load and shorten the burning duration, it gives rise to good thermal efficiency but affects badly on peak pressure attained and pressure rise rate. Nehmer et. al.[13] carried out an experiment of pilot injection strategy by changing the quantity of fuel and varying the time of pilot injection and they found that NOx could be reduced by using small pilot injection while the smoke level remains the same. As a quantity of pilot injection increased results more NOx and less smoke. Moreover, dwell time doesn't have a significant relation to emission characteristics between pilot injection and main injection. Tows et.al.[14] proved in their experiment that using two-stage pilot injection, smoke as well as NOx can be lowered more than single-stage pilot injection. With the help of piezo operated injector Kastner et.al.[15] observed the effect of timing of injection and its quantity on the performance of an engine and emissions in which dwell time of pilot injection which is prior to main injection and main injection becomes zero hence NOx and HC instantaneously increased. It was because the latent heat of the main injection increases ignition delay gives rise in high-pressure penetration makes mixture too lean results incomplete burning which causes HC emissions. Babu et.al.[16] mentioned that using split injection method NOx was reduced while smoke level maintained this was possible because of oxidation after the combustion process.

Conversely Park et.al.[17] mentioned in their research that if the temperature at the main injection is high then PM increases due to pilot injection.

An experiment performed by Ehleskog et.al.[18]on the main injection, initially which were split into two injections which results, lowered CO and PM, while higher NOx observed. Later when it was split into three or four times results lowered NOx but enlarged CO, HC, and PM. Su.et.al.[19] mentioned that there was a reduction in friction between air and spray results in higher penetration in pilot injection. From the above researches, it is cleared that multiple injection timing, quantity and dwell timing among each injection are observed as the key constraints to achieving low emission in multiple injection strategies. However, common rail multiple injections offer high DOF in injection scheduling, so it is impossible to study all the cases at the same time.

Influence of pilot-I injection

ilot injection means before the main injection a small quantity of fuel injected, due to which NOx plus smoke could be lowered by advancing the timing of pilot-I injection and increasing its quantity at medium load conditions and low pressure. It is observed that smoke is mainly affected in the main combustion by the diffusion burn phase[20]. As the timing of pilot-I injection advanced over 40 degrees as shown in Fig. 2 and Fig. 3 there was a decrease in NOx (ppm) and smoke (FSN) respectively, however, HC increased by advancing pilot-I injection time and increased in fuel quantity, this effect observed due to a higher amount of wall-wetted fuel as shown in Fig. 4.

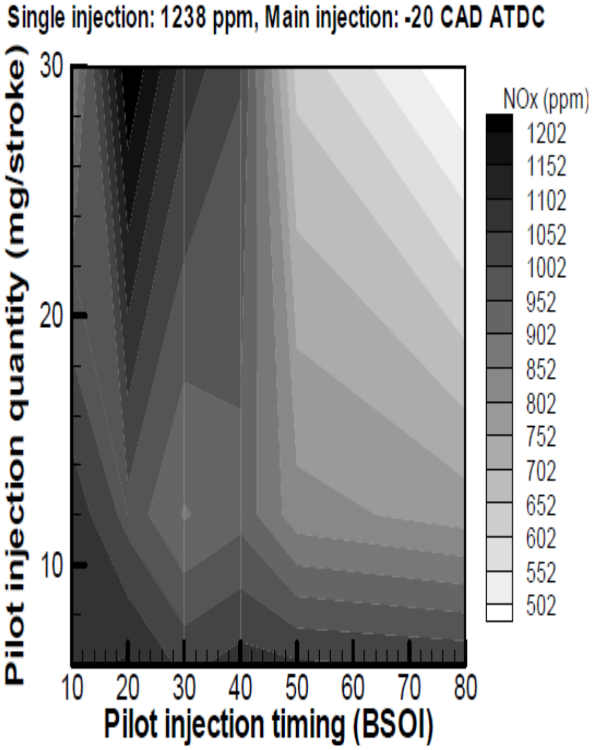

Fig. 2: Influence of Pilot-I injection on NO_x [20].

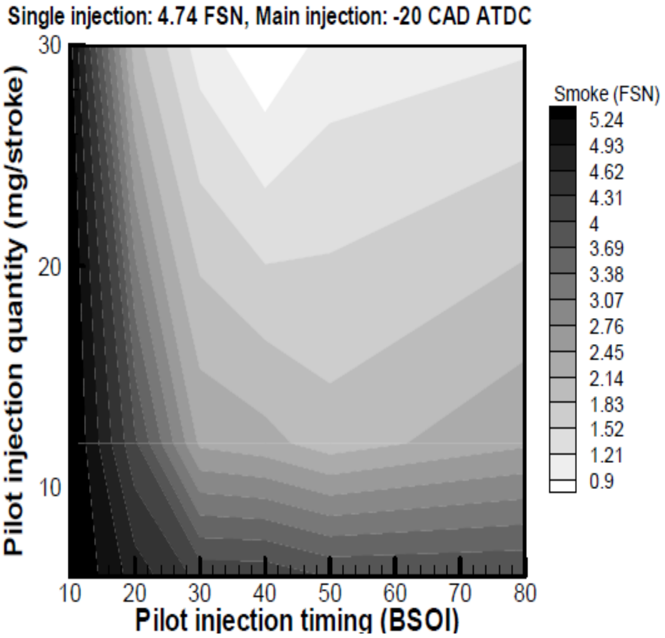

Fig. 3: Influence of Pilot-I injection on smoke [20].

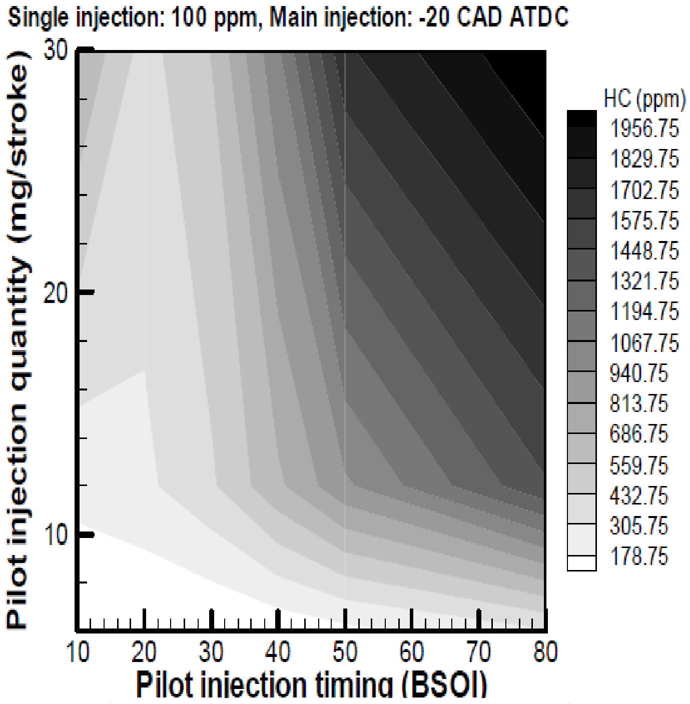

Fig. 4: Influence of Pilot-I injection on HC [20].

Influence of pilot-II injection

Quantity of first pilot injection and second injection were set to 15% to 25 % of the entire injection respectively, while each pilot injection timing varied from 100 to 800 CA BSOI. At less injection pressure and moderate load condition, NOx and smoke could be lowered even more than by pilot-I injection due to improved premixed mixture creation from 73% to 84%[20] as shown in Fig. 5 at (15%):(15%) and in Fig. 6 at (25%):(25%) for NOx, similarly Fig. 7 at (15%):(15%) and in Fig. 8 at (25%):(25%) for the smoke. HC could be lowered to half value compared with pilot-I injection by reason of shortening spray tip penetration.

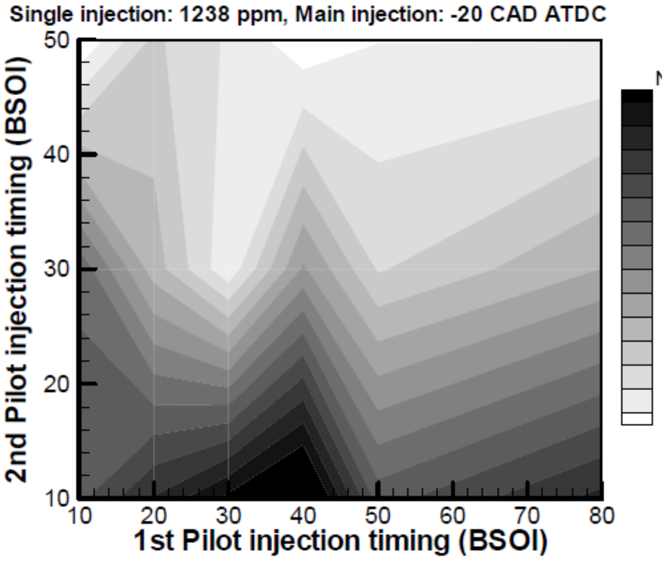

Fig. 5: Influence on NO_x by pilot-II injection at (15%):(15%)[20].

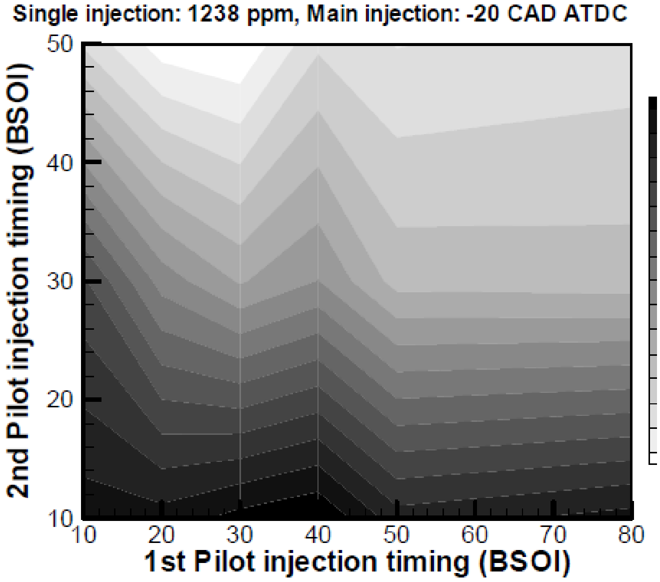

Fig. 6: Influence on NO_x by pilot-II injection at (25%):(25%) [20].

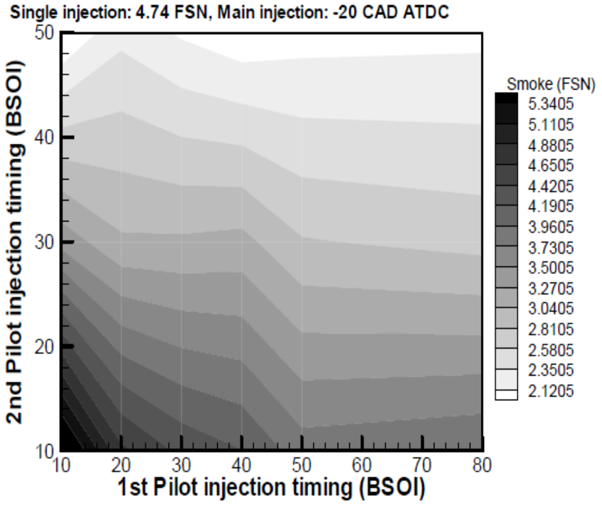

Fig. 7: Influence on smoke by pilot-II injection at (15%):(15%)[20].

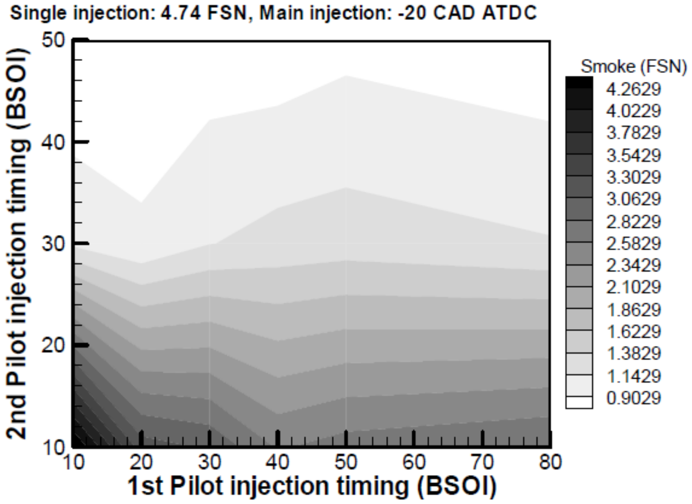

Fig. 8: Influence on smoke by pilot-II injection at (25%):(25%)[20].

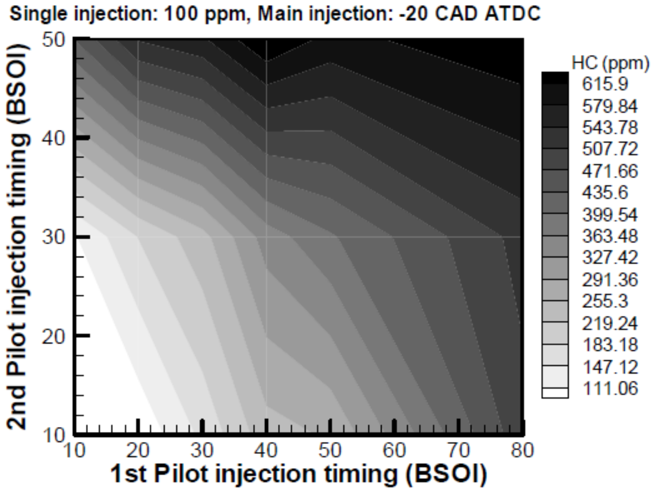

Fig. 9: Influence on HC by pilot-II injection at (15%):(15%)[20].

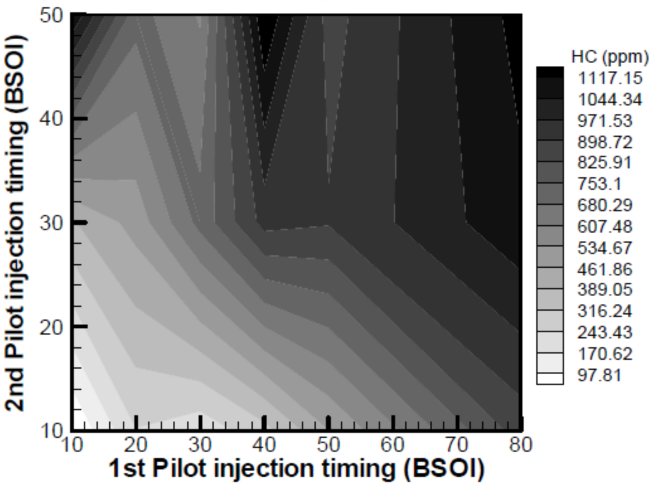

Fig. 10: Influence on HC by pilot-II injection at (25%):(25%)[20].

From the above pilot injection strategies, a pilot-II injection was found to be a suitable technique to lower NOx more than Pilot-I injection at all conditions, while NOx increased by advancing 2nd pilot injection timing to 300 CA BSOI.

IV. RESULTS AND DISCUSSION

In this segment, we discuss how are the operating parameter affecting the performance of the engine. These parameters include EGR, Intake pressure, intake temperature all of which normally varied through the literature.

Exhaust Gas Recirculation (EGR):

Jeongwoo et al.[21] carried out an experiment with pilot injection at 30% EGR then 60% EGR and studied the engine exhaust emissions. They observed, moderate EGR rate conditions NOx is reduced through advanced injection timing and its quantity. To decrease PM emission, advanced pilot SOI is very useful. However, pilot injection is too early, BSFC turns out to be more deteriorated due to wall-wetting. For heavy EGR rate conditions, ignition delay becomes shortened due to which pilot-injection would not ignite. So to avoid this SOI is further advanced. By advancing pilot SOI, the CO and total hydrocarbon emissions could be lowered without distressing the PM emission because of improvement in the local over mixing region as shown in Fig. 11.

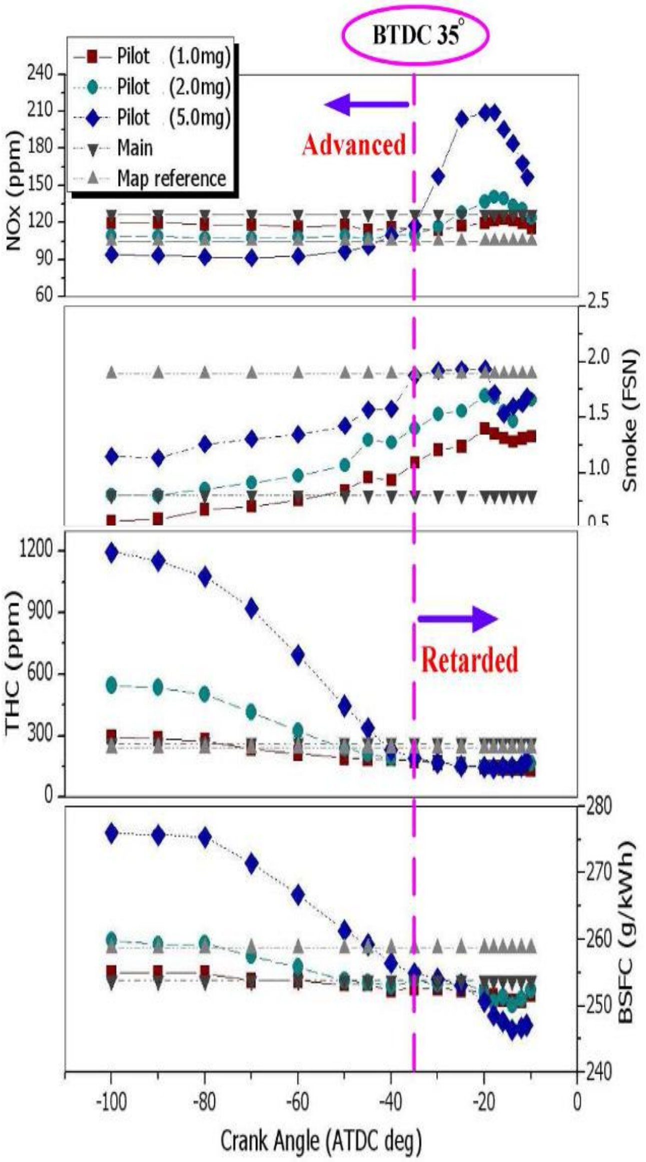

Fig. 11: Engine-out emission and BSFC with respect to crank angle.[21]

Intake pressure:

Increased intake pressure or boost has a number of effects on in-cylinder disorders. An increase in the intake pressure and density results in high peak pressure and temperature due to which decrease in BSFC. Boost has a significant effect like by increasing pressure the total in-cylinder O2 mass increase while O2 concentration and fueling rate held constant which creates an overall leaner mixture. Furthermore, physical characteristics like penetration rate, liquid-length and lift-off length, alter due to change in ambient in-cylinder density[22]. Fig. 12 shows the drop in average equivalence ratio observed with increasing intake pressure however Fig. 13 shows the effect on ambient in-cylinder density with O2 concentration.

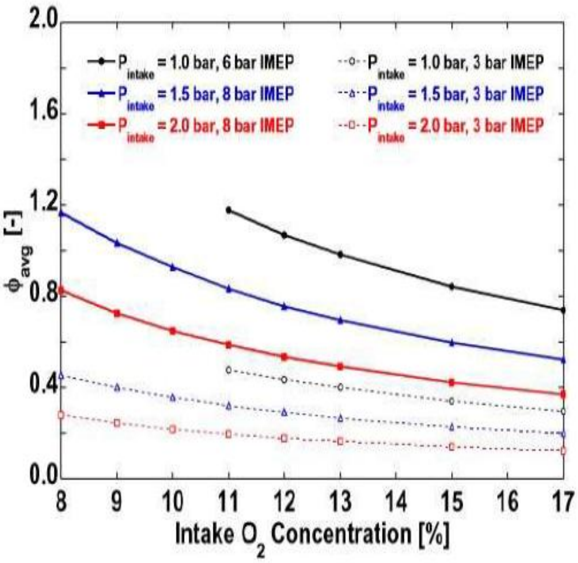

Fig. 12: Average equivalence ratio Vs. O_2 concentration for different pressure and load conditions [23].

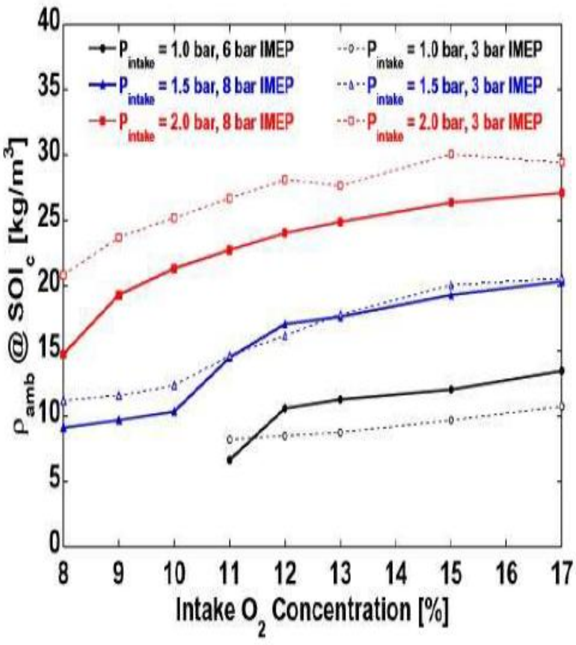

Fig. 13: Ambient in-cylinder density at SOI for variation in O_2 concentration at different pressure and load conditions [23].

Intake temperature:

The effect on NOx and soot emissions by increasing temperature represented in Fig. 14. It shows that, there is a reduction of NOx emissions without an increment in soot, with completely cooled intake and an increase in the EGR rate[6]. At higher intake temperature and same EGR, it shows lower exhaust emissions but greater intake temperature needs a greater level of EGR to attain LTC. Therefore, as shown in Fig. 15, it results in an increase in hydrocarbon and monoxide emissions.

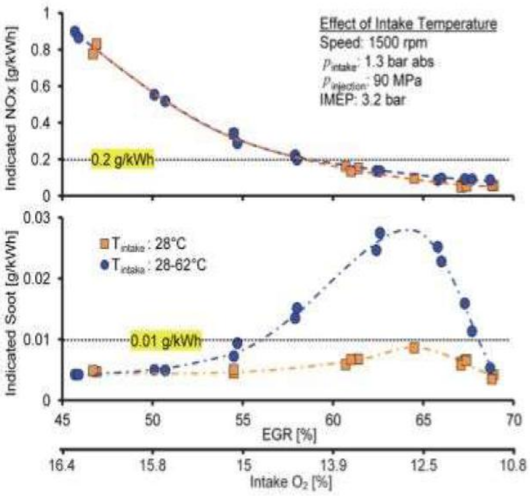

Fig. 14: Effect on NO_x and soot emission[6].

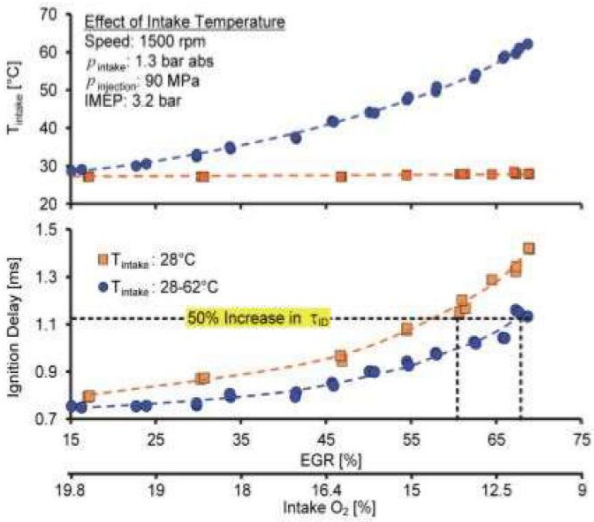

Fig. 15: Effect on ignition delay for different EGR and O_2 concentrations [6].

V. CONCLUSION

The study of multiple fuel injection strategies with low-temperature combustion and effect of engine parameters on exhaust emissions carried out and the outcomes are summarized as follows: NOx, as well as smoke, could be lowered by advancing the timing of pilot injection and its quantity but even more, it could be lowered by the pilot-II injection. From the heat release rate, NOx plus smoke was affected more by pilot-II than a pilot-I injection. HC could be reduced down to half of the pilot-I injection because of shortening spray tip penetration resulted in lesser wall-wetted fuel, in pilot-II injection.At the same EGR rate and high intake temperature, engine-out emissions are reduced but high intake temperature needs a heavy rate of EGR to attain LTC, results in higher hydrocarbon and monoxide emissions.Increased intake pressure or boost results in lower unburned HC and CO emissions, lesser NOx, lesser soot with an increase in combustion efficiency.With fully cooled intake, increasing exhaust gas recirculation results in the reduction of NOx emissions without a significant increment in soot formation, while high-temperature intake NOx emissions show similar reduction but soot emission rise rapidly with EGR.

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ABBREVIATIONS:

ATDC- After Top Dead Centre
BSFC- Brake Specific Fuel Consumption
BSOI- Before Start of Injection
CA- Crank angle (degree)
CO- Carbon Monoxide
CO$_2$- Carbon dioxide
CR- Compression Ratio
DICI- Direct Injection Compression Ignition
DOE- Design of Experiment
EGR- Exhaust Gas Recirculation
HC- Hydrocarbon
HCCI- Homogeneous Charge Compression Ignition
IMEP- Indicated Mean Effective Pressure
LHR- Low Heat Rejection
LTC- Low-temperature Combustion
NO$_x$- Nitrogen Oxide
O$_2$- Oxygen
PCCI- Premixed Compression Charge Ignition
PM- Particulate Matter
RCCI- Reactivity Controlled Compression Ignition
RPM- Rotations Per Minute
SFC- Specific Fuel Consumption
SN- Signal to Noise
SOI- Start of Injection
THC- Total Hydrocarbon
ρ_0- Ambient density
Φ- Equivalence Ratio
VVT- Variable Valve timing
CR- Compression Ratio
VCR: Variable compression ratio
DOF- Degree of freedom
Ppm- parts per million
FSN- Filtered smoke number