Effect of Combustion Parameters on Performance, Combustion and Emission Characteristics of a Modified Small Single-Cylinder Diesel Engine

Dipak Kisan Dond, Nitin Parashram Gulhane

Abstract: ***This paper represents the relative performance of a small single-cylinder diesel engine having capacity 3.5 kW. This paper covers experimental investigations of most influencing combustion parameters such as compression ratio, injection pressure and start of injection timing and their values on performance, emission and combustion characteristic of the small single-cylinder CRDI diesel engine for which the mechanical fuel injection system retrofitted with a simple version of the CRDI system. CRDI has yielded good results for large diesel and petrol engines but still not incorporate for cheaper small single-cylinder engines, typically used in the agricultural sector and decentralized power sector for a country like India. It is observed that starts of injection timing and injection pressure are the key parameters for improving the combustion characteristics and therefore engine performance while compression ratio mainly affects the emission characteristics of the engine. Retrofitted CRDI system yielded improved exhaust emission and performance of the engine.***

Keywords : Small diesel engine; CRDI system; Injection Pressure; Injection timing; Combustion characteristics; Emissions characteristics; Performance characteristics.

I. INTRODUCTION

Most of the cities in our country are highly polluted, which is very harmful to leaving being. One of the reasons being exhausted emission from I.C. engines used for stationary as well as the mobile application. Problems of pollution due to large diesel and petrol engines have been overcome by the use of catalytic converters, CRDI technology, recirculation of exhaust gas in the suction port (EGR) etc. use of high IPs in conjunction with electronic controlled fuel injection in CRDI has yielded good results for various applications mentioned above due to lot of benefits offered by these combustion systems, such as better fuel saving and higher power output as compared to conventional diesel and gasoline engines [1, 2]. Find out the proper injection parameters based on the requirement is an important task in front of the researchers in order to improve the thermal efficiency and reduce the harmful emission in case of small single cylinder diesel engine [3, 4].

Electronic fuel injection systems has an ability to easily modified the injection strategy which can be used to change the fuel injection parameters such as IP, fuel injection rate, multiple injections and the timing of pilot and main injection (SOI) under different operating range of the engine. [5,6]. However, these measures have not been taken for small diesel (say up to 5 hp) engines being used for stationary as well as mobile application leading to fuel wastage and atmospheric pollution [7]. Many of these engines uses mechanical fuel injection system for delivering the required quantity of fuel depending upon the conditions like for different speed and load requirement, which does not having precise control over the delay period, IP, duration of injection and rate of injection. This paper deals with experimental investigations of effect of combustion parameters such as CR, IP and SOI on overall performance characteristics of the engine, which was retrofitted with economical CRDI system developed for a small single-cylinder engine.

Lot of experimental work was carried out on small diesel engine by changing the combustion parameter simultaneously such as fuel, IP, IT, % EGR, and CR as well as by splitting the quantity of injection. For the same, researchers conducted experiments on conventional diesel engine, which uses mechanical injection system and some of them also carried out work with CRDI electronic control injection system by making modification in the existing setup. Narsinga et al. [8] have performed the experimental work on single-cylinder diesel engine fuelled with biodiesel mahua (B50) with added metal oxide nanoparticles. A trial conducted at different IP, range from 200 bar to 240 bar and IT take as 19°, 23° and 27° bTDC. The performance and emission characteristics were observed and it was noted that 240 Bar and 19° bTDC gives better performance with lower emission. F.mallamo et al. [9] investigate the effect of CR & IP on emission, combustion noise and fuel consumption of a small displacement CRDI diesel engine.

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The compression ratio of an engine (having baseline CR as19) was varied by using a different piston with a deeper bowl by keeping the same bowl architecture from 19 to 17.5.An experiment was carried out for different IP (700, 550 & 400 bar) and SOI (15° and 13° CA bTDC). Lower value NOx and PM were observed when the engine was running at lower CR.

The best value of SOI found was 7° bTDC for CR17.5 while 9° bTDC for CR19.Theja et al. [10] were taken a trial on a single-cylinder diesel engine at 1500 rpm which fuelled with diesel and added linseed oil in three concentration ratios of 10%, 20% and 30%. Performance characteristics were calculated and compared those with the mineral diesel for different IP (200, 220, 240 bar).L30 observed optimum BTE while diesel was showing higher mechanical efficiency, lower BSFC and lower emission properties compared with blending. Carpenter [1] replaces the mechanical fuel injection system by EFI for small industrial diesel engines. After taking a trial with this modified system, it was found that NOx and smoke opacity decreases but other parameters like HC and CO were increases. But BSFC was not found satisfactory. Suggest that by optimizing the parameter of EFI gives better results. S. Pai et al. [11] find out the effect of injection system parameters such as IP and IT on the performance and emission of a modified (CRDI) single-cylinder diesel engine. Engine was fuelled with a simaraba biodiesel (SOME) in different proportions with mineral diesel. It was found that, 800 bar pressure at all IT, especially at 18° bTDC, gives best results. The overall conclusion of the paper says that with increasing IP and proper injection timing results into quality combustion. Considering an objective as a reduction of engine-out NOx emission to a level which can easily meet the next emission target, O. laguitton [12] investigate the effect of CR on exhaust emission from a PCCI diesel engine. It was observed that NOx emission get decrease for retarded SOI, which was further lowered when CR reduced from 18.4 to 16. But at the same time, HC and CO emission were more at low CR. Nader Raeie et al. [13] was simulated the spray and combustion process of diesel for early and late injection timing (6° bTDC to 5.5° aTDC) at six different IP ranges from 275 to 1000 bar. It was observed that for early injection results into lower soot and higher NOx emission occurred as compared to late injection. Agrawal et al. [14-17] conducted series of experiments on CRDI assisted single-cylinder diesel engine for different IP as well IT. For the same, take fuel as mineral diesel as well as biodiesel blends without making any drastic modification in the hardware system or ECU recalibration of existing CRDI system. One of the paper finding shows that, addition of 10% karanja biodiesel gives higher thermal efficiency with reduction in emission. Hwang et al. [18] carried out an experiment on a single-cylinder engine attach with a high-pressure CRDI system. In this, he observed that at high load with high IP, peak in-cylinder pressure increases. Observations were recorded as maximum cylinder pressure of 7.31 MPa (2° CA aTDC) for diesel, 7.22 MPa (at 2.4° CA aTDC) for biodiesel at IP 80MPa. Jain et al. [3] the aim of the study was to developed a new combustion concept which was achieved by using partially homogeneous charge combustion (the main aim of shifting combustion towards increasingly premixed combustion phase). It was proposed that, fuel injected at higher pressure with injection timing set away from TDC improved PCCI combustion characteristics. But at the same time very high injection pressure (say beyond 1000 bar) shows inferior combustion behavior. H. Liu et al. [19] conducted a trial by using polyoxymethelene dimethyl ethers (PODE) as a fuel blended with diesel, which having a property like high cetane number, low viscosity and high oxygen content. Split injection strategy was used in this case. The pilot injection was carried out at 14° bTDC while the main injection at 2° bTDC. Mobasheri [20] determined the influence of the different fuel spray included angle and split injection on CRDI diesel engine. Different included spray angle 145°, 105°, 90° were considered. The start of main injection angle kept at 9° bTDC while the start of pilot injection vary from 30° to 15° bTDC.105° angle offers more flexibility for simultaneous reduction of NOx and Soot emission. S.mithun et al. [21] investigate the effect of CR on the performance of a single-cylinder CRDI diesel engine. The baseline CR (CR18) of the engine changed to CR14 by making changes in piston bowl geometry.CR14 shows lower NOx, smoke opacity and higher BTE & mechanical efficiency as compared to that at CR18.Also, It was observed that CR14 reduced blow-by losses. Srivastva [22] studied the effect of IP on a diesel engine which was fuelled with acetylene. During the study, IP varied from 180 to 210 bar at different load (vary from 20 to 100% load) and compared the result with baseline diesel.200 bar IP found the optimum for diesel acetylene duel fuel mode. Shameer P. and K. Ramesh [23] were enlightened the momentous of injection parameters, mainly consider parameters are injection timing and injection pressure in his review paper. At the same time, explain in details about the current scenario of biodiesel in the Indian and global market. Alaatin emiroglu et al. [24] carried out an experiment on a single-cylinder diesel engine powered with diesel fuel and butanol diesel blend for different injection pressure (190,210 & 230 bar) and engine speed (1600,2400 and 3200 rpm). Increasing injection pressure shows lower ignition delay, smaller combustion duration, higher cylinder pressure and HRR. Geo V et al. [25] were conducted an experiment on a single-cylinder diesel engine in which ethanol was injected into intake port during the suction stroke while rubber seed oil blend with diesel during main injection in order to improve the engine performance. It was observed that due to injected ethanol results in a reduction in combustion duration, which reflected as a result of higher heat result rate. Chaudhary K et al. [26] conducted a trial on single-cylinder multi-fuel engine which was operated with acetylene in combination with diesel. The trial was conducted for different CR such as 18, 18.5,19 and 19.5. Acetylene was added with a flow rate of 7 liters per minute. The result shows that cylinder pressure as well as heat release rate increases with CR. 19.5 CR shows higher BTE with simultaneously reduction in NOx and CO emission. Balasubramaniem D et al. [27] have manufactured 11 combustion bowls with varying geometry such as aspect ratio, reentrancy ratio and bore to bowl ratio. Experiment was carried out at 1500 rpm and CR 17.5 with full throttle condition. A result shows that, minimal bowl diameter and bore to bowl ratio gives higher average pressure inside the cylinder and also lower the value of fuel consumption. Gopal K et al. [28] was conducted a trial on a single-cylinder diesel engine for different EGR rate and IT.

Fuel used was n-octanol-diesel, which was blended as 10%, 20% and 30% by volume in the mineral diesel. It was predicted from the response surface method that injection timing affects more for NOx emission while EGR rate affects smoke opacity.

IT 20° CA bTDC and 10% EGR for 10% blend show higher BTE with minimum NOx and smoke emission. Sohan lal et al. [29] observed the effect of CR on performance of single cylinder engine, which uses biomass derived producer gas for their functioning. Besides engine emission characteristics, diesel replacement and noise level at different load and CR were also carried out. From the obtain results, diesel saving was achieved as 8.7%, 31.82%, 57.14% and 64.3% when the CR of the changes from 12-18 with increment of 2 after each trial. The large reduction (average 63.62%) was observed in HC emission, when CR of the engine increases from 12 to 18.

There are many number of small single-cylinder constant speed engines used in the decentralized power generation sector, agricultural farm machinery and irrigation purposes [30]. These engines have not yet reaped the benefits of the newly developed CRDI electronic fuel injection technology because this technology is very expensive [1]. As per available literature, most of the research work was concentrated on diesel engine parameters which were operating with conventional mechanical fuel injection system. Very few works are observed on newly developed CRDI technique which can be used for a small single-cylinder diesel engine. Also, no work is observed, which shows a combined effect of IT, IP and CR with CRDI injection system. This paper covers experimental investigations of most influencing combustion parameters and their values selected from literature as well theoretical investigation from developed mathematical modeling particularly for small diesel engine on performance and emission characteristics of the engine [30]. Combustion parameter such as cylinder pressure, net heat release rate and rate of pressure rise variation inside the cylinder during the combustion period for a different combination of selected parameters are analyzed and discussed in details. Performance parameters consider are thermal efficiency, volumetric efficiency, mechanical efficiency and exhaust gas temperature, while emission parameters like CO, CO_2, NOx, HC and smoke opacity are considered and effect of all these observed simultaneously.

II. EXPERIMENTAL METHODOLOGY

The test engine used for this experimental work is a single-cylinder kirloskar company manufactured diesel engine. Water is circulated for cooling purposes. Engine is having capacity 3.5 kW and running at constant 1500 rpm, which attached to an eddy current dynamometer for apply load on it. The specifications of the conventional engine on which experiment is carried out are as per given in Table 1. The pictorial view of the experimental setup with modified CRDI small single cylinder diesel engine is as shown in Fig. 1. Modifications have been done in the present engine (measurably in cylinder head) in order to accommodate solenoid injector (detail specification mention in Table 2), common rail, fuel injection pump and CRDI electronic control system. High pressure CRDI pumps, Electronic injector and only a few numbers of sensors, which give their input to the control unit which analyze it and further signal give to injector driver circuit were used. Fuel flow meter and air transmitter are also there for measurement of fuel and air intake by the engine, respectively. (AVL, 444) Exhaust gas emission analyzer was used for measurement of exhaust gas composition which detected gaseous group in the exhaust as NOx, HC, CO and CO_2 as well the exhaust smoke opacity was also measured using the smoke meter (AVL, 437).

Table 1: Engine Specifications

Engine type	Kirloskar
Number of cylinders	Single (01)
Combustion	Direct Injection
Bore	80mm
Stroke	110mm
CR	12 to 18
Rated Speed	1500 RPM
Power	5 HP

Table 2: Details about CRDI system

Injector	Bosch (Mahindra Maxximo)
Nozzle Diameter	0.215 m
Number of Holes	7
Fuel Injector Opening Pressure	300-1400 Bar
High Pressure System	Common rail direct injection BOSCH CP4.1
Data Acquisition Device	NI-USB -6210 bus Powered
Software used to operate ECU	Nira (Developed for the Engine)

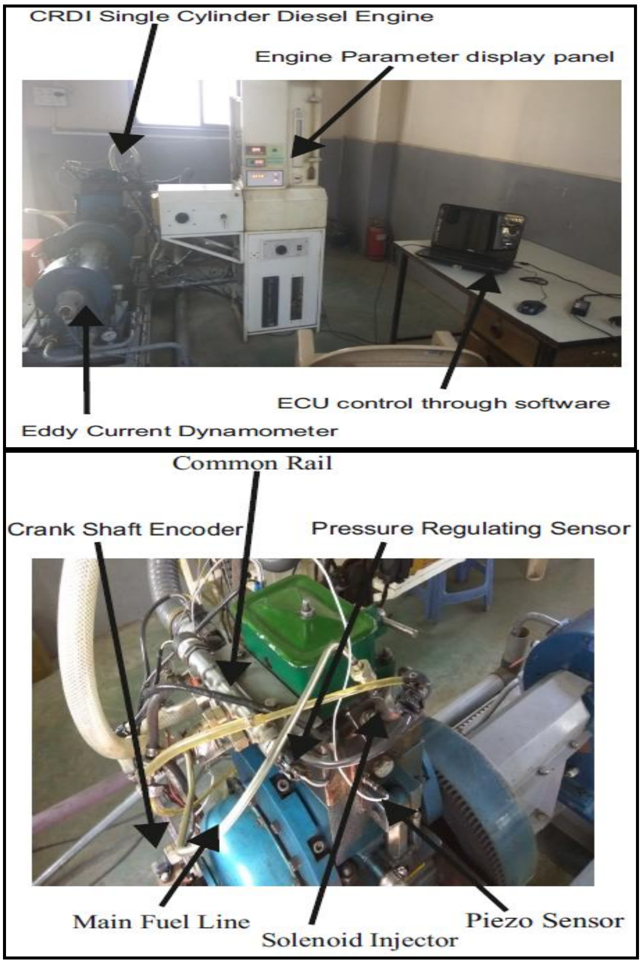

Fig. 1 Pictorial view of experimental setup with modified small single cylinder diesel engine.

III. RESULTS AND DISCUSSION

The aim of this study was to investigate the effect of combustion parameter on overall performance characteristics of a small single-cylinder modified CRDI system.

This objectives was achieved by conducting an experiment at different injection timings (25°, 20° and 15° bTDC), compression ratio (14, 16 and 18) and injection pressure (400, 500 and 600 bar). Engine run with a constant speed of 1500 rpm, while at 12 kg load and mineral diesel was used as the test fuel. Obtained results were divided into part as combustion, performance and emissions characteristics.

A. Combustion characteristics

Combustion directly affects on the overall engine performance as well on noise, vibrations and durability. Hence in order to get these important combustion characteristics, data for 50 consecutive engine cycles were taken by using data acquisition system. Averaged data were considered for further analysis in order to avoid cyclic variation. In-cylinder pressure, RoPR and HRR were then calculated, and all these parameters were compared for different IT, IP and CR conditions.

A.1in-cylinder pressure: rise in-cylinder pressure is one of the important parameter from the perspective of combustion, performance and emission of the diesel engine. The in-cylinder pressure variation with the crank angle for different CR at various IT and IP is as shown in Fig. 2. It can be seen that, shifting IT away from top dead center leads to a higher in-cylinder pressures at all IP as well as CR. As retarding IT, combustion also shifted and took place after TDC, which results in lowering maximum cylinder pressure. Increase in the IP as well as CR shows rise in cylinder pressure, but at the same time due to high IP, the span of fuel injection get decreases, which further depends on the IT. Also, as SOI timing shift towards a top dead center (i.e. retarded), pressure and temperature present inside cylinder at the time of injection was high which decreases the ignition delay period. Hence, more fuel fraction burning in diffusion combustion which causes the lowering maximum cylinder pressure [35]. Also, due to a decrease in the ignition delay period pressure peak get smaller and shifted in expansion side (i.e after TDC). Addition of fuel in the compressed air at lower CR will cause further drop in cylinder temperature and hence increases delay period with reduction in In- cylinder pressure [12, 21].

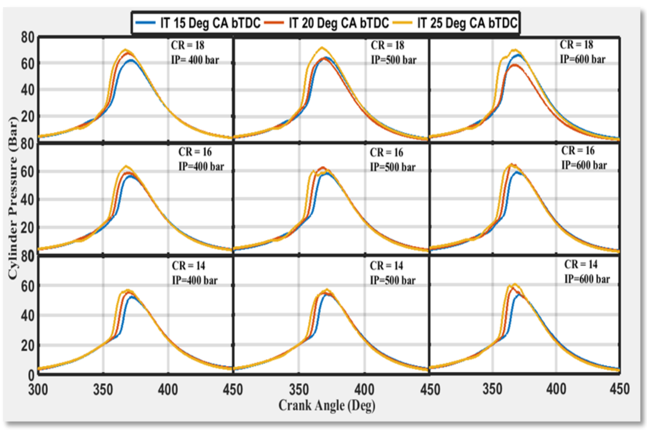

Fig. 2 In-cylinder pressure variation for a different combination IP, IT and CR

A.2 Rate of pressure rise: Accumulation of fuel during delay period gives the idea for maximum cylinder pressure that can be rise after combustion. As IP increases, the ignition delay decreases due to parameters associated with it such as smaller sauter mean diameter, shorter breakup length, higher dispersion and better atomization of injected fuel [3]. Fig. 3 shows variation RoPR curve for different combination IT and IP at various CR. The RoPR attends maximum value after ignition delay phase i.e during uncontrolled combustion phase because of sudden burning of fuel gives large amount of heat release as fuel attained its self ignition temperature during this phase. After attaining the peak value, rate of pressure rise decreases in the expansion stroke due to next controlled combustion phase in which the combustion take place relatively at slower rate as well increased combustion chamber volume due expansion stroke. IP as well as IT both affects on RoPR. RoPR was found increase with the increase in IP as well as CR. Also, for retarded injection timing, the RoPR curve is shifted, and it was found after TDC for CR14, at TDC for CR16 while before TDC for CR18.

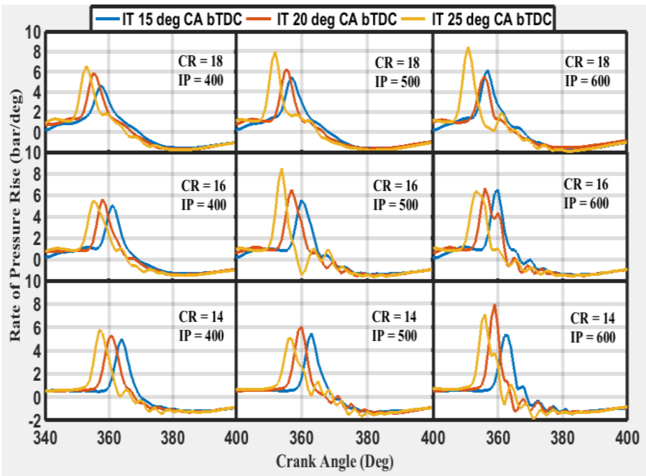

Fig. 3 RoPR inside the cylinder for a different combination of IP, IT and CR

A.3 Heat release rate: Work potential available in the heat energy is can be get from heat release rate curve. Fig.4 shows the behavior HRR curve with respect to crank angle for different variation in parameters as IP, IT and CR. A higher value of the heat release rate curve was observed for advanced SOI and at high injection pressure, and it decreases with a decrease in IP as well as for retarded SOI. For advanced SOI the value of delay period is more, hence accumulated fuel get suddenly burn in the next phase results into high heat release rate. While for retarded SOI sufficient pressure and temperature present inside the cylinder, which decreases the delay period. Hence, fuel is getting burn as soon as injected inside cylinder due to which the heat release rate curve get lowered and spread over that combustion duration [31]. For longer ignition delay, fuel and air mixture get more time to mix properly, and net HRR is increased when the combustion is performed. It is also observed that compression ratio also affect the heat release rate. At CR14 with retarded injection, maximum heat release observed after TDC position which is get shifted towards TDC for CR16 and CR18 it is found before TDC.

This behavior affects the performance and emission nature of the engine. At high IP with retarded IT, combustion duration also get reduced (reduced HRR curve width) due to faster fuel-air chemical kinetics. Similar trends are also reported by agrawal et al. in his research [3].

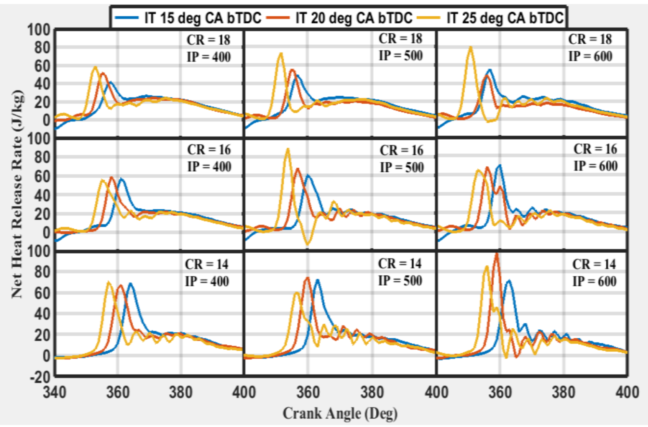

Fig. 4 Net heat release rate variation for a different combination IP, IT and CR

B. Performance characteristics

In order to evaluate the performance characteristics of this modified CRDI engine the trials were taken for a different combination of selected parameter with their different values. The experiments were repeated number of time and an average values are consider for further calculation.

B.1 Brake thermal efficiency (BTE): BTE is nothing but out of total thermal energy of the fuel get transmitted into mechanical work, which is further effectively utilized for application. The variation of BTE with respect to CR for different injection timing and IP when the load on the engine was kept 12 kg is as shown in Fig. 5.

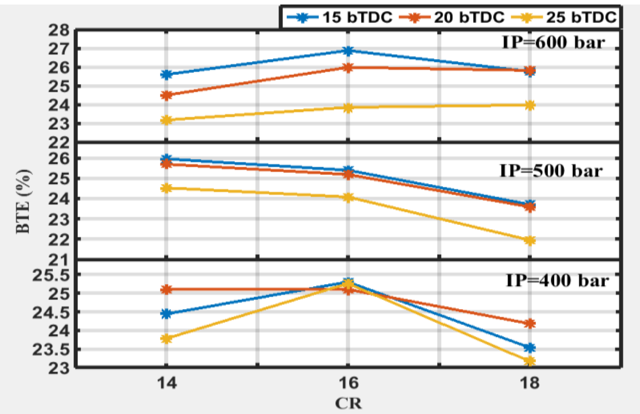

Fig. 5 Effect of IT and CR on BTE for a different IP

High IP with retarded injection timing gives higher BTE at all CR. The intermediate IT (i.e. 20° CA bTDC) shows a higher value of BTE at all CR for 400 bar IP. Variation in CR shows significant variation in the brake thermal efficiency at 12 kg load. It was observed that CR 16 shows higher value of efficiency for a different combination of IP and IT, while increase or decrease in CR ratio to either side results into decrease in BTE.IP 500 bar shows gradually increased in efficiency with retarded IT, while further increase in IP shows rise in the efficiency up to IT 20° bTDC further retardation of IT (15° bTDC) shows a decrease in the efficiency. It was observed that 600 bar IP and 15° bTDC IT gives a higher value of BTE at all CR. Overall high IP with moderate injection timing (i.e. 20° bTDC) shows better results. The reason for the same was due to high IP fuel droplet get breakdown into finer, which can put into a cylinder within less time as compared to conventional low IP system [32]. Due to this, sprayed fuel is properly mixed with compressed air. Retarding the IT at a higher IP increase the power output, which is might be due to a decrease in negative work, which was acted on piston if the maximum pressure occurred before TDC [33]. Since, maximum BTE is obtained at 15° bTDC with IP of 600 bar at all compression ratio, this IT and IP said to be optimum for this modified CRDI system.

B.2 Mechanical efficiency: Mechanical efficiency shows, how effective transfer of energy that is generated inside the cylinder to the engine crank shaft .Fig. 6 shows the behavior of mechanical efficiency with respect to variation CR for different IT and IP. It was clearly shows that mechanical efficiency increase with an increase in IP as well for advance injection timing at all CR, But at the same time it decreases with increase in CR at all IP as well for IT. With increased IP (600 bar) and IT at 25° bTDC shows a higher mechanical efficiency at all CR. Retarded SOI timing shows decreased in mechanical efficiency compared with advanced IT at all CR. Reason of the same was that with retarded injection timings, pressure and temperature generated inside cylinder after combustion was less compared to advance.

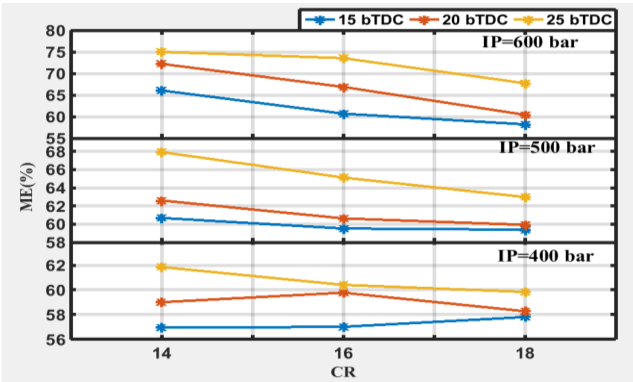

Fig. 6 Effect of IT and CR on mechanical efficiency for a different IP

Also, due to retarded IT, late combustion phase takes place, and a result in combustion extends well into the expansion stroke [33]. The maximum pressure generated after TDC. Piston is get pushing down by combusting gases pressure force during the expansion stroke. But it was less due to increased combustion chamber volume in the later part. Hence in order to get the maximum benefit of high IP, selection of optimum SOI timing is important. At lower CR, the pressure of the compressed air is lower as compared to that at higher CR which is also help in reduction of engine friction [21].

B.3 Exhaust gas temperature: Exhaust gas temperature is important from the point of view formation of dissociation of exhaust gases and increase in the NOx formation, which is generally take place at higher temperature. Hence, in the present study we limit the maximum injection pressure up to only 600 bar.

Fig. 7 gives the variation of EGT with respect to CR for different IT and IP. It was inferred that exhaust gas temperature was found higher for 25° bTDC IT while it gradually decreases as retarding the IT at all CR as well as IP. It is observed that 25° bTDC gives higher EGT at all CRs and IP. At high injection pressure the exhaust gas temperature is seen higher which further decreases with injection pressure [2].Due to high injection pressure, breakdown of fuel particle take place, which result into rapid and more complete combustion of fuel leads to an increase in temperature and pressure inside cylinder after the combustion.

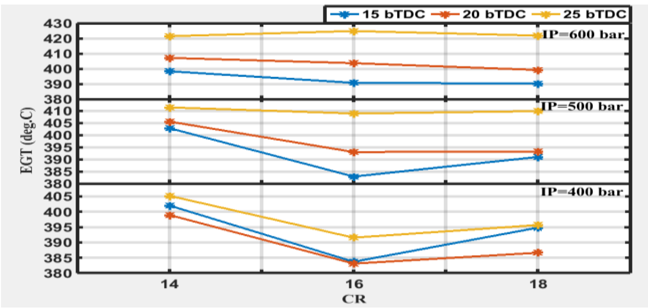

Fig.7 Effect of IT and CR on EGT for a different IP

Duration of main combustion of fuel and delay periods decides the maximum rise in cylinder temperature. The actual combustion occurs near TDC either before or after give peak exhausts gas temperature. Fuel injected with retarded injection timing shift actual span of combustion into expansion stroke which results into decrease in after combustion temperature while advanced IT shows maximum exhaust gas temperature.

B.4 Volumetric Efficiency: Mass of air and fuel present inside the cylinder at the time of combustion decides the performance and emission quality of the engine. Availability of air for combustion depends on volumetric efficiency. High volumetric efficiency shows present of sufficient air for combustion inside the cylinder. Fig. 8 shows the trends for variation of volumetric efficiency with CR for IT and at different IP. It was observed that volumetric efficiency was not affected by IP as well as CR, but it somewhat affected by SOI timing. Retarded IT shows higher volumetric efficiency as compared to advanced IT at all CR and IP. Also, it was observed that the volumetric efficiency of this modified CRDI engine was 2-3 % less than the conventional small diesel engine at 12kg load.

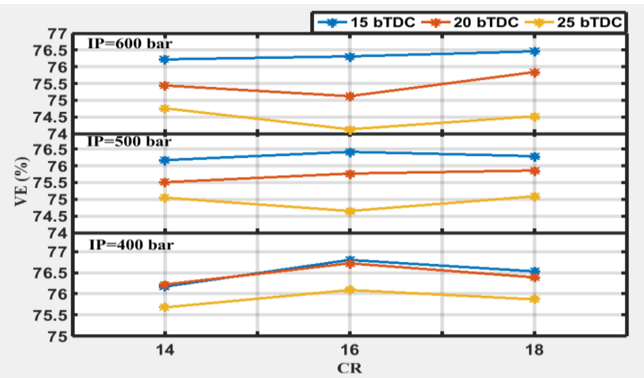

Fig. 8 Effect of IT and CR on volumetric efficiency for a different IP

C. Emissions characteristics

Emissions characteristics are very important from environment point of view as well as the euro norms put into action.

C.1 NOx emissions: As per the theory of NOx formation in CI engines shows that it mainly depends on the three parameters concentration oxygen inside the combustible mixture, maximum temperatures rises after combustion and the combusting mixture duration at the peak cylinder temperature. The variation in mass emission of NOx for different SOI timings and different CR at 600, 500 and 400 bar injection pressure are shown in Fig.9.

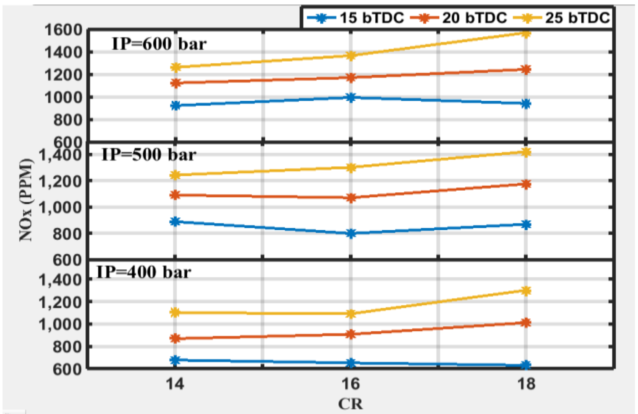

Fig. 9 Effect of IT and CR on NOx for a different IP

The increasing in engine CR showed increase in the mass emission of NOx with IP, and at the same time, it was found getting decrease as retarding IT from 25 to 15° CA bTDC at all IP. It is observed that, NOx emissions are less when combustion parameters set as retarded IT (15° CA bTDC) , low IP (400 bar) for all compression ratio. High injection pressure with advanced injection timing shows relatively higher NOx emissions for all CR. The factor responsible for an increase in mass emission of NOx with compression ratio as well with advance injection timing mainly at 25° bTDC is longer delay period observed due to less pressure and temperature present inside the cylinder when fuel is get injected, which results into higher HRR in the premixed combustion phase.

Hence, relatively higher combustion temperatures take place inside the cylinder because of longer combustion durations [33]. For low compression ratio, at the end of the compression stroke, pressure and temperature inside the cylinder are less as compared with higher CR, which increases the ignition delay. Also, due to retarded injection timing, the actual combustion takes place after top dead centre, which results into reduction in combustion temperature and longer delay period [9, 12]. High IP shows relatively higher NOx emissions as the greater spray penetration, and better distribution of fuel inside compressed air take place at high injection pressures which results into rise in temperature as compared to at low IP [34, 35].

C.2 HC emissions: HC emissions mean the unburned fuel that goes into the exhaust of engine are mainly because of availability of the less density of oxygen in the combustion chamber or not properly mixing of fuel and air.

Hence stoichiometric mixture is required for complete oxidation of HC.

A mixture which is on either side of stoichiometric leads into the formation of HC emission. Variations in HC emissions in PPM at different IT for varying engine CR and IP are shown in Fig.10. It was observed that injection timing as well as compression ratio both affect HC formation. There was a low hydrocarbon emission take place when injection timing was set to 20° CA bTDC. CR16 shows the lower HC formation at all IP except at 600 bar. Higher IP and advanced IT combination show a higher value of HC emission at CR -18. Overall, an increase in the IPs (from 400 to 600 bar) shows a decrease in HC emission.

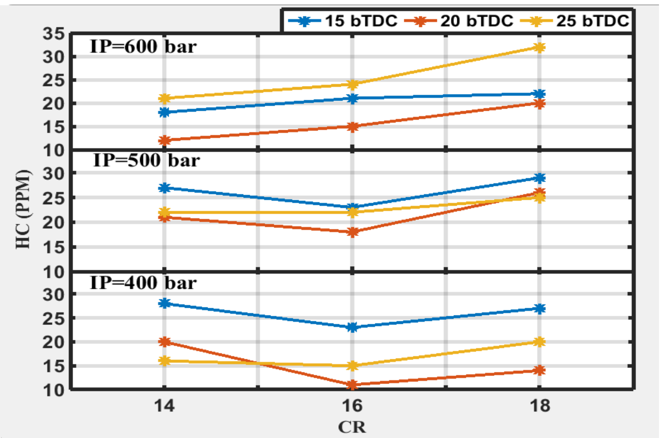

Fig. 10 Effect of IT and CR on HC for a different IP

As high injection pressure along with small nozzle hole diameter reduces fuel droplets size which is easily get evaporated when mix with hot compressed air inside the cylinder, hence shorter ignition delays and complete combustion can be achieved [18].Unburned hydrocarbon (HC) and carbon monoxide (CO) level increases with increased with CR for increase level of injection pressure. CR18 shows somehow more emission value when compared to CR14. The one of the reason is that, at lower CR with high injection pressure get the sufficient time for proper mixing of fuel and air due to longer ignition delay.[21].

C.3 *CO emissions:* Due to the availability of less oxygen during combustion than required for complete combustion of fuel, complete oxidation of carbon particles does not take place and results in the formation of CO [3, 15]. Fig. 11 gives the variation of CO with respect to IP for different injection timing and CR. It was observed that compression ratio mainly affects the formation of CO. At CR 18, a higher value of CO was observed at all IP. At high IP and lower CR, 15° bTDC show lower value of CO, which is gradually increase with advance SOI timing, while CO value remains unaffected for CR16 and at 600 bar IP. For 400 and 500 bar IP, CO value was gradual increases with CR while 15° CA BTDC shows a higher rate of CO emission. Advance IT shows a lower rate of CO emission at 400 bar IP, which was increases with an increase in IP. When fuel injection pressure increases, fuel droplet size get reduces as well as better penetration of fuel take place inside compressed air present inside cylinder .Both this leads into homogenous air- fuel mixture formation; therefore CO emission reduces [18]. Overall, High IP results into decrease in the CO value. At high IP, there is an increase in the turbulence because of which proper mixing of air and fuel take place inside the cylinder. As CR increases, the relative air-fuel ratio also increases and more heterogeneous mixture form inside the cylinder, which results in higher CO emissions conditions.

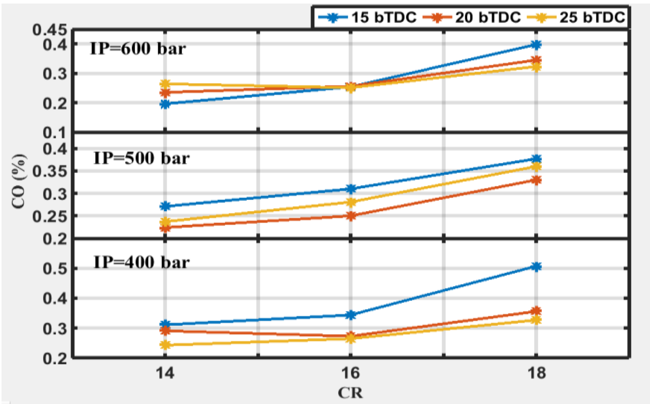

Fig. 11 Effect of IT and CR on CO for a different IP

Retarded injection timing pushed the majority of combustion after TDC means into expansion stroke, which leads into reduces the pressure and temperature of the later part of the combustion which is the cause of the formation of CO [17].

C.4 Smoke opacity: Oxygen content of the fuel decides the formation of smoke opacity and their value. Fig. 12 shows % smoke opacity with respect to IP for a different combination of injection timing and CR.

From the trends shown for smoke opacity in the figure, the values of smoke opacity is least for lower IP and advance IT at all CR. High injection pressure with retarded injection timing also shows lower emission of smoke. But at advance injection timing, smoke emission increases with injection pressure.

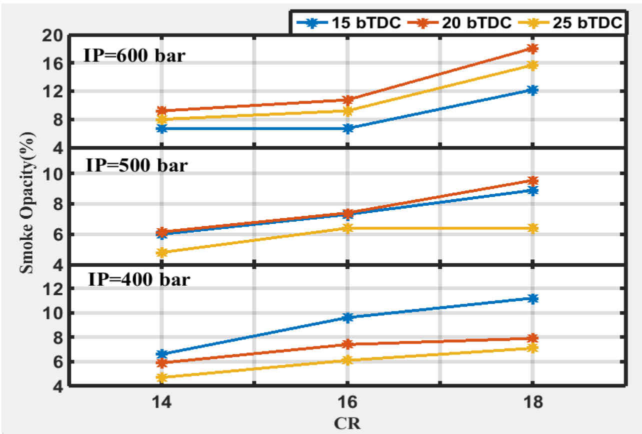

Fig. 12 Effect of IT and CR on smoke opacity for a different IP

The higher injection pressure gives effective fuel spray atomization results in improved fuel-air mixing, which further decreases the smoke emission. The same effect observed by Jain et al. [3]. Lower compression ratio with advanced injection timing combination gives increased ignition delay and gets more time to react with oxygen with fuel, hence results in a decrease in smoke opacity. While an increase in CR from 14-18 shows higher smoke emission for all combination of injection pressure and injection timing.

This might be due to a decrease in the time available for better mixing of fuel-air mixture and formation of heterogeneous mixture inside the cylinder.

The minimizing CR results in the decrease in the pressure and temperature along with increased ignition delay (ID) [16]. This increase in ID, gives more time for fuel and air mixing leading to reduced spatial stratification, which reduces the soot levels [21]. It is also observed that smoke opacity was increased with engine CR. The reason behind it that, during combustion as increase in CR delay period get reduces and result in long mixing controlled combustion phase, because of which high pressure and temperatures generated inside cylinder but lower the oxygen density inside the combustion chamber, therefore the value of smoke opacity increases. Hence, IP and IT plays an important role for smoke opacity formation.

IV. CONCLUSIONS

The effects of combustion parameters such as IP, IT and CR on the combustion, performance and emission characteristics of the modified CRDI small single cylinder diesel engine are investigated in the present study. It was observed that, CR has major influence on emission parameter of the engine followed by the injection pressure, while injection pressure as well as injection timing has found great impact on performance characteristics of the engine.

From the effect on combustion characteristics, it can be concluded that,

- High IP with advanced IT at CR 18 gives maximum rise in cylinder pressure.
- RoPR increases with an increase in IP.
- A higher value of the HRR curve get for advanced SOI and at high injection pressure

From the effect on performance characteristics, it can be concluded that,

- BTE was found to be high at moderate CR (16) with retarded IT. The reduction in fuel consumption was found at the high IP with retarded IT and low CR.
- Mechanical efficiency increases with IP and decreases with CR.
- Exhaust gas temperatures value increases with increase in IP and CR value.
- Retarded IT shows higher volumetric efficiency.

From the effect on emission characteristics, following conclusion can be made,

- High CR (18) and the retarded injection timing (15°CA) show lower NOx emissions.
- High IP with advanced IT and low CR give less CO emission.
- High IP (600 bar) and moderate injection timing (20° bTDC) shows lower HC emission
- Smoke opacity was found low at high IP, CR set at 14 and injection timing set away from TDC.

Overall, a simpler version CRDI system is very much effective for single-cylinder engines with this we can achieve minimum emission and better fuel economy.But still, some parametric modification is required to get the better results as compared to the conventional engine for higher load. This is might due to decrease in the airflow rate inside the engine cylinder, which will result in a reduction in volumetric efficiency, which causes to availability of less oxygen for proper burning of fuel. Also, a lower value of mechanical efficiency shows the area of improvement which might be decreased due to negative work done on the piston, so an adequate selection of SOI is essential.

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NOMENCLATURE

bTDC	Before top dead centre
aTDC	After top dead centre
EFI	Electronic fuel injection
EGT	Exhaust gas temperature
CRDI	Common rail injection system
BTE	Brake thermal efficiency
BSFC	Brake specific fuel consumption
EGR	Exhaust gas recirculation
ME	Mechanical Efficiency
CR	Compression ratio
IT	Injection timing
IP	Injection pressure
SOI	Start of injection
HC	Hydrocarbon
CO	Carbon Monoxide
NOx	Nitrogen Oxides
CA	Crank Angle
VE	Volumetric Efficiency
RoPR	Rate of Pressure Rise
HRR	Heat Release Rate

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