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ORIGINAL ARTICLE

Effect of Injection System Parameters on Performance and Emission Characteristics of a Small Single Cylinder Diesel Engine

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ABSTRACT – Limited fossil fuel reservoir capacity and pollution caused by them is the big problem in front of researchers. In the present paper, an attempt was made to find a solution to the same. The conventional fuel injection system was retrofitted with a simple version of the common rail direct injection system for the small diesel engine. Further, the effect of injection system parameters was observed on the performance and emission characteristics of the retrofitted common rail direct injection diesel engine. The parameters such as injection pressure, the start of pilot injection timing, the start of main injection timing and quantity of percentage fuel injection during the pilot and main injection period were considered for experimental investigation. It was observed that all the evaluated parameters were found vital for improving the engine's performance and emission characteristics. The retrofitted common rail direct injection system shows an average 7% rise in brake thermal efficiency with economic, specific fuel consumption. At the same time, much more reduction in hydrocarbon, carbon monoxide and smoke opacity with a penalty of a slight increase in nitrogen oxides.

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Emissions characteristics;
Performance characteristics

NOMENCLATURE

bTDC	before top dead centre	CA	crank angle
aTDC	after top dead centre	IT	injection timing
TDC	top dead center	IP	injection pressure
EGT	exhaust gas temperature	SOMI	start of main injection
CRDI	common rail injection system	SOPI	start of pilot injection
BTE	brake thermal efficiency	HC	hydrocarbon
BSFC	brake specific fuel consumption	CO	carbon monoxide
EGR	exhaust gas recirculation	NOx	nitrogen oxides

INTRODUCTION

Small single-cylinder diesel engines are mainly used for stationary as well as mobile applications. Exhaust gases emitted from these engines had polluted most of the cities in our country [1]. Many of these engines use a mechanical fuel injection system for delivering the required quantity of fuel at the time of combustion stroke. Such a conventional injection system does not have precise control over the delay period, injection pressure, duration of injection and rate of injection. All these factors lead to fuel wastage and atmospheric pollution from small diesel engines. Electronic fuel injection systems used earlier for large diesel engines have the flexibility to change the injection strategy and multiple injection capabilities. The fuel injection system parameters such as injection pressure (IP), fuel injection rate, multiple injections, and the start of injection under different engine operating conditions can be effectively control using an electronic injection system [2]. Researchers had tried to design and implement such an electronic injection system for small diesel engines.

In the past, a lot of experimental work was carried out on small single-cylinder diesel engines in order to improve efficiency and reduced emission. Most of the researchers carried their research work by changing the combustion parameter simultaneously, such as fuels, IP, injection timing (IT), percentage of exhaust gas recirculation (EGR) and compression ratio on conventional small diesel engines. Mehmet [3] and Emiroglu [4] done the trial on a diesel engine at different IPs (190, 210 and 230 bar) for two different loads and speeds. The result shows that the increase in IP shows a reduction in soot formation. Also, similar type experiments were carried out by many other researchers [5-6]. The mechanical injection system of conventional small diesel engines could not solve the problem of pollution and performance. For the last decade, researchers had tried to implement the electronic injection system for small diesel engines. Many authors had retrofitted the conventional injection system with an available electronic common rail direct injection (CRDI) system on a small diesel engine and conducted trials. Until today, the work will find the optimum injection system parameters to maximise the overall engine performance. Agrawal et al. [7-9] conducted experiments on a small single-cylinder diesel engine. The conventional injection system of the engine was replaced with CRDI without

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making significant hardware changes in the available system. The trials were conducted for different values IP and IT. The results show a large improvement in the combustion and emission characteristics. Carpenter et al. [10] had replaced the mechanical fuel injection system with electronic injection for a small industrial diesel engine. After taking a trial with this modified system, it was found that nitrogen oxides (NOx) and smoke opacity decreased, but other parameters like hydrocarbon (HC) and carbon monoxide (CO) increased while brake specific fuel consumption (BSFC) was not satisfactory. Hwang et al. [11] analysed the effect of high IP on the combustion characteristics of the diesel engine. The result shows the increase of peak in-cylinder pressure at high load with a rise in IP. Observations were recorded as maximum cylinder pressure 73.1 bar (2° CA aTDC) for diesel, 72.2 bar (at 2.4° CA aTDC) for biodiesel at IP 800 bar. Pai et al. [12] analysed the effect of input parameters such as IP and IT on the performance and emission of a modified (CRDI) single-cylinder diesel engine. The 800 bar fuel IP at all IT, especially at 18° bTDC, recorded the best results. In conclusion, the authors say that the rise in IP and proper injection timing results in quality combustion. A similar kind of study was also done by Jiaqiang et al. [13]. Results show that higher injection pressure up to 600 bar gives higher brake thermal efficiency (BTE) but further increased IP shows a decrease in performance of the engine.

Effective reduction of soot from a diesel engine by using post-injection technology was explained by Jacqueline and Musculus [14]. Raeie et al. [15] simulated the spray and combustion process of diesel for early and late injection timing at six different IP reneges from 275 to 1000 bar. It was observed that early injection results in lower soot and higher NOx emission than late injection. Shameer and Ramesh [16] and Shameer et al. [17] enlightened the momentous injection parameters, mainly IT and IP, on the engine emission characteristics in their review paper. From studies, it was found that the increased fuel IP was also responsible for higher NOx and soot formation. Splitting the injected fuel quantity during combustion was found effective to reduce NOx and soot emission without too many effects on engine thermal efficiency. Jafarmadar [18] analysed the effect of split injection technology on the combustion and emission characteristics of a small diesel engine. It was found that 75% fuel injection during the pilot period and 25% fuel injection in post-injection with a dwell period of 20° CA was found optimum for these engines. Nguyen et al. [19] developed the soot model to study the effect of split injection on the soot emission of the diesel engine. The 75% fuel injected during the pilot and the remaining 25% injected in post-injection with an 8° CA dwell between these two injections found effective for reduced soot from the engine. Jain et al. [20] proposed that increasing fuel IP at the advanced start of main injection (SOMI) improved combustion; however, too high (1000 bar) resulted in slightly inferior combustion performance and emission characteristics.

Mobasheri [21] determined the influence of the different fuel spray included angle and split injection on the CRDI diesel engine. Different included spray angle (145°, 105°, 90°) effects were analysed in comparison with the conventional spray angle (at 125°) on engine combustion. The 105° angle offers more flexibility for simultaneous reduction of NOx and soot emission. Anand [22] employed a split injection technology to reduce the NOx and soot formation from the diesel engine. The SOMI timing was varied from 17° to 25° CA bTDC with a gap of 2° CA, while the SOPI was taken at 5° CA before and after TDC. Results show that high IP and split injection technology effectively improved atomisation of fuel and engine performance. The effect of split injection strategy on the overall performance of the engine fuelled with biodiesel blend was analysed by How et al. [23]. The quantity of fuel injected was divided into two injection pulses, 25:75, 50:50 and 75:25 as the pilot and main, respectively, with a fixed duration of 15° CA. The result shows that split injection technology gives a reduction in NOx and soot emission. Edara et al. [24] examined the effect of split injection strategy on combustion characteristics of the small diesel engine. For split injection, the pilot injection was set 54° CA bTDC with 10% fuel mass share, and the main injection was set at 11° bTDC with 90% fuel mass share. The result shows improved overall performance compared to single injection. Molina et al. [25] analysed the effect of variation in injection system parameters such as IP, SOMI and SOPI on combustion and emission characteristics of diesel engines. Results show that delay in SOMI and triplet injection results in better performance and lower emission. Yousefi et al. [26] investigated the combined effect of injection pressure and split injection on performance as well as emission characteristics of the dual-fuel mode diesel engine. Experimental work was carried out with different IPs as 525, 650 and 800 bar. The result shows that combined technology improves performance and emission characteristics.

From the available literature, it was observed that very little work was done on the effect of split injection technology at high fuel injection pressure on a small diesel engine. Also, the considered range in the previous study for the pilot and main injection timing, injection interval gap between two injections and dividing fuel injection quantity during the pilot and main injection period was limited. Very few authors studied the combined effect of all the injection system parameters simultaneously on the performance and emission characteristics of the small diesel engine. Hence, this paper covers experimental investigations of these electronic injection system parameters to obtain better performance with the least emission for a small single-cylinder diesel engine. The injection system parameters and their values were selected based on the simulation study performed in MATLAB and studied literature. The present work found adequate for designing the electronic injection system for small diesel engines.

EXPERIMENTAL METHODOLOGY

Experimental work was carried out on a 4-stroke single cylinder CRDI small diesel engine. The detailed specification of the engine is mentioned in Table 1. The engine was attached to an eddy current-type dynamometer for loading. The speed sensing unit is incorporated on the dynamometer at one end. The piezoelectric transducer was flush-mounted in the cylinder head and used to measure cylinder pressure. Volumetric fuel flow rate and intake air flow rate were also measured using a fuel flow meter and air transmitter. IP, SOMI and SOPI timing and percentage fuel injection values were varied with the help of software attached to the electronic control unit of the CRDI system. The specification of the retrofitted CRDI system is given in Table 2. The analysis of experimental data related to combustion has been getting through a data acquisition system and software. Emissions were measured using an exhaust gas analyser and smoke meter. Table 3 gives the range, accuracy and percentage uncertainty of these instruments. Figure 1 shows the pictorial view of the complete setup of the CRDI small diesel engine and devices used to measure exhaust parameters. Experiments were performed for a different combination of injection system parameters, as shown in Table 4. Figure 2 gives the information about SOPI and SOMI timing and injected fuel quantity with respect to CA. The trials were repeated three times and considered average values from these for further analysis. A mineral diesel was used as the test fuel. The engine speed was constant at 1500 rpm by keeping a load 12 kg load on the engine for the entire experimental work. Figure 3 shows the flowchart of the methodology.

Table 1. Engine specifications.

Engine type	Kirloskar
Number of cylinders	single (01)
Combustion	direct injection
Bore	80 mm
Stroke	110 mm
CR	18
Rated Speed	1500 rpm
Power	5 hp

Table 2. Details about CRDI system.

Injector	BOSCH (Mahindra Maxximo)
Nozzle diameter	0.215 mm
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)

Table 3. Range, accuracy, resolution with measuring method of instruments used.

Exhaust Gas	Measurement range	Resolution	Accuracy	Measuring method
CO	0-15.0% vol	0.01% vol	+ 0.06% vol	NDIR
HC	0-30000 ppm (Propane)	1 ppm vol	+ 12ppm	NDIR
NOx	0-5000 ppm	1 ppm vol	+ 50% vol	Electrochemical
Smoke opacity	0-100%	1 ppm vol	±1%	Filter paper

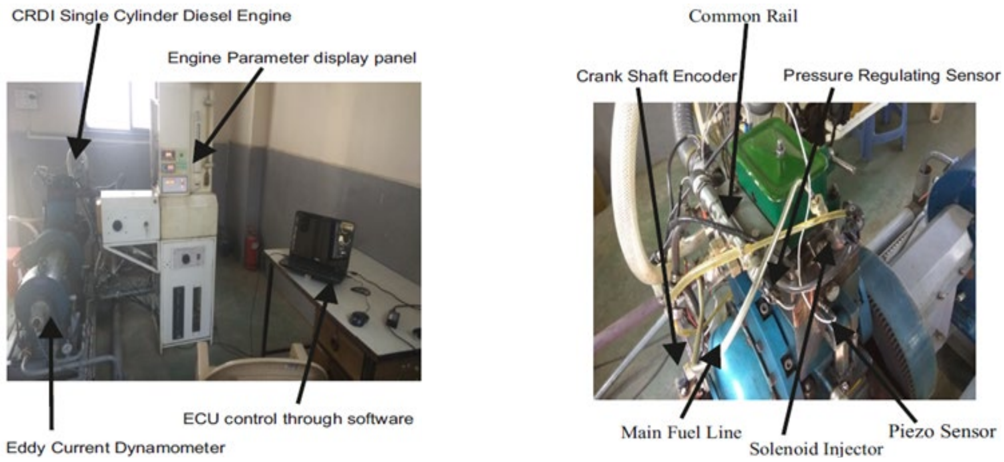

Figure 1. Pictorial view of the experimental setup for CRDI single-cylinder diesel engine.

Table 4. Injection system parameters consider for experimental investigation.

Sr. No	IP (bar)	IT (°CA bTDC)		Injected quantity (%)	
		SOPI	SOMI	SOPI	SOMI
1	400	30	10	10	90
2	500	35	15	20	80
3	600	40	20	30	70

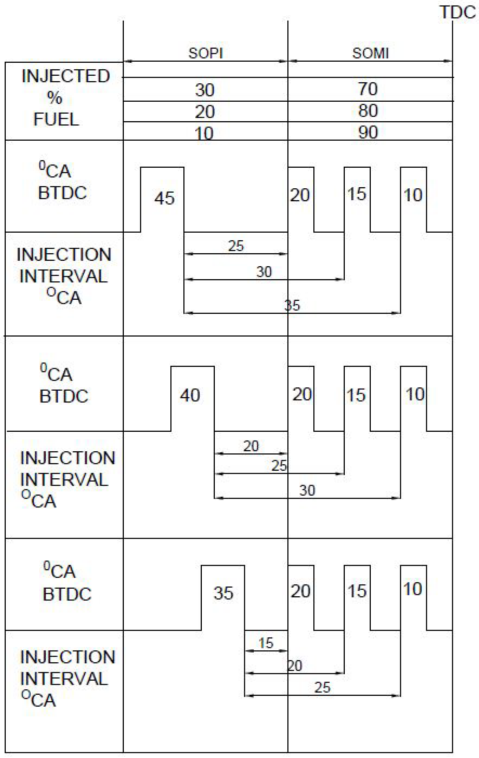

Figure 2. SOMI and SOPI timing and a quantity of injection with injection interval.

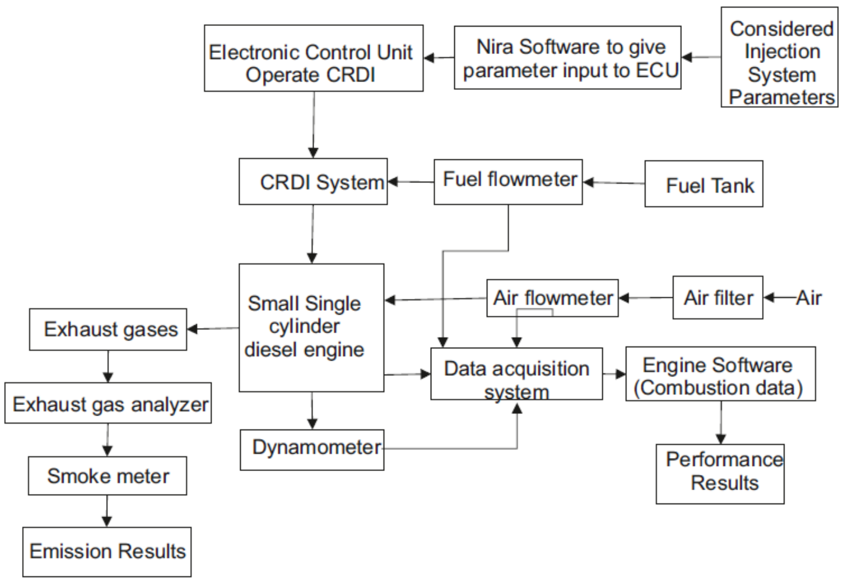

Figure 3. Flow chart for experimental methodology**.**

RESULTS AND DISCUSSION

Obtained results were divided into two categories, namely performance and emissions characteristics. During experimental work, the detonation has been observed when SOMI was set at 20° CA and SOPI 45° CA bTDC for all IP and percentage quantity of injection. The inferior fuel-air kinetics and large injection interval gap between pilot and main injection might cause the detonation.

Performance Characteristics

Brake thermal efficiency

The term brake thermal efficiency (BTE) gives the fraction of the total thermal energy of fuel converted into useful mechanical power. The variation of BTE with respect to SOMI for different SOPI, the quantity of fuel injection percentage and IP is shown in Figure 4.

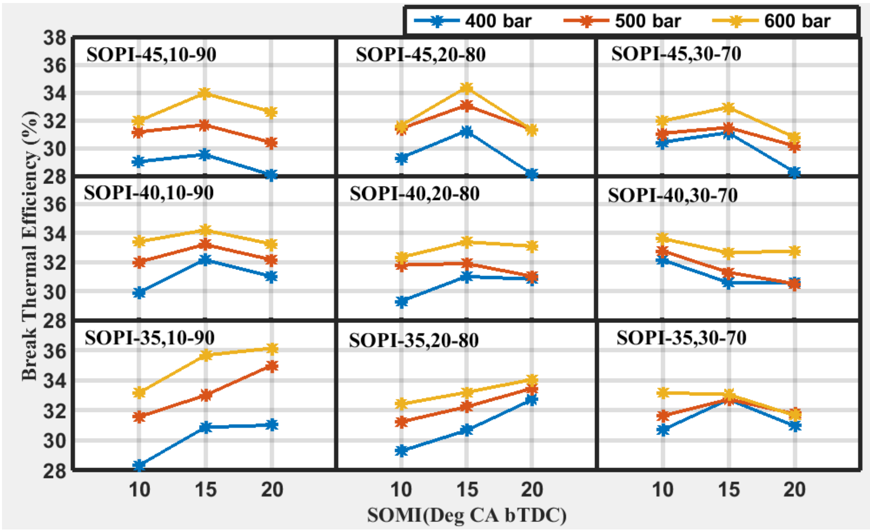

Figure 4: Effect of SOPI, SOMI and injection quantity on BTE for different IPs.

An increase in IP gives a boost in BTE at all different combinations of other parameters. The reason for the same was due to high IP breaks down the diesel droplet into finer which can put into a cylinder within less time as compared to a conventional low IP system, due to this; sprayed fuel is appropriately mixed with compressed air. The intermediate SOMI (i.e. 15° CA bTDC) shows a higher value of BTE for different SOPI and quantity of percentage fuel injection. Variation in the amount of fuel injection shows significant variation in the brake thermal efficiency. An increase in the fuel injection percentage during pilot injection results in a decreased BTE. Injection quantity set as 30-70 shows a significant reduction in BTE, which was might be due to a decrease in fuel percentage during the main injection period. The decreased fuel quantity at the main injection period results in lower mean effective pressure, further getting acted on the piston during the expansion stroke. It was observed that 15° CA SOMI showed a higher efficiency value when SOPI was set at 45° CA for a different combination of IP and injection quantity. Advancing or retarding the SOMI to either side of 15° CA results in a decrease in BTE. Overall high IP with moderate SOMI (i.e. 15° bTDC) shows better results. Retarded SOMI means shifting the main injection towards TDC increases the power output. This was due to decreased negative work, which acted on the piston if the maximum pressure occurred before TDC [27]. The maximum BTE was obtained at 35° CA SOMI, 15° CA SOMI with IP of 600 bar when a quantity of injection set as 10-90 from out of all possible combinations. Hence, all the parameters mentioned above were optimum for this single-cylinder CRDI engine from the performance point of view. Also, the retrofitted CRDI injection system gives an average 7% rise in BTE compared to the convention injection system.

Brake specific fuel consumption

BSFC gives the fuel consumed by the engine to produced unit power output. The mass of fuel consumed per hour obtained through the fuel flow meter and measured brake power gives a BSFC for each trial. The BSFC shows exactly the opposite nature as that of BTE. Figure 5 shows the variation of BSFC with respect to SOMI for a different combination of SOPI, percentage fuel injection quantity and IP.

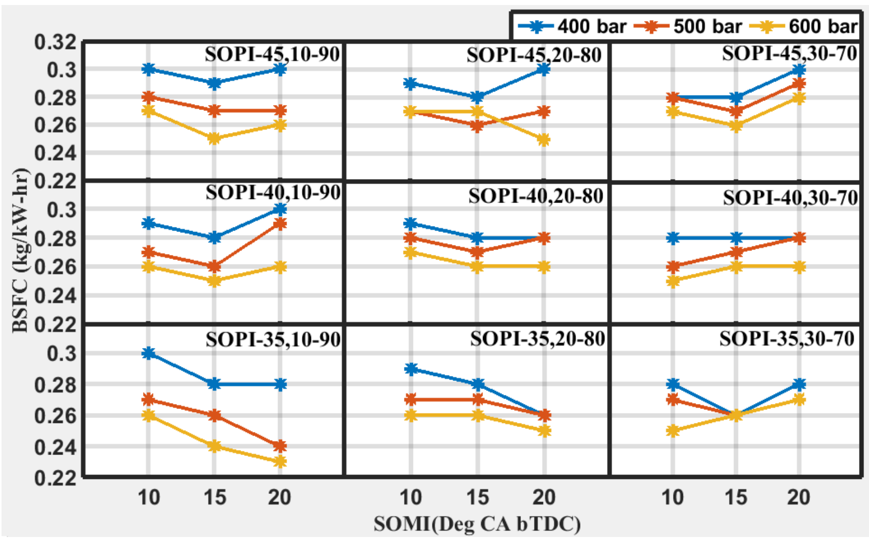

Figure 5. Effect of SOPI, SOMI and injection quantity on BSFC for different IPs.

An increase in IP from 400 bar to 600 bar gives a much more decrease in BSFC value at all different combinations of considered parameters. The lowest BSFC value was observed at 35° CA SOPI for advanced (shifting away from TDC) SOMI at 600 bar IP. The intermediate SOMI (i.e. 15° CA bTDC) shows a lower value of BSFC for different combination SOPI and quantity of fuel injection. Variation in the amount of fuel injection percentage shows significant variation in the BSFC. An increase in the fuel injection percentage for pilot injection results in an increase in the BSFC value for 600 bar IP. While on the other hand, BSFC value found to decrease for 400 bar. A reduction in the percentage of fuel-burning during the main injection period to get sufficient time to mix with hot air at a lower IP was the reason for the observed lower BSFC at 400 bar IP [28]. The 500 bar IP shows the intermediate values of BSFC compared to the 400 bar and 600 bar IP. All IP shows similar nature for a different combination of other parameters, expect few results. Overall high IP and split injection phenomena show better results. The same was due to a breakdown of fuel droplets into finer because of high IP. Further, these droplets get correctly mixes with the air and form a homogenous mixture, which results in nearly complete combustion of fuel. Also, injecting sufficient pilot quantity before the main injection raises the pressure and temperature inside the combustion cylinder, decreasing the combustion and physical delay during the main injection. Selecting appropriate SOPI and SOMI gives effective piston work from this combustion. Here, 35° CA SOPI and 15° CA SOMI at 600 bar IP when the percentage injection set at 10-90 shows the lowest BSFC value.

Mechanical efficiency

Mechanical efficiency shows how effective the transfer of energy is generated inside the cylinder to the engine crankshaft. The mechanical losses are one reason to have an overall low thermal efficiency of IC engines. Figure 6 gives the variation of mechanical efficiency with respect to SOMI for different SOPI, a quantity of injection and IP.

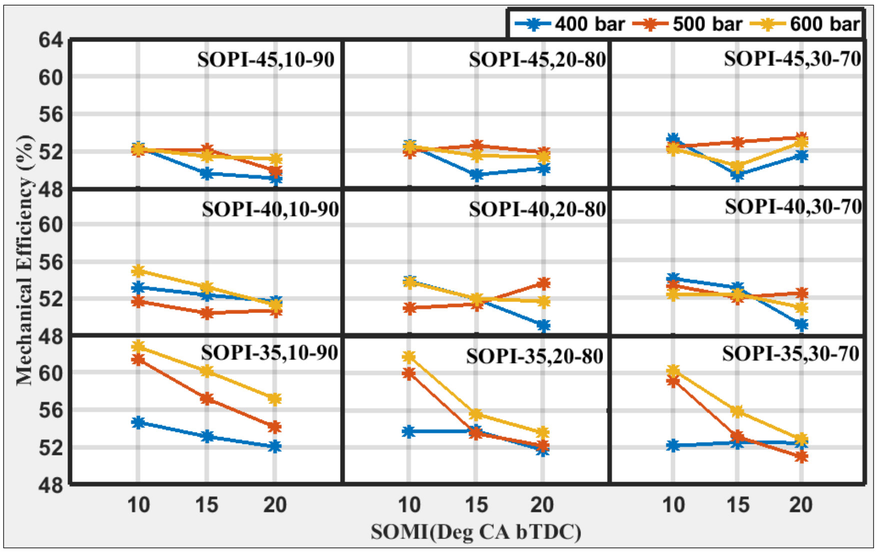

Figure 6. Effect of SOPI, SOMI and injection quantity on mechanical efficiency for different IPs.

The maximum mechanical efficiency was observed for 35° CA SOPI and 10° CA SOMI with 600 bar IP. This value of maximum mechanical efficiency decreases as advancing SOMI from 10° CA to 20° CA at all fuel injection quantities. The same phenomenon was observed in the case of 500 bar IP with a slight decrement in mechanical efficiency. Also, a slight reduction in mechanical efficiency was observed at 400 bar IP than 500 and 600 bar IP at 35° CA SOPI. The 40° and 45° SOPI do not show much more variation in the mechanical efficiency at all IP. The variations in the quantity of fuel injection during the pilot and main injection decreased mechanical efficiency, mainly at 600 bar IP for all SOPI. The mechanical efficiency value slightly decreases as advancing SOPI from 35° CA to 45° CA. Decreasing the delay period of the main injection phase was the reason for reducing mechanical efficiency for much more advanced SOPI timings. Decreased delay period results in shift the combustion stages much before TDC, which causes negative piston work and more friction. On the other hand, retarded SOMI shifts combustion duration near TDC and hence maximum pressure achieved near TDC [27]. At the same time, too retarded SOMI timing was also not feasible. At too retarded SOMI, the pressure force exerted by the combusting gases on the engine piston 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 SOMI and SOPI timing is essential.

Volumetric efficiency

Volumetric efficiency gives the breathing ability of the engine. The air transmitter attached to the intake manifold line for air consumption per cycle and cylinder geometry provides a volumetric efficiency for each run. Figure 7 shows the trends for variation of volumetric efficiency with SOMI for SOPI, the quantity of injection and at different IP.

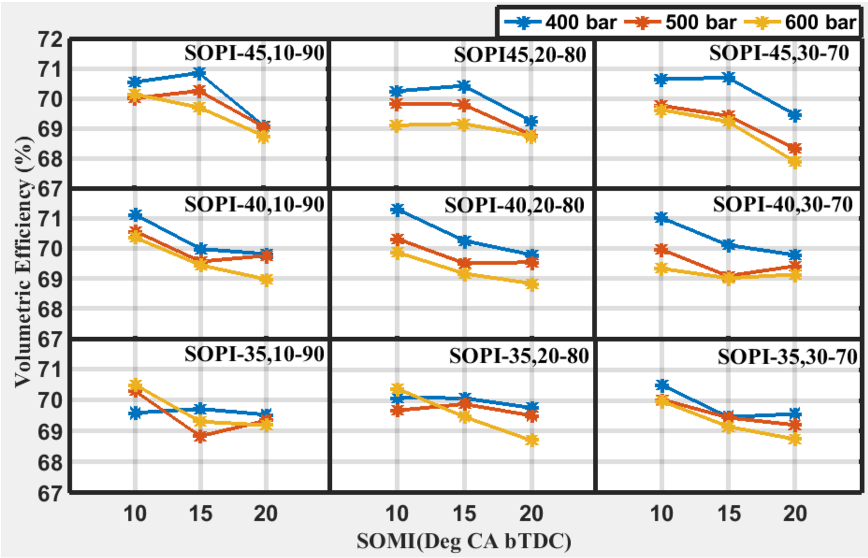

Figure 7. Effect of SOPI, SOMI and injection quantity on volumetric efficiency for different IPs.

It was observed that at 400 bar IP shows a higher value of volumetric efficiency followed by 500 bar and 600 bar IP at all other considered parameters. The 10° CA bTDC offers the maximum value of volumetric efficiency for all IPs, which gradually decreases as advancing SOMI from 10° to 20° CA bTDC. The 40° CA SOPI shows a maximum value of volumetric efficiency compared to the other two SOPI. Also, it was observed that the increase in fuel injection percentage during pilot quantity results in a slight decrease in the volumetric efficiency at all SOMI and SOPI. The maximum value of volumetric efficiency obtain from all considered parameters was nearly up to 71% for this CRDI diesel engine, which was 2-3 % less than the conventional small diesel engine at 12 kg load. The reason for decreasing the volumetric efficiency with increasing IP might be due to the left high-pressure exhaust gases inside the clearance volume of the cylinder. The high-pressure exhaust gases left in the clearance volume act as a barrier for fresh incoming air during suction stroke until they get expanded up to the atmospheric pressure, resulting in a decrease in the accumulation of air inside the cylinder and, hence, volumetric efficiency. The value of SOMI, SOPI and quantity of fuel injection changes the volume and pressure of the exhaust gases left in clearance volume and hence the volumetric efficiency.

Emissions Characteristics

Emissions characteristics are critical from the point of view of the environment, and the euro norms come into action. Emissions characteristics were observed by measuring the raw emission of oxides of nitrogen (NOx), unburnt hydrocarbons (HC), carbon monoxide (CO) and smoke opacity.

NOx emissions

As per the theory of NOx formation in CI engines, NOx value mainly depends on the three parameters. The overall oxygen concentration present in the combustible mixture, peak cylinder temperatures developed inside the cylinder after fuel combustion, and the combusting mixture's residence time at the peak cylinder temperature affect the NOx formation [2]. The variation in mass emission of NOx for a different SOMI, SOPI, IP and the quantity of fuel injection is shown in Figure 8. The results showed an overall increase in the mass emission of NOx for increased IP. Also, it was observed that NOx emissions increase as advancing SOMI timing from 10° CA to 20° CA bTDC and SOPI from 35° CA to 45° CA at all different combinations of considered injection parameters. The nature of variation of NOx emission was similar for all IP at all other combinations of parameters. The increase in fuel injection percentage during pilot duration slightly increases the rate of NOx formation at all IPs for 35° and 40° CA SOPI. Still, this rate of NOx formation suddenly increases for 45° CA SOPI. The 500 bar IP at 40° CA bTDC SOPI shows slight higher NOx emission compared to 600 bar IP, which remains the same as advancing SOMI from 10° to 15° CA and suddenly decreases as further advancing SOMI up to 20° CA.

The factor responsible for increased mass emission of NOx for advance main and pilot injection timing at high injection pressure was mainly because of longer ignition delay. A longer ignition delay occurred due to lower pressure and temperature inside the cylinder at fuel injection. An accumulated fuel during the delay period suddenly burns, resulting in a higher heat release rate in the premixed combustion phase. Hence, relatively higher combustion temperatures occur inside the cylinder because of longer combustion duration and increased NOx formation [29]. Due to retarded SOMI, the actual combustion takes place after the top dead centre. Such combustion results in low combustion temperature and decreases NOx formation [30]. High IP shows relatively higher NOx emissions. Rising in IP gives greater spray penetration and more acceptable droplet sizes of the fuel. Also, the rise in IP reduced injection and combustion duration, resulting in a temperature rise compared to a low IP.

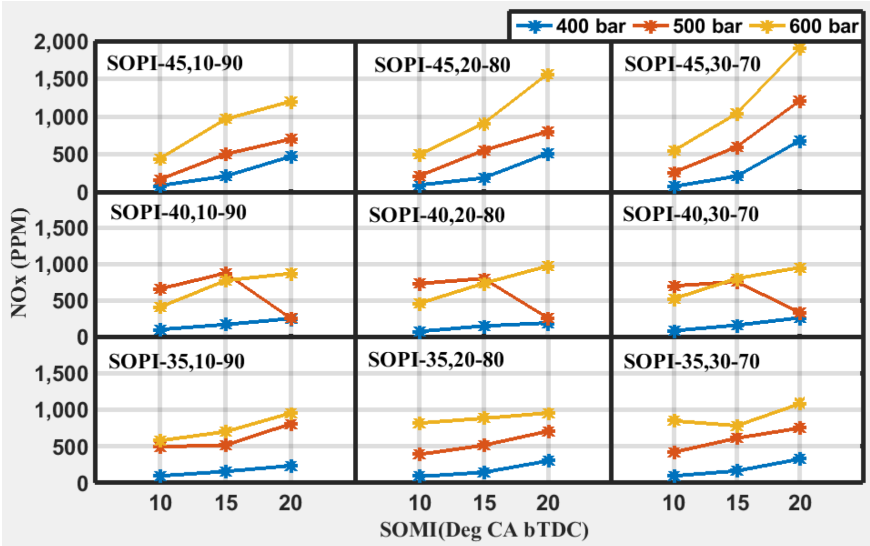

Figure 8. Effect of SOPI, SOMI and injection quantity on NOx emission for different IPs.

HC emissions

HC emissions mean the unburned fuel that goes into the engine's exhaust. A stoichiometric mixture is required for the complete oxidation of HC. A mixture that is on either side of stoichiometric leads into the formation of HC emission. Variations in HC emissions for a different combination of SOMI, SOPI, a quantity of injection and IP are shown in Figure 9. It was observed that all considered parameters affect HC formation. A low HC emission occurred when the main injection timing was set to 15° CA bTDC for all different combinations of parameters. 600 bar IP with retarded SOMI combination shows a lower value of HC emission at 35° CA SOPI with 10° CA SOMI than 400 bar IP. This HC emission gets gradually increased as advancing the SOMI from 10° CA to 20° CA. Also, an increase in the fuel injection percentage in the pilot period from 10% to 30% slightly increases the HC formation, mainly at 600 bar IP. The same was because an increased quantity of pilot percentage not properly get mixed with air and does not get combust [31]. The fuel penetration and injection duration were much faster for the main injection period than the pilot period. 600 bar IP shows higher HC emission for retarded SOPI, which was decreases with an advance in SOPI from 35° CA to 45° CA. The opposite phenomenon was observed in the case of 500 bar IP. HC emission at 400 bar IP was not affected by other considered injection parameters. Overall, an increase in the IP shows a decrease in HC emission. High IP with small nozzle hole diameter results in tiny droplets, and increased penetration depth of fuel jet enhances the fuel-air mixture quality, providing shorter ignition delays and complete combustion [30]. However, a prominent pilot injected quantity absorbs heat for evaporation and reduces pressure and temperature at the time of the main injection. Because of this, longer ignition delays were observed at SOMI and result in wall impingement of fuel. Hence, increased pilot fuel quantity causes higher unburned hydrocarbon and carbon monoxide (CO).

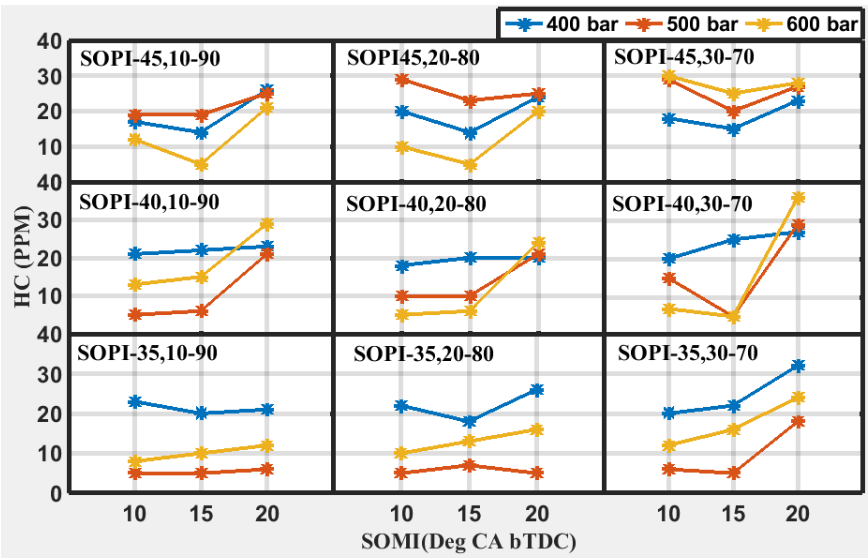

Figure 9. Effect of SOPI, SOMI and injection quantity on HC emission for different IPs.

CO emissions

Due to less availability of oxygen during combustion than required for complete combustion of fuel, complete oxidation of carbon particles did not occur and results in CO formation [34]. Figure 10 gives CO variation with respect to SOMI for different SOPI, the quantity of injection during pilot injection and main injection, and IP.

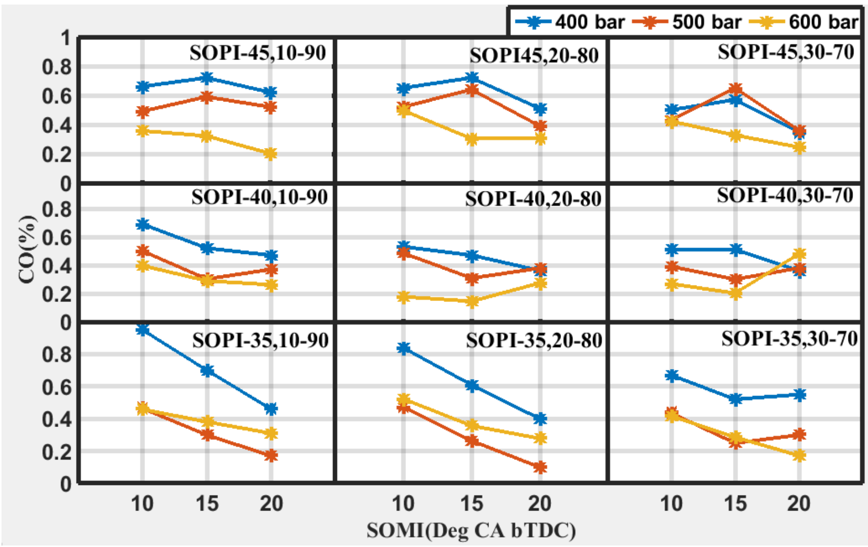

Figure 10. Effect of SOPI, SOMI and injection quantity on CO emission for different IPs.

It was observed that the parameters SOMI and IP primarily affect the formation of CO. CO value decreasing with an increase in IP. 400 bar IP shows a higher CO% at all different combinations of considered parameters. Fuel-injected with low IP results in reduced penetration inside the compressed air. This causes an improper interlocking of carbon with oxygen, resulting in an increased CO level. The nature of variation of CO emission with respect to SOMI was nearly the same at all IP for all other considered parameters. At high IP with advance, SOMI (20° CA bTDC) shows a lower value of CO at all IP, which was gradually increased as retarding the SOMI timing from 20° CA to 15° CA bTDC. The 500 bar IP shows lower CO emissions for 35° CA SOPI, which increased with advancing SOPI for all combinations of the considered parameters. An increase in the quantity of fuel during pilot injection decreases the CO formation percentage at all IP and other considered parameters. The reason for the same was the increased delay period, which provides sufficient time for fuel-air mixing. Due to which nearly complete oxidation of carbon particles takes place. It was observed that CO emissions are less for 40° CA SOPI compared to the other two SOPI timing. Overall, high IP results in a decrease in the CO percentage. At high IP with a divided fuel injection strategy, proper mixing of air and fuel takes place inside the cylinder. Retarded SOMI pushed the majority of combustion after TDC means into expansion stroke, which reduces the pressure and temperature of the later part of the combustion. Such retarded combustion was also the cause of the increased CO%.

Smoke opacity

The smoke emission mainly depends upon the oxygen content of the fuel. Figure 11 shows the percentage of smoke opacity with respect to SOMI for a different combination of SOPI, a quantity of injection and IP. It can be inferred from the figure that an increase in fuel IP decreases the percentage of smoke opacity value. The rate of reducing percentage smoke opacity increased as advancing SOMI from 10° CA to 20° CA bTDC at all IP and quantity of fuel injection percentage. Low values of smoke emissions were also evident with an increase in fuel injection rate during the pilot period at all IP and SOPI. The 40° CA SOPI shows a lower value of percentage smoke opacity for all IP and fuel injection quantities than the other two SOPI. A lower smoke percentage at 40° CA SOPI might be due to insufficient time and duration for injected fuel during the pilot and main combustion period. The nature of smoke opacity value variation was the same for all IP at different combinations of other considered parameters. The higher injection pressure gives effective fuel spray atomisation results in improved fuel-air mixing, which further decreases the smoke emission.

The same effect was observed by Jain et al. [20] in their research work. Advanced SOMI gives increased ignition delay, resulting in more time for accumulated fuel to react with oxygen. Hence, it results in a decrease in smoke opacity for advanced SOMI. There was a decrease in length of fuel penetration inside compressed air at low IP, resulting in improper fuel-air mixing and the formation of too lean heterogeneous fuel-air mixture inside the cylinder. This increases the chances of percentage smoke opacity. The increase in the percentage of fuel during pilot injection with SOMI 20° CA decreased the pressure and temperature inside the cylinder results in growth in the delay period [32]. Such an increased delay period gives more time for better mixing of fuel and air, leading to reduced spatial stratification, resulting in lower soot levels. From the obtained results, injection system parameters such as 600 bar IP, 15°CA bTDC SOMI, 40° CA bTDC SOPI and quantity of injection set as 10-90 was giving maximum performance with most negligible emission for this CRDI small diesel engine. The top BTE obtain from a conventional diesel engine was 28% at complete load condition, while that of a retrofitted CRDI engine was 36 %, with much more reduction in exhaust gases. Hence, we can say that the parameters mentioned above were found optimum for this engine.

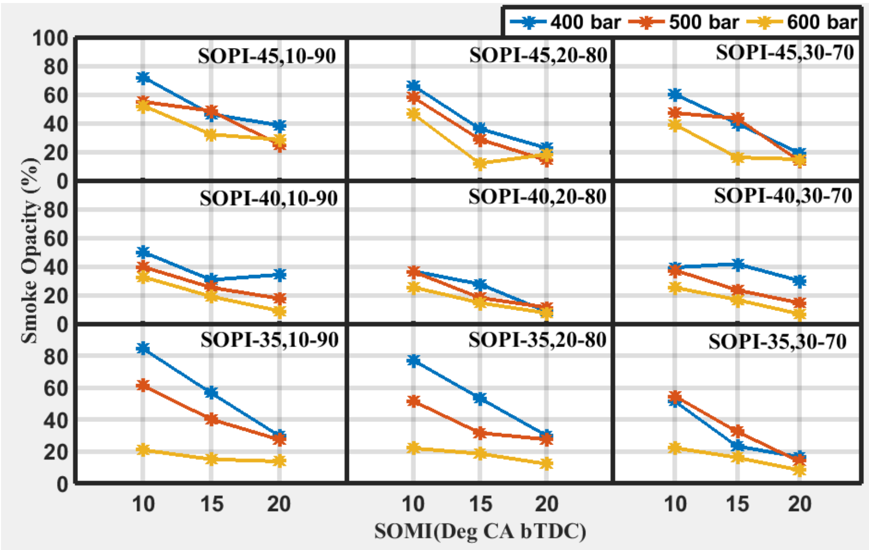

Figure 11. Effect of SOPI, SOMI and injection quantity on smoke opacity for different IPs.

CONCLUSION

This study experimentally investigated the effect of CRDI system parameters such as SOMI and SOPI timings, IP and quantity of fuel injection variation on small single-cylinder diesel engine's performance and emissions characteristics. From the effect on performance characteristics, it can be concluded that,

i. BTE was high for the rise in IP with moderate SOMI (15° CA). Also, retarded pilot injection timing and quantity of injection set as 10-90 gives maximum BTE.
ii. The best fuel economy happens at the high IP with advanced SOMI timing.
iii. Mechanical efficiency was found to be high for retarded SOMI.
iv. Retarded SOMI timing with lower IP shows higher volumetric efficiency.

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

i. NOx emissions were low at retarded SOMI and SOPI. NOx emissions slightly higher for increased IP. An increase in pilot fuel percentage gives higher NOx emission.
ii. The rise in IP decreases the CO emission. CO emissions were also found to be low for advanced SOMI.
iii. HC emission observed less value when IP set at 500 bar and main injection timing set to 15° bTDC at all different combinations.
iv. Smoke opacity was the least at high IP and advanced SOMI. However, low smoke emissions were also evident, increasing fuel percentage during the pilot injection.

Overall, a simpler version of the CRDI system with a split injection strategy was very effective for single-cylinder engines to get the desired emissions and fuel economy. NOx emission was found slightly higher for increased IP. Hence to minimise NOx emission, we will apply the EGR technique in our future study. For the experimental work, we will consider the parameters that give the best performance and emission characteristics from the present study.

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