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Combined Impact of High Injection Pressure and Injection Timing on the Performance and Combustion of Common Rail Direct Injection (CRDI) Engine Fueled with a Simarouba Biodiesel Blend

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Abstract

This paper discusses the combined impact of high injection pressure and injection timings on the performance and combustion characteristics of a diesel engine using biodiesel ester of Simarouba oil (SOME) blends. A Kirloskar make single cylinder 3.7 kW (5 HP) capacity diesel engine was modified to operate with Common Rail Direct Injection (CRDI) system. Experiments were carried on this engine with CRDI setup, fueled with diesel and SOME biodiesel to optimize the combined Injection Pressure (IP) and Injection Timing (IT). A combination of three different IP of 600 bar, 800 bar, 1000 bar and four different injection timings (IT) of 10°, 18°, 23°, 28° before Top Dead Centre (bTDC) were tested at a constant Compression Ratio (CR) of 16.5, engine speed of 1500 rpm by varying load from 25% to 100% of full load. Maximum Brake Thermal Efficiency (BTE) was recorded at IP of 800 bar and IT of 18°bTDC CA combination for HSD, SOME 20 and SOME 30. Peak pressure and Heat Release Rates (HRR) were studied for IT of 23°bTDC and found maximum values with IP 800 bar for neat diesel (HSD). The findings of this study encourage and emphasize the probability of admitting the higher percentage biodiesel blends with HSD by the make use of a proper combination of high fuel injection pressure and injection timing. Hence it serves to overcome the depletion of neat diesel and its environmental issues.

Keywords: Biodiesel, Combustion Characteristics, Common Rail Direct Injection (CRDI) Engine, Injection Pressure, Injection Timing, Performance

1. Introduction

Diesel engines are world widely used in substantial transport applications. The performance of diesel engine depends on its combustion capacity. More complete combustion can be obtained by the proper selection of engine parameters such as fuel IP and IT, which influences the performance of the diesel engine. Therefore, a precise combination of IP and IT will lead to proper spray, atomization, and fuel-air mixing, which is fundamental to making enhancements to the combustion process. Combustion improvement will be possible for better air movement within the cylinder and high-pressure injection. Increased peak in-cylinder pressure, maximum heat release rate and decreased ignition delay was obtained due to Increased IP[1].

On the other hand, the quest for substitute fuel is vital to beat fast exhaustion of petroleum fuel huge demand

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required for all sectors. However, biodiesel is demonstrated as a substitute for diesel from the past couple of years and its use in internal combustion engines has turned into a need. Research is still under advancement to satisfy the best option fuel necessity at a reasonable expense with less environmental pollution. Apart from the renewability, biodiesel has advantages like biodegradability, minimal sulphur, higher flash point, better cetane number, aromatic content; and reduced toxicity. Competencies for lessening engine wear from the biodiesel gasoline used to be confirmed by the associated studies. Whereas Direct Injection (DI) diesel engine blended with biodiesel up to 20% usage with diesel is accepted without any modifications in any diesel engine[2]. According to the literature, diesel engines fueled with biodiesel produced equal power output, but reduced the thermal efficiency with increased emissions have restricted the blending ratio to 20% with diesel. As a contrary, the increased percentage of blending is possible in high-pressure fuel injection system[19]. Injection timing also influences the combustion. Advanced the injection timing with high injection pressure have proved the BTE improvement[2,3].

Balusamy et al. conducted an experimental study, to discover the impact of IT and IP on a DI diesel engine fuelled with Thevetia Peruviana biodiesel blend. They have noticed that, the combination of injection timing advancement with increasing the injector opening pressure an increase in the Brake thermal efficiency. They concluded the best results were observed at the IT 27° bTDC and IP 225 bar combination[3]. Venkatraman et al. conducted an experiment on DI diesel engine fueled with Pungam biodiesel blends (10%, 20% and 30%) with diesel. From the experimental investigation, it was found that the increase in Compression Ratio (CR), IT and IP increased the BTHE reduced BSFC while having lower emissions for 20% blend. The outcomes demonstrated that at a CR of 19:1 with increased IP of 240 bar, advanced IT of 27°BTDC and PME20 resulted in improved performance and reduced emissions[4]. Gumus et al. investigated the impact of fuel IP on the exhaust emissions and brake specific fuel consumption (BSFC) of a DI diesel engine using biodiesel–diesel blends. The engine was tested at four different fuel IPs (18, 20, 22, and 24 MPa) and four different engine loads. They concluded that BSFC for higher percentage biodiesel–diesel blends (B20, B50, and B100) decreased with the increased IP[5]. Kannan et al. in their study utilized a fuel called diestrol, which is a combination of 30% blending of Waste Cooking Palm oil (WCO) methyl ester with 60% of diesel and 10% of ethyl alcohol. The impact of diestrol fuel in a diesel engine at different IP and IT was studied by experimental investigation. Their results showed a maximum BTE of 31.3% at an IP of 240 bar and IT of 25.5° bTDC. They found a huge improvement in BTE by 2.6% and the decrease in BSEC by 6.9% for diestrol fuel when compared to HSD[6]. Karabektas et al. experimentally investigated the performance and emissions of a diesel engine effects for the blends containing different alternative fuels with diesel.They have concluded that canola oil methyl esters (COME) biodiesel blends resulted in performance parameters almost similar to the diesel fuel[7]. Sayin et al. conducted a test on a Lombardinimake 6 LD 400 type single cylinder, air cooled, DI diesel engine at four different IPs (18, 20, 22 and 24 MPa) at a constant engine speed and different loads. From the study, it has been concluded that the increased IP gave the best results for BTE and BSFC, and also higher IP resulting in the Maximum Cylinder Gas Pressure (MGP) due to increased premixed combustible mixture[8]. An et al. investigated the performance, combustion and emission qualities of a diesel engine fueled by biodiesel at partial load conditions without changes made with injection parameters. The results showed the largest increment in BSFC of about 28.1% at 10% load. Though for BTE, the outcomes demonstrated that the utilization of biodiesel results in decreased Thermal Efficiency (TE) at lower engine loads and enhanced TE at higher engine loads[9]. Kannan et al. have utilized a biodiesel obtained from waste cooking oil for finding the effect of IP and IT on performance and the combustion attributes were carried out on a single cylinder, Kirloskar make four-stroke water cooled, diesel engine. On varying the IP with IT, they have found that the combined effect of higher IP of 280 bar and an advanced IT of 25.5°bTDC resulted in a huge improvement in the BTE, cylinder gas pressure and Heat Release Rate (HRR) [10]. Belagur et al.in their study investigated experimentally the performance and combustion of a direct injection (DI) diesel engine, when fuelled with Honne Oil Methyl Ester (HOME) and diesel. The IT was varied from 23°bTDC Crank Angle (CA) to IT 28° bTDC CA. From the outcomes they acknowledged the improved combustion parameters for HOME with increased IT and the BTE was found to be maximum at HOME with IT 27–28° CA bTDC [11]. Jaichandar et al. made an attempt to study the combined effect of IP and combustion chamber geometries impact using a Pongamia Oil Methyl Ester blend about 20% (POME20) in diesel. Their investigation showed an improvement in BTE of about 34.31% at high IP of 220 bar andlow SFC (0.243 kg/kW-hr) than that of the standard engine operation (0.288 kg/kW-hr)[1]. Shehata had carried out an investigation on biodiesel fuel consequences on diesel engine performance, exhaust gas temperature (EGT) and cylinder pressure with and without the usage of exhaust gas recirculation (EGR). From his study, he concluded that biodiesel fuels give marginally less BP, BTE and somewhat high BSFC and high fuel mass flow rate per cycle[12]. Raheman et al.in their study used Mahua and Simarouba oils blends in equal portion with High-Speed Diesel (HSD) as a testing fuel in a 10.3-kW single-cylinder water-cooled DI diesel engine. From their investigations, they found that when engine operated with biodiesel blends at different engine loads, BSFC and EGT were found to increase by 3.13% and 0.76%, respectively, while BTE was found to diminish by 1.74% with an increase in biodiesel addition. They have also concluded that a decrease in BTE with an increase in biodiesel percentage in the fuel blends due to the drop in the calorific value of fuel blend[13]. Mohan et al. from their review work, concluded that Ultra high IPs results in the lessening of soot emissions, mostly attributed by better spray atomization and air entrainment, it prompts increased Nitrous oxides (NOx) and BSFC[14]. Agarwal et al. examined the impact of 10%, 20% and 50% Karanja biodiesel blends on injection rate, atomization, engine performance and combustion attributes in a single cylinder CRDI research engine at 300, 500, 750 and 1000 bar fuel IPs at various ITs and engine speed maintained constant for 1500 rpm, for all trails. From their investigation, it has been reported that at less blends of Karanja biodiesel, combustion duration was found lesser than HSD and at higher fuel IP, a combustion duration of 50% blend was more than HSD. They concluded that biodiesel blends in a CRDI engine enhances BTE and decreases the emissions[15]. Sonar et al. conducted a test to determine the performance and output emission characteristics using various diesel-Mahua oil blends with changing IP. They have noticed that at IP of 226 bar, maximum BTE and better BSFC have recorded for M10, M20 and M30 blends[16]. Dhar et al. carried out a study on Karanja biodiesel blends (10%, 20% and 50% blending with HSD) to conclude the impact of IPs and ITs on biodiesel blends with a single cylinder CRDI engine. IP used were 500 and 1000 bar for different ITs. The results showed increased BSFC, with increment in Karanja biodiesel concentration and they too noticed that BTE of Karanja biodiesel blends were marginally higher than diesel[17]. Pai et al. proposed that; higher IP will enhance the combustion, which improves the performance and lessening the emission. They underscored the high IP influence to produce excellent atomization of fuel droplets those decreases the delay duration, combustion time, particulate matter and NOx emissions. They understood that biodiesel inherent and interference properties like viscosity and volatility can be enhanced, high IP will improve the atomization, penetration and evaporation of denser biodiesel blend and also blend percentage can be enhanced to make the most extreme utilization of it[18]. Gaurav Paul et al. in their study inferred that the BSFC increases and BTE decrease with the use of Jatropha biodiesel (JB100). Experimental results show that HSD has 29.6% maximum BTE, whereas pure biodiesel has 21.2% maximum BTE. From the results, they have concluded that use of Jatropha biodiesel increases BSFC, decreases BTE with respect to increment in biodiesel percentage in the blends[19]. Wamankar et al. from their study concluded that, for a single-cylinder four stroke diesel engine operating with the CR 16.5 at different ITs and at full load using for CBWD10 emulsion. They found that the BTE was reduced from 7.8% to 4.3% compared to that of HSD [20]. Ramalingam et al. did the investigation to find the combined effects of the CR and IT on the performance parameters SFC, BTHE using Annona methyl ester (A20) as fuel. Experimental results showed that CR 19.5 with IT of 30°bTDC resulted in lower emission with a better performance, which was really close to neat diesel performance. They have concluded that the combined increase of CR and IT increases the BTE and reduces SFC [21]. Mikulski et al. studied the use of animal-origin biodiesel blends in a CRDI engine. From the results obtained they have concluded that the increment in BSFC was found to be 3.2% for B25, 8.5% for B50 and 13.8% for B75 respectively. They also observed that the brake fuel conversion efficiency reduced by 1.6%, for B25, 4.8% for B50 and 7.8% for B75 respectively[22]. Senthil et al. have carried out an experimental investigation with various Annona methyl ester blends at varying ITs. They found that the BTE was higher by about 6.4% at the advanced IT of 33°CA bTDC, while the SFC was found lowered by about 11.9% than those of the original IT [23].

In this paper, a prompt attempt has been made to find out the combined effect of IP and IT on Performance and combustion characteristics. Ultimately, several crucial conclusions were drawn from the obtained results from the investigation.

2. Material and Method

2.1 Biodiesel Preparation from TransesterificationProcess

In this investigation, biodiesel used was prepared from the seed of Simarouba Glauca is a species of flowering tree, that is basically from Florida available in South America, and also found in different regions of India. It has other common names like paradise-tree, dysentery-bark, bitter wood and Laxmi Taru. Simarouba Glauca seed contains about 40% kernel and kernel content 50-55% oil.

Transesterification is the process of converting the free fatty acids and triglycerides to fatty acid esters and glycerin. In this work transesterification of Simarouba oil with methanol was done in a 2-litre three-necked round bottom flask equipped with a water-cooled condenser, a high-speed motor with a magnetic stirrer as a rotating element used for proper mixing of the oil and a thermometer was used to measure the temperature. About 0.5 liters of Simarouba oil have taken in a flask, having round bottom and it is heated to 60°C before adding the mixture of methanol and catalyst. The total mixture has to be maintained at 60°C and should be stirred continuously using a magnetic stirrer about 2 hours. When transesterification was got over, segregated ester was mixed with 250 gram of hot water and the mixture was permitted to descend under gravity for next 24-hour duration. Subsequent to settling of products in different layers, biodiesel Simarouba Oil Methyl Ester (SOME) and the catalyst is separated in separator funnel. The properties of HSD and SOME used in this investigation are given in Table 1.

Table 1. Properties of Diesel and Simarouba

Properties	Diesel	Simarouba (SOME)
Density in kg/m^3	840	868
Cetane number	50	52
Calorific value in kJ/kgK	44800	39800
Flash point °C	55	165
Viscosity at40°C in (cSt)	2.7-5	4.8

Table 2. Fuel Injector Specification

Sl. No.	Parameter	Specifications
1	Injector Make	Delphi TVS
2	No of holes	1
3	Diameter of the nozzle	0.19mm
4	Injectors withstand operating pressures	Up to 2000 bar
5	Injection Pressure used	1000 bar

Table 3. Specifications of CI engine

Sl. No.	Parameter	Specifications
1	Engine Type	AV1 (Kirloskar make)
2	No of cylinders	Single cylinder
3	Rated power	3.7 kW (5 HP) @1500 RPM
4	No of strokes	Four stroke
5	Nozzle opening pressure	200 bar
6	Rated injection timing	23°bTDC
7	Cylinder diameter (Bore)	0.0875 metre
8	Stroke length	0.11 m
9	Compression ratio	16.5 : 1
10	Specified Fuel	H. S. Diesel

Figure 1. Photographic view of the Fuel injector

2.2 Experimental Setup and Procedure

Experiments were carried on a Kirloskar make, AV1 model single cylinder, four stroke, water cooled 5 HP (3.7 kW) capacity diesel engine. The fuel injector specifications and engine specifications are given in Tables 2 and 3, with their photographic views shown in Figures 1 and 2 respectively. The same engine is having the provi-

Figure 2. Photographic view of Engine setup

sions like a calorimeter for the required amount of water variation,temperature sensors for the measurement purpose of jacket water, calorimeter exhaust gas inlet and outlet temperature to analyse the heat carried away by the water and also supplied with pressure piezoelectric sensors for the accurate measurement of gas pressure obtained from the combustion and fuel injection pressure. An encoder is set up and utilised for crank angle record. The engine is directly coupled to an electrical eddy current dynamometer. The dynamometer is used to measure the brake power, produced by the engine.

Engine specifications as per manufacturer's standard for the given model had a CR of 16.5, IP of 200 bars and IT 23˚ BTDC at a constant 1500 RPM speed with a power capacity of 3.7 kW (5 HP). The conventional injector of the diesel engine which has the capacity to inject to 200 bar pressure is replaced by a Delphi TVS injector for supplying fuel at high pressure through the electronically controlled CRDI system. The CRDI engine operation was better with no inconvenience. The test was accomplished for four different loading conditions (25%, 50%, 75% and 100%) and for four different ITs 10˚ 18˚, 23˚ and 28˚ bTDC and three different IPs 600 bar, 800 bar and 1000 bar with 20% (SOME20), 30% (SOME30) and 40% (SOME40) Simarouba biodiesel blend with HSD. Under steady state conditions, for each IT and different loading conditions, for each IP, performance parameters such as, BSFC and BTE and Exhaust Gas Temperature (EGT), combustion parameters like Peak pressure and HRR are recorded and tabulated.

3. Results and Discussions

The experiments were conducted for four different loads, from 25% to100% in steps of 25% loading, while engine speed was maintained constant(1500 rpm). Using CRDI system rail pressure was varied for three different IP 600 bar, 800bar and 1000 bar respectively. For each trail with SOME20 and SOME30 IT was varied from 10° 18°, 23° and 28° bTDC to find the combined effect of IP and IT on BTE, BSFC, EGT, Peak Pressure and HRR. Similar Experiments were conducted using HS Diesel for comparison. On the other hand, for all the SOME blend and HSD, knocking with rough engine running was noticed at IT 28°bTDC and also for all IPs, a heavy knocking was observed with SOME 40 for standard IT 23°bTDC (as recommended by the manufacturer).Further knocking tendency was reduced with improvement in IP for all IT and load. Due to the uncontrolled knock noticed at 23°bTDC IT with SOME 40 at IP 600 bar, next testing for the same IP with the other ITs combination was not conducted. Hence, using SOME 40 combined effect study comparison was done only with IT 23°bTDC for IP 600, 800 and 1000 bar respectively for 100% load.

3.1 Optimization of Injection Pressure and Injection Timing

3.1.1 Brake Thermal Efficiency

Figures 3 to 6 shows the results of the combined effect of IP and IT on BTE for 100% load by the usage of the CRDI system with HSD, SOME blends. Similar outcomes were observed for the other load. The maximum BTE was found for HSD at IP 800 bar with IT 18°bTDC combination, this may be due to result of proper atomization and more complete combustion occurred as a result of increase in the injection pressure[1,6,8], which suggests that higher IP is most effective in improving the spray characteristics of fuels with low viscosity fuel like HSD [15]. Too much advancement and retardation of IT from the standard value of 23°bTDC have resulted in the decrement in BTE as shown. Among the used fuels BTE was found highest for HSD for almost all combination trials. This is due to the fact that the biodiesel will have higher

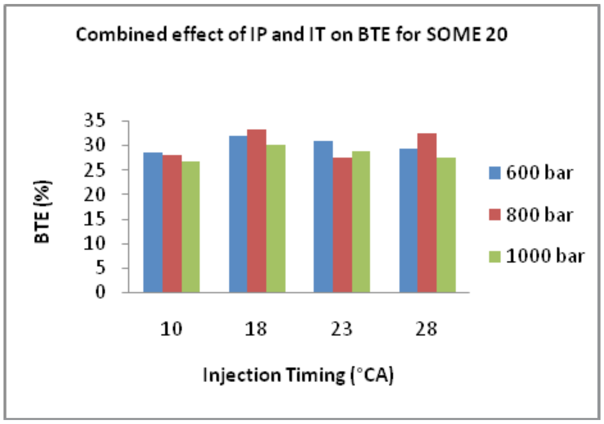

Figure 3. Combined effect of IP and IT on BTE for SOME 20.

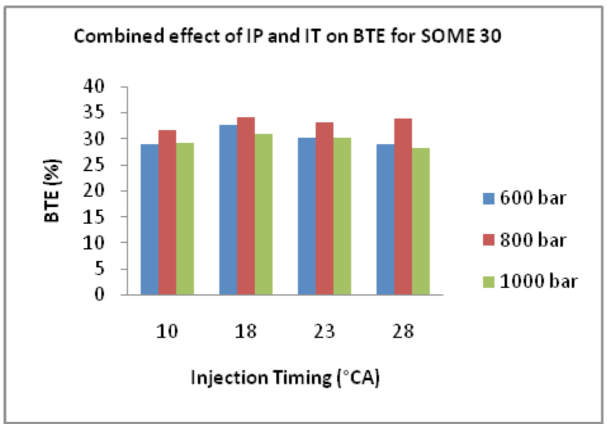

Figure 4. Combined effect of IP and IT on BTE for SOME 30.

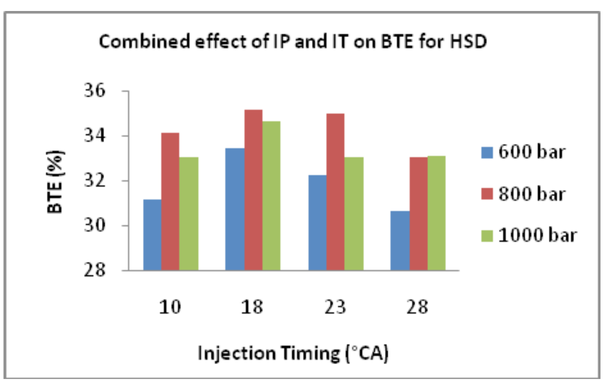

Figure 5. Combined effect of IP and IT on BTE for HSD.

viscosity and lower calorific value compared to neat diesel[12]. Among the blends SOME 30 was proved to be better in terms of BTE for IP 800 bar and similar results were

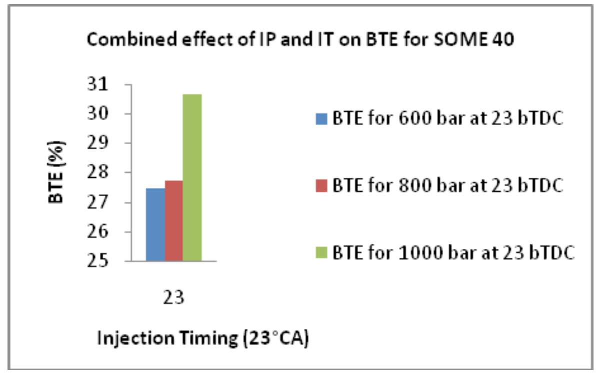

Figure 6. Combined effect of IP and IT on BTE for SOME 40.

reported in the literature[5]. Improved BTE was due to the increased biodiesel content in the blended fuel for all IPs. The blended fuel contains more oxygen, in turn; it helps to increase the combustion efficiency resulting in increased BTE.

3.1.2 Specific Fuel Consumption

The variations of the BSFC, with the engine with a 100% load for SOME20, SOME30, SOME40 and HSD are shown in Figures 7 to 10. The same types of outcomes were obtained for the other load. BSFC was found less for HSD with almost every combination of IPs and ITs in comparison of SOME blends, least value was found to be 0.22854 kg/ kW-hr at IP 800 bar at 18° bTDC, a same type of conclusion are available in the literature[14]. This is may be due to the high density, more volatility and less heat content of biodiesel[26,28]. That means more amount of biodiesel is required to obtain the same power as produced by the diesel[27] and this fact justifies the mentioned trend in the BSFC [21]. However, it was observed that the BSFC decreases with increase the IP. Lower IP attributed to least combustion, as a result of oxygen starvation due to less penetration, least dispersion of the fuel and improper air entrainment[1].

3.1.3 Exhaust Gas Temperature

From the experimental results, combined effect of IP and IT on EGT for 100% load for IT 23°bTDC on SOME20, SOME30, SOME40 and HSD fuel is plotted shown in Figures 11 to 14. Similar results were recorded for other loads. Generally, it is believed that combustion quality of any engine will be indicated by the exhaust gas tem-

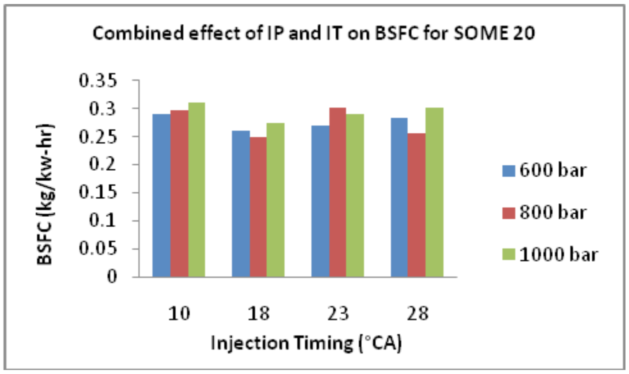

Figure 7. Combined effect of IP and IT on BSFC for SOME 20.

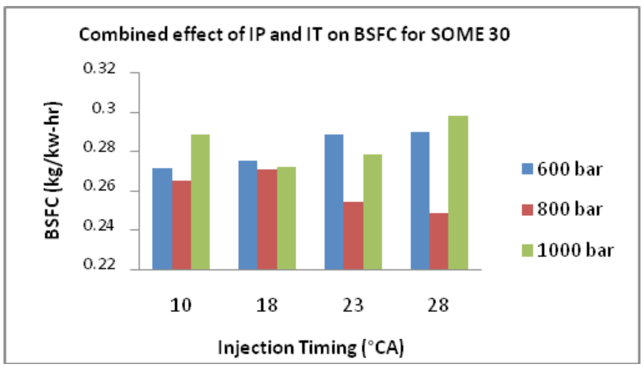

Figure 8. Combined effect of IP and IT on BSFC for SOME 30.

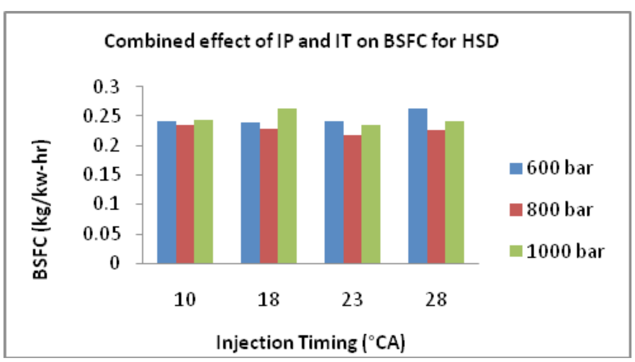

Figure 9. Combined effect of IP and IT on BSFC for HSD.

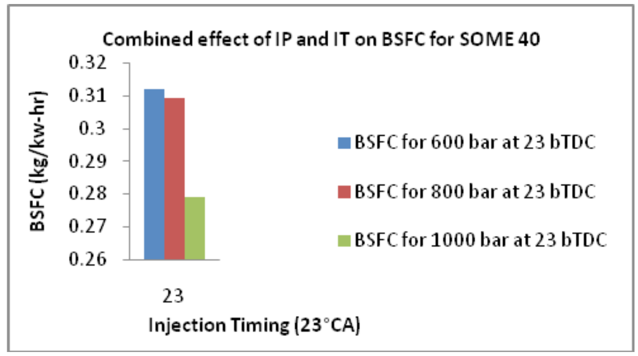

Figure 10. Combined effect of IP and IT on BSFC for SOME 40.

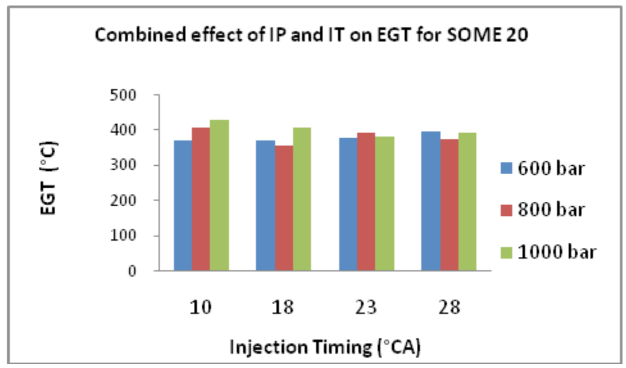

Figure 11. Combined effect of IP and IT on EGT for SOME 20.

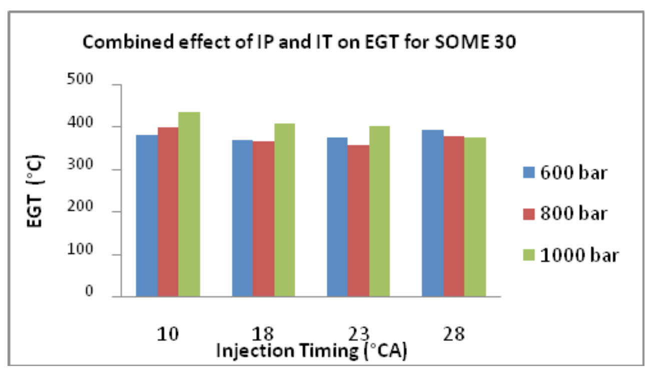

Figure 12. Combined effect of IP and IT on EGT for SOME 30.

perature. It is observed from the obtained results; SOME blends exhibit a slight decrease in the EGT than those of HSD similar results was described in the literature quoted that biodiesel blends were obtained less exhaust temperatures than those of conventional diesel due to their highoxygen content and low heating value[24]. Whereas, a higher amount of the heat is released in mixing controlled combustion regime is due to delayed combustion hence the more amount of heat will be departing to the exhaust gases[23]. This can be overcome by high-pressure fuel injection. Basically, fuel with a higher velocity and leaves

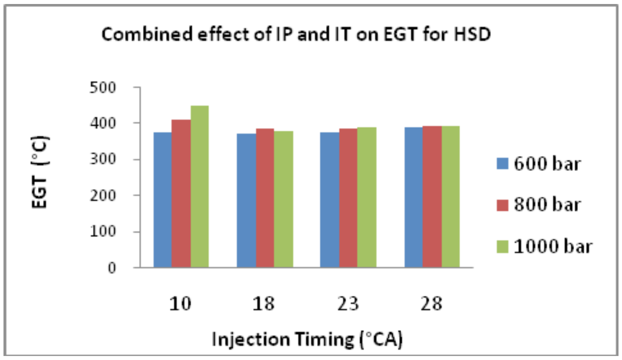

Figure 13. Combined effect of IP and IT on EGT for HSD.

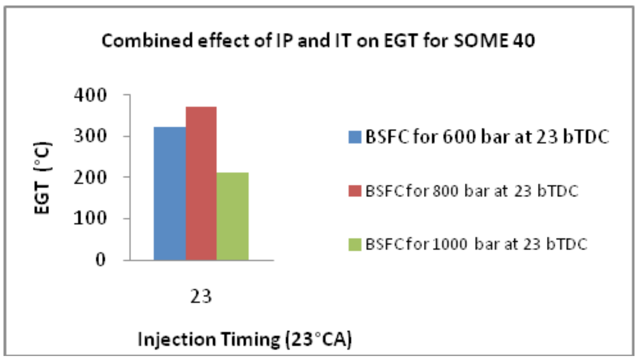

Figure 14. Combined effect of IP and IT on EGT for SOME 40.

the nozzle holes only due higher injection pressure. The higher velocity of the injected fuel yields a higher level of dispersion, hence quicker air-fuel mixing leads to better atomization, and as a result of the high-temperature in-cylinder gases at high IP abbreviates the ignition delay. In general, the increase in injection pressures and with advanced injection timings enhances the peak bulk-gas temperature[25]. The EGT trend is obtained reflecting the same, where outcomes are better for IP 800 bar at IT 18° BTDC for SOME20, SOME30 and HSD. Meanwhile, it is also observed that greater values of advancing and retarding IT with applied IPs have shown more EGT for SOME.

3.2 Combustion characteristics:

Combustion characteristics of a CRDI engine in terms of the Peak pressure and HRR of HSD and SOME are investigated and presented as follows

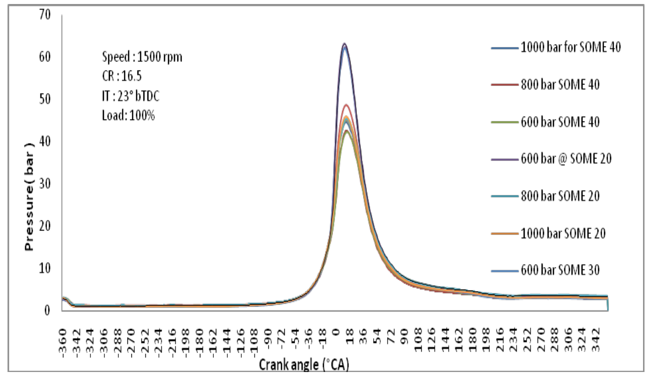

Figure 15. Effect of IP variation on peak pressure with IT 23°bTDC.

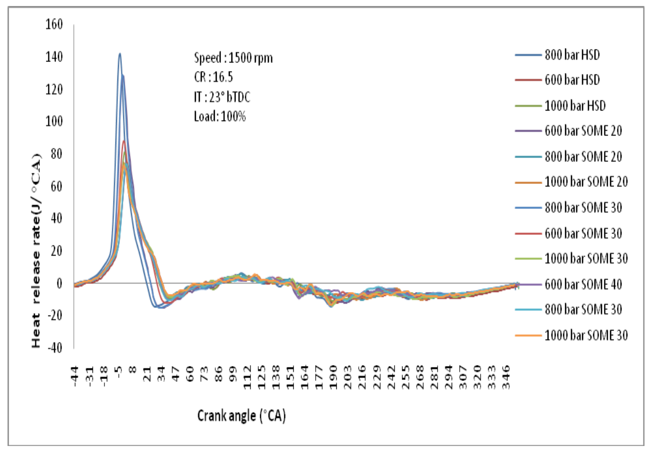

Figure 16. Effect of IP variation on HRR with IT 23°bTDC.

3.2.1 Peak Pressure and Heat Release Rate (HRR) Variation

Effect of IP variation on peak pressure and HRR with the crank angle of the CRDI diesel engine fuelled with HSD, SOME20, SOME30 and SOME40 for standard IT 23°bTDC (manufacturer's specified value) and100% loading conditions results are shown in Figures 15 and 16. Similar results were noticed for other loads. Peak pressure and HRR were founded maximum at HSD at IP 800 bar and next highest value is for SOME30 at IP 800 bar. It is noted that on all IPs the peak pressure and the peak HRR of the SOME blends were lesser than that of the HSD. This might be because of the net HRR and the peak cylinder pressure of all types of biodiesel is lower than petrol diesel due to lower heating value, shorter ID and lower premix combustion phase of biodiesel[26]. The peak pressure is increased in those phases might be because of the homogeneous fuel-air mixture is formed will give out a strong premixed combustion phase prompting a higher peak pressure. The higher heat release rate attributed to shorter ignition delay. The higher HRR attributed to minimum Ignition Delay (ID). Usually, higher viscosity and surface tension leads to the poor spray atomization characteristics of biodiesel might be the response to the lower HRR. With the high IP, maximum HRR further gets enhanced may be from the improved premixed combustion phase[1].

4. Conclusion

This paper discusses the combined effect IP and IT on the performance and combustion characteristics of Common Rail Direct Injection (CRDI) engine fueled with HSD and SOME blends and the following conclusions have been made in this study,

- It is concluded from this study that Injection pressure with proper injection timing will change any engine performance.
- For the given engine optimum results were found at 800 bar pressure in combination with all ITs, especially IP 800 bar and IT 18°bTDC combination have recorded the best results for all fuels tested.
- For all IPs with SOME blends and HSD, knocking was observed for IT 28°bTDC.
- Decrease in BTE is observed on both extremities of ITs (IT 10°bTDC and IT 28°bTDC) from its optimum value IT 23°bTDC.
- Increase in BSFC for SOME blends in comparison with HSD may be due to biodiesel have high viscosity, more density, less volatile and less heat content when compared with that of HSD.
- For all IPs the peak pressure and the peak HRR of the SOME blends are less than those of the HSD might be because of almost all biodiesel having low heating value, low premix combustion phase and shorter ID than that of HSD.
- Even though BTE found to be low for SOME 40 in comparison with other SOME blends and HSD, experiments proved that with higher injection pressure, engine works smoothly and also BTE was gained maximum value 30.66% for IP 1000 bar in comparison with IP 600 bar with BTE 27.44% and IP 800 bar with BTE 27.70%.
- The findings of this study encourage and emphasize the probability of admitting the higher percentage biodiesel blends with HSD by proper utilization of a combination of high fuel injection pressure with correct injection timing. Hence it helps to overcome the depletion of neat diesel and its environmental issues.

5. Acknowledgement

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