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Effect of injection timing and injection pressure on the performance of biodiesel ester of hongeoil fuelled common rail direct injection (CRDI) engine

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Abstract

This paper discusses the feasibility study on the utilization of biodiesel ester of Honge oil (EHO) in common rail direct injection (CRDI) engine. Biodiesel of EHO has been obtained by transesterification process and characterization has been done. Existing single cylinder diesel engine fitted with conventional mechanical fuel injection system (CMFIS) was suitably modified to operate on Common Rail Direct Injection (CRDI) facilities where the biodiesel can be injected with higher injection pressures. Experiments were conducted on CRDI engine fuelled with diesel and biodiesel to optimize the injection timing (IT), where the IT varied from 25^o before top dead centre (bTDC) to 5^o after top dead centre (aTDC) keeping injector pressure (IP)of 600 bar, compression ratio (CR) of 17.5 and constant engine speed of 1500 rpm at 80 and 100% loading conditions. Improved brake thermal efficiency (BTE) IT was obtained at 10^o. Further experiments were conducted on CRDI engine fuelled with diesel and EHO to optimize the injector opening pressure (IP) where IPs were varied from 600 bar to 1000 bar keeping optimized IT of 10^o bTDC and revealed that maximum BTE was obtained at 900 bar. From the experimental study, IT of 10^{o}bTDC and IP of 900 bar were concluded as best engine operating parameters to obtain maximum BTE with lower hydrocarbon (HC), carbon monoxide (CO), smoke emissions but oxides of nitrogen (NOx) emissions were higher for the fuels used in the study. Peak pressure and heat release rates were observed maximum for IT of 10^{o}bTDC and IP of 900 bar compared to other ITs and IPs used.

Keywords: Diesel engine, Ester of Honge Oil (EHO), Common Rail Direct Injection (CRDI), Emissions

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1. Introduction

Renewed interest in searching suitable alternative and renewable fuels for fossil fuels in diesel engine applications with capability of meeting the emission norms of Bharat stage, EURO norms is the need of the hour. Biodiesel isone such alternative which is capable of replacing diesel as India hasa large agriculture base that can be used as a feed stock to obtain these newer fuels. Use of biodiesels in compressionignition (CI) engines demands higher fuel IP as they have higher viscosity compared to diesel. The advantages of electronic fuel injection system generally called CRDI are that very high fuel injection pressures up to 2500 bar to atomize fuel into very finer droplets for fast its vaporization is realized in practical nature (Pundir, 2007). High velocity of fuel spray due to high IP penetrates the combustion chamber (CC) within a short time to fully utilize the air available. Research has shown that by further increasing the IP more benefits in terms of engine performance and reduction in emissions can be realized (Wloka, 2010, 2011). Researchers also found that spray penetration improved at higher IP (Pan, 2012; Lesnik, 2013).

CRDI engine fuelled with both diesel and biodiesel produced lesser smoke due to the better atomization of the fuel at higher IP and resulted in improved combustion due to better air fuel mixing and it was reported that soot oxidation enhanced due to the higher in cylinder temperatures. Also it is reported that an improvement in local fuel-oxygen ratio during combustion process reduced the smoke emission because of oxygen molecular content and the absence of aromatic and sulfur compounds in biodiesel fuel compared to diesel (Octavia 2006). At ITs of 10 to 5^o BTDC the combustion occurred near to TDC that resulted in maximum BTE and it could be due to more efficient mixing of fuel with air and also due to better fuel atomization (Monyem, 2001; Sonatore, 2008). HC emissions decreased at IT between 10^o to 5^o bTDC where fuel BTE was higher (Carlo, 2002). The smaller droplets of fuels obtained at higher IP improved mixing of fuel with air inside the combustion chamber CC resulting in complete combustion of mixture that resulted into lower smoke emission (Yakup, 2003). The higher fuel droplet velocity and smaller droplet size obtained due to higher fuel IP led to better overall mixing of fuel and air and shortened ignition delay (ID) (Lee, 2005). Higher IP causes the diesel and biodiesel spray to vaporize quickly that enhances combustion rates resulting in higher combustion temperatures. The earlier start of combustion (SOC) and higher heat release peak that yielded in higher in-cylinder temperature led to an increased NO_x emissions (Charles, 2009).

The BTE decreased with start of injection (SOI) later then 5^{o}bTDC (Ye, 2011). The peak cylinder pressure and the peak heat release rate (HRR) of the biodiesel were slightly lower but the ID was slightly higher. In terms of emissions, the biodiesel had benefits in reduction of smoke, CO, HC emissions especially with higher fuel IP. The NOx emissions of the biodiesel were relatively higher than the diesel (Hwang, 2014). Biodiesel blend (B20) showed better engine performance in terms of reducing particulate matter (PM) emission at all engine operating conditions compared to diesel. This could be due to lower sulphur and aromatic content of biodiesel. Benzene soluble organic fraction (BSOF) showed decreasing trend with increasing engine operating load for both diesel and biodiesel. For B20, the BSOF content of PM was higher than that of diesel. This could be due to relatively lower volatility of constituents of biodiesel, indicating possibly higher toxic potential of biodiesel particulates (Jitendra, 2012).

The objective of thestudy mainly focus on the effect of IT and IP on the combustion, performance and emission characteristics of CRDI engine when fuelled with ester of non-edible oil i.e., EHO. CRDI engine performance fuelled with EHO were studied to optimize the fuel ITand IP for best BTE and then keeping optimum IT, IP for best BTE was found. Finally critical conclusions were drawn from the experimental study on CRDI engine fuelled with EHO.

2. Material and method:

2.1Transesterification of EHO

The transesterification set up consists of round bottom flask with three necks to it placed in a water container for heating the oil and it is of 2 liters capacity. A heater with temperature regulator was used for heating the oil. A high speed motor with a magnetic stirrer in the form of rotating element was used for mixing the oil vigorously. In the transesterification process triglycerides of Honge oil react with methyl alcohol in the presence of a catalyst NaOH to produce fatty acid ester and glycerol. In this process 1000 gm of Honge oil, 240 gm methanol and 8 gm sodium hydroxide were taken in a round bottom flask. All the contents were heated up to 70^{0}C and stirred by the magnetic stirrer vigorously for one hour when the ester formation begins. The mixture was transferred to a container and allowed to settle down under gravity for overnight. The upper layer in the separating funnel forms the ester and the lower layer being glycerol was removed from the mixture. The separated ester was mixed with 250 gm of hot water and allowed to settle under gravity for 24 hours as shown in figure 1. Water washing removes the fatty acids and catalyst dissolved in the lower layer and was separated. Fatty acids and dissolved catalyst were removed by using a separator funnel. Silica gel crystals were added to remove the moisture from the ester.The properties of diesel and EHO used for the study are given in table 1.

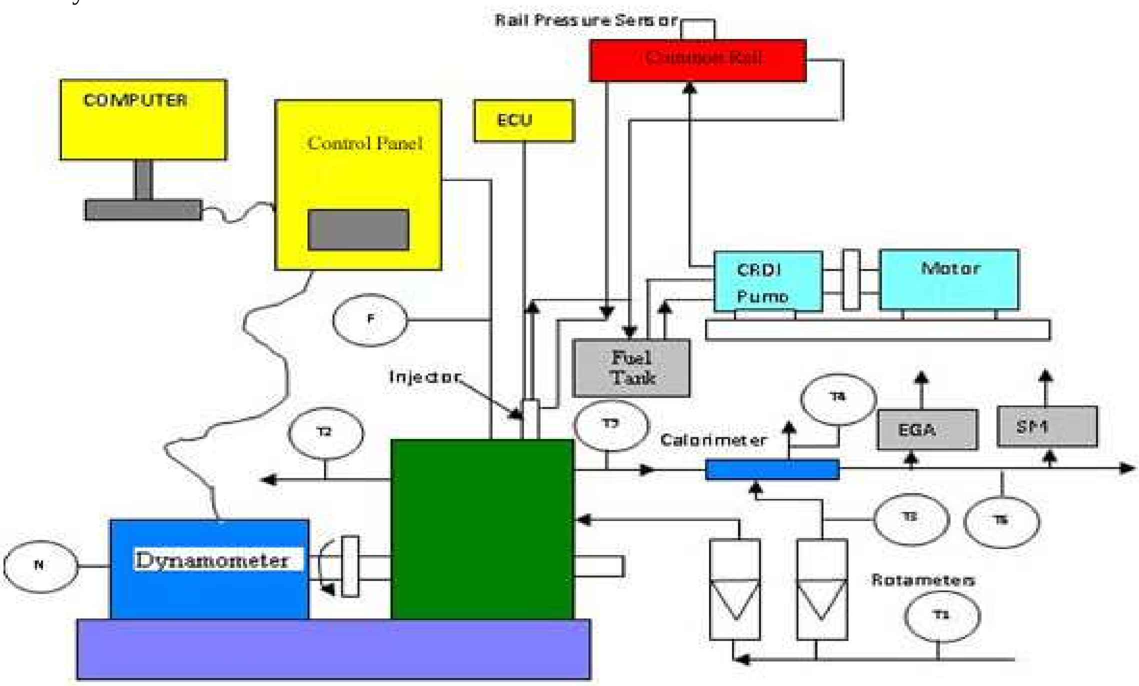
Fig. 1. Biodiesel separation flask

2.2 Experimental methodology

Experiments were carried out at the rated speed of 1500 RPM at 80 and 100% loads. Readings were taken after achieving stable engine operation. The temperature of cooling water at the exit was maintained at 70^{0}C. The experiments were conducted on CRDI engine using diesel, EHO with IT varying from 25^{o}bTDC to 5^{o}aTDC to optimize IT keeping IP constant at 600 bar and then IP was varied from 600 bar to 1000 bar at the said speed and loads to optimize IP.

3. Engine setup

Experimental set up is shown in Figures 2 (a) and (b). Specifications of injector and engine used for the study are shown in Tables 2 and 3 respectively.



T1, T3 – Inlet Water Temperature, T2 – Outlet Engine Jacket Water Temperature
T4 – Utlet Calorimeter Water Temperature, T5 – Exhaust Gas Temperature before Calorimeter
T6 - Exhaust Gas Temperature after Calorimeter, F – Fluid Flow differential pressure Unit
N – Speed Encoder, EGA – Exhaust Gas Analyser, SM – Smoke Meter

Fig. 2. Experimental set up

Table 2 Injector Specification

No of holes	1
Diameter of the nozzle	0.201
Angle of injector hole	Parallel to head
Injection pressure	1000 bar

Table 3 Specifications of CI engine

Sl. No.	Parameter	Specifications
1	Type	TV1 (Kirlosker make)
2	Software used	Engine soft
3	Nozzle opening pressure	200 to 225 bar
4	Static injection timing	23^{o}bTDC
5	Governor type	Mechanical centrifugal type
6	No of cylinders	Single cylinder
7	No of strokes	Four stroke
8	Fuel	H. S. Diesel
9	Rated power	3.7 kW (5 HP) @1500 RPM
10	Maximum torque and Engine speed	1500 rpm
11	Cylinder diameter (Bore)	0.0875 mtr
11	Stroke length	0.11 m
12	Compression ratio	17.5 : 1

4. Results and discussions

The existing diesel engine fitted with conventional injector was replaced by electronically controlled CRDI system for supplying fuel at higher pressure. CRDI engine operation was smooth without any difficulty. The experiments were conducted at 80 % &100% loads and the rated speed of 1500 rpm keeping rail pressure of 600 bar by adjusting the pump flow and the pressure regulator valve to optimize the IT. The rail pressure was than varied from 600 to 1000 bar keeping the optimized IT. The effect of IT and IP on BTE, HC, CO, Smoke and $NO_x$are presented in this section. The IT is varied from25^{o}bTDC to 5^{o}aTDC in steps of 5^{o}CA. Beyond 5^{o}aTDCconsiderable knock was observed. It may be noted that the injector employed was well suited with the engine and the results represent the variation of parameters and demonstrate the capability of the system.

4.1 Optimization of Injection Timing

Brake thermal efficiency

Figure 3 shows effect of IT on BTE for CRDI system operation with diesel, biodiesel with selected ITs for 80% and 100% loads. The maximum BTE occurred at IT between 10^o to 5^{o}bTDC for both higher loads at constant IP of 600 bar for two fuels used. The advancement or retardation from the optimum value of IT deteriorated BTE as shown and the similar results were reported in the literature(Monyem A 2001, Senatore A 2008, Peng Ye 2011). From the figure, it is observed that higher BTE seems to be at SOI between 10 and 5^{o}bTDC and the BTE decreases with SOI later then 5^{o}bTDC. Engine operation with diesel and biodiesel at 10^{o}IT performed better than other ITs tested. However performance of biodiesel was poor compared to its counterpart diesel due to its higher viscosity and lower calorific value.

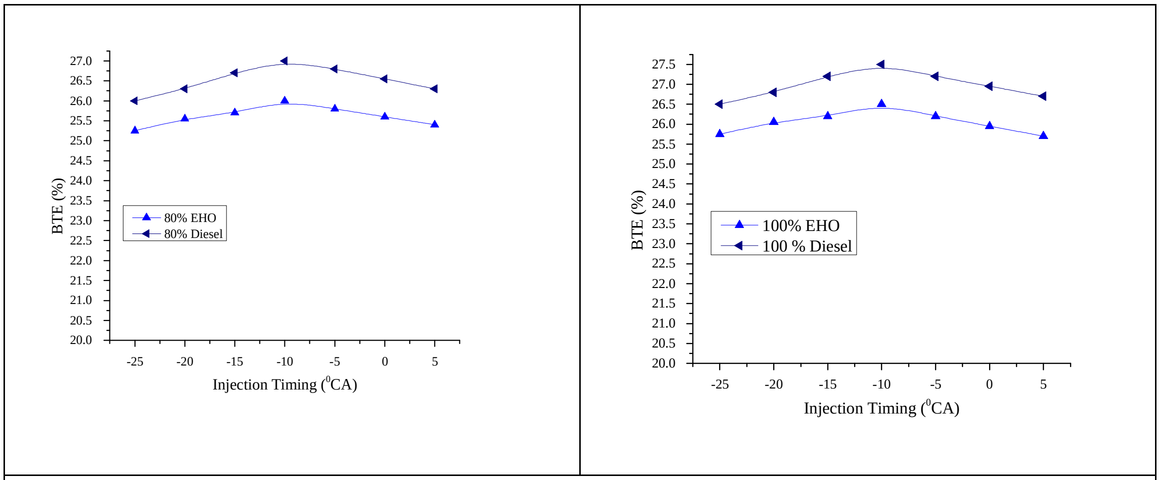


Fig. 3: Effect of IT on BTE at 80% load and 100% load.

Emission characteristics:

Hydrocarbon emission

Figure 4 shows effect of IT on HC emission for CRDI system operation with diesel, biodiesel with selected ITs for 80% and 100% loads. HC emissions of biodiesel are slightly higher than neat diesel operation and the reason for this could be the lower BTE obtained with biodiesel compared to diesel. Biodiesel have higher viscosity that resulted in poor atomization compared to diesel at the same injection pressure. The associated wall wetting observed with biodiesel could also be responsible for the observed trends. HC emissions showed decreasing trend at IT between 10^o to 5^{o}bTDC where fuel BTE was found to be higher (Carlo N 2002).

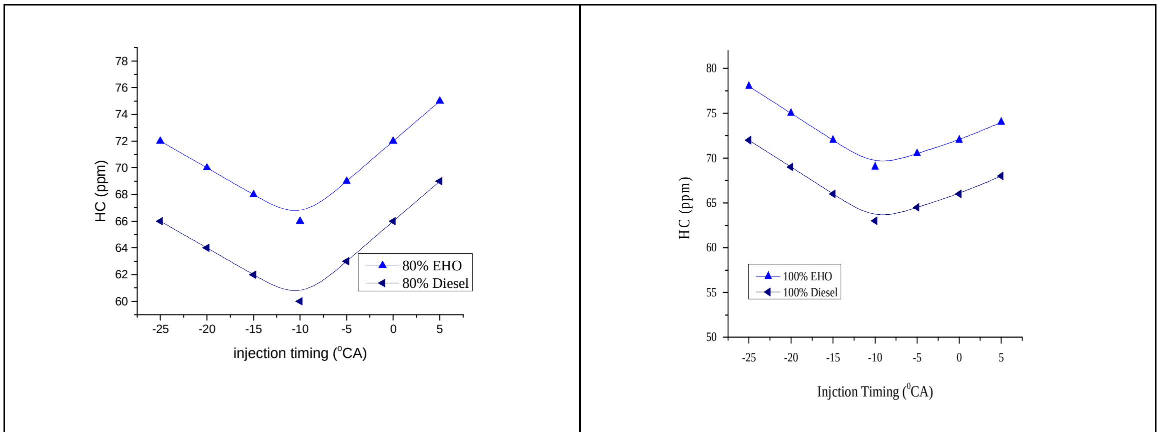


Fig. 4: Effect of IT on HC emissions at 80% load and 100% loads.

Carbon monoxide emission

Figure 5 shows effect of ITs on CO emissions for diesel and biodiesel (EHO) at 80% and 100% loads. CO emissions at higher loads showed similar trend as that of HC emission up to 5°bTDC and showed an increasing trend with IT was retarded. CO emissions was lower for IT between 10° and 5°bTDC while it increased with retarded IT and this could be due to the gas temperature variation observed inside the combustion chamber (CC). Similar results were reported in the literature (Carlo N 2002). In fact, as the IT is retarded, the BTE decreases and for the same power output this increases the amount of fuel delivered. This may be the reason for increase in CO emission level. At retarded IT where the initial pressure and temperature of air is higher with higher oxygen content of biodiesel, increases the oxidation process between carbon and oxygen molecules. The lower hearing value and lower volatility of EHO compared to diesel resulted into higher HC and CO emissions and this could be due to lower BTE obtained on biodiesel operation.

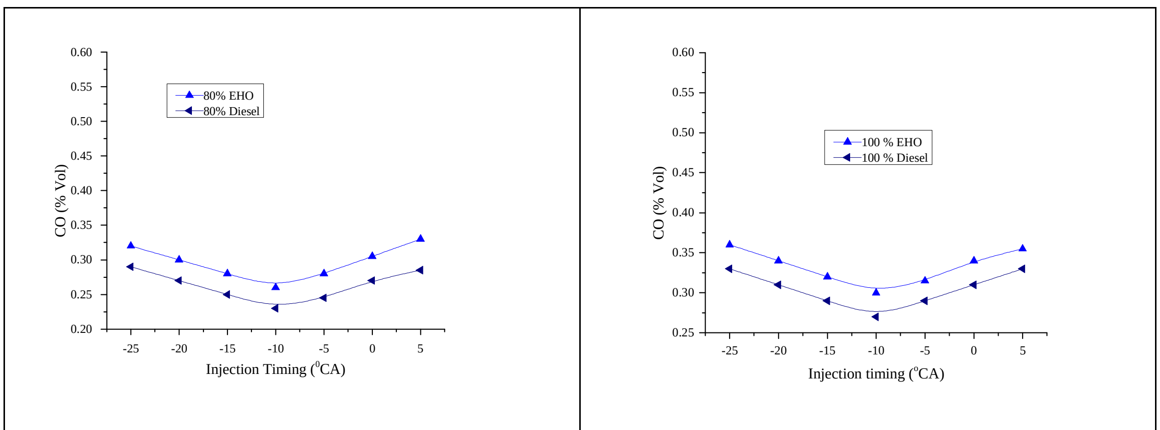


Fig.5: Effect of IT on CO emissions at 80% load and 100% load.

NO_x emission

Figure 6 shows the effect of IT on the emission of nitrogen oxides for CRDI system of operation with diesel and EHO at 80% and 100% loads. NO_xemissions were lower for EHO operation compared to diesel as they provide lower in cylinder gas peak temperature. NO_x emission levels increased with advanced IT for biodiesels and diesel. Advancing the fuel IT increases the peak in-cylinder pressure due to longer ID resulting in higher peak cylinder temperatures and vice-versa. Similar trends were reported in the literature (Leung D 2006). The lower NOx emissions with EHO used could be due to their lower premixed combustion and cetane number (CN) which lowered peak pressure and gas temperature when compared to diesel fuel.

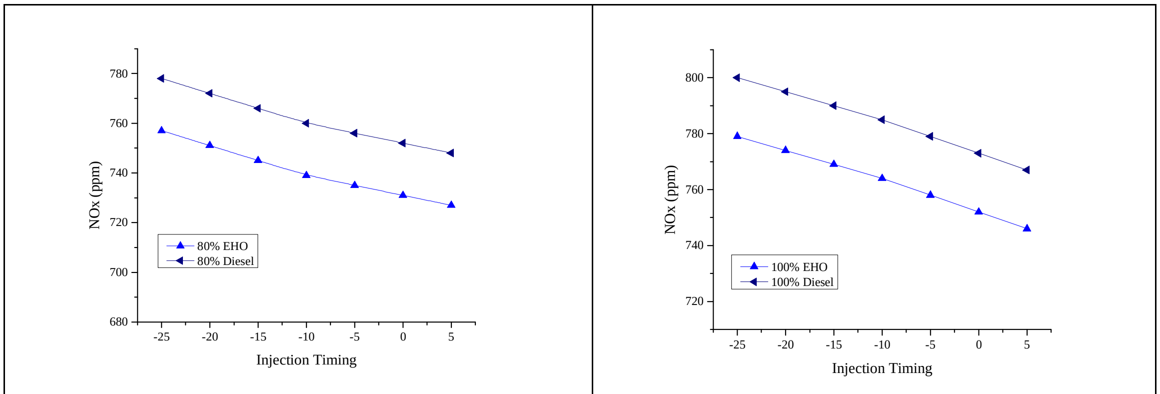


Fig. 6: Effect of IT on NO_x at 80% load and 100% load.

Smoke emission

Figure 7 shows effect of IT on smoke opacity for CRDI system operation with diesel and EHO at 80% and 100% loads. The smoke emission of EHO was higher than those of the diesel under the same operating conditions. This could be attributed to the presence of free fatty acids (FFA) in the biodiesel leading to poor air-fuel mixture. At an IP of 600 bar the smoke emissions of injected fuels decreased with retarded IT up to 10^{o}bTDC and was minimum between 10^{o} and 5^{o}bTDC. This could be due to better combustion process on account of more time available for the oxidation. Smoke emissions of all fuels used are increased when the IT is retarded due to sluggish and diffusion combustion phase caused by reduced rate fuel-air mixing due to later injection (Sayin C 2009). Smoke formation is basically a process of conversion of molecules of diesel fuels into soot particles. The lesser smoke emission of biodiesel are mainly due to emission of lower molecules of HC and particulate matter. At the IT of 10^{o}bTDC higher BTE was resulted but the emissions of smoke, CO and NO_xwere higher. However slightly retarding the IT by 5^{o}bTDC lowers the emissions with a small compromise in the BTE. However IT of 10^{o}bTDC was optimized for diesel and EHO.

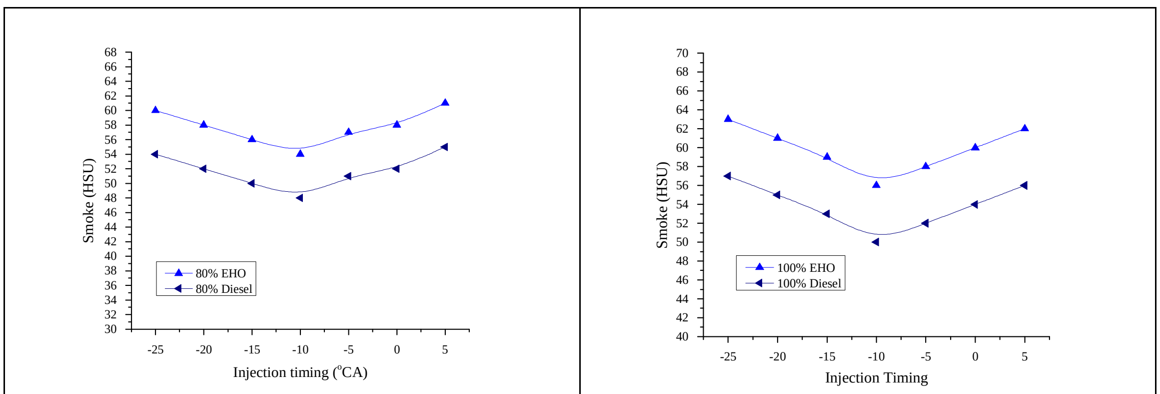


Fig. 7: Effect of IT on Smoke at 80% load and 100% load.

Combustion characteristics:

Peak pressure and Heat release rate (HRR) variation:

Figures 8 and 9 shows the effect of IT on variation of pressure and HRR with crank angle for CRDI diesel engine fuelled with diesel and EHO for 100% loading conditions. From Fig. 8 it can be observed that HRR gradually increased with advanced IT at a given loading condition. It can be noted that at different ITs [20^{o}bTDC to 5^{o}aTDC] the peak pressure and the peak HRR of the EHO are slightly lower than those of the diesel. The peak pressure is increased as the IT is advanced and this could be due to the increase of the ignition delay period. More homogeneous fuel-air mixture is formed which results in a strong premixed combustion phase leading to a higher peak pressure (Narayana RJ 2006). Earlier start of combustion due to advanced IT reduces the effect of slow vapourization and higher viscosity of the biodiesel that lead to poor mixing of fuel with air (Jindal S 2009). At 100%load when the IT is 25^{o}bTDC, the peak of HRR is evidently higher than those at ITs of 15^{o}bTDCand TDC. The main reason is that the heat loss to the cylinder wall was not significant because of higher wall temperature of cylinder even though cylinder wall surface area was larger at IT of 25^{o}bTDC. In addition more fuel was physically prepared for chemical reaction which increased the premixed combustion phase (Joonsik Hwang 2014).

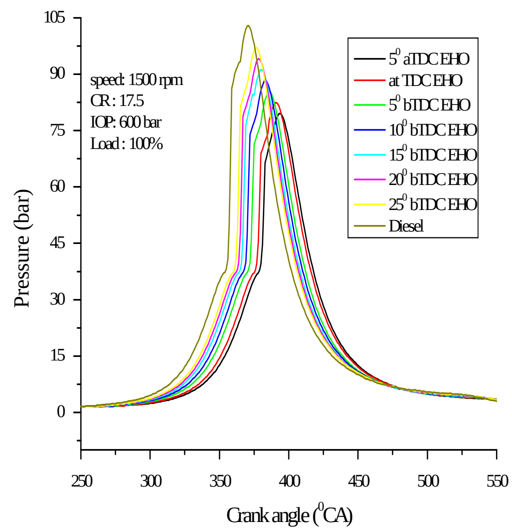


Fig. 8: Effect of IT on Peak Pressure at 100% load.

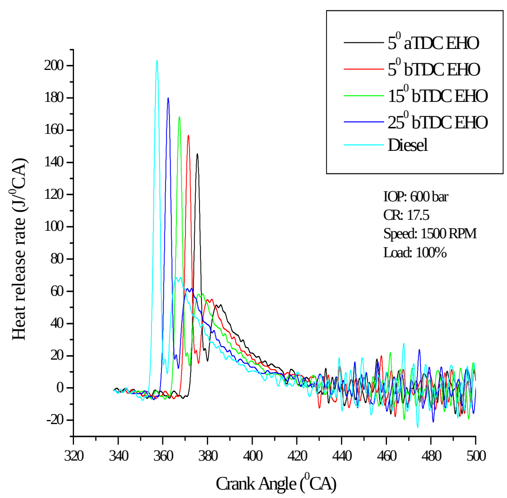


Fig. 9: Effect of IT on HRR at 100% load.

4.2 Optimization of Injection Pressure

The experiments were conducted to study the influence of IP on CRDI engine operation using electronic control unit (ECU). The fuel IP was varied from 600 bar to 1000 bar keeping the engine speed constant at 1500 rpm. Optimized IT was used during the whole experimentation.

Brake thermal efficiency

Figure 10 shows the effect of IP on BTE of CRDI engine operation using diesel and EHO for different IP of 600, 700, 800, 900 and 1000 bar at 80% and 100% load respectively. At higher IP the BTE improved due to efficient utilization of fuel associated with better atomization as well (Pundir, 2007; Bakar, 2008). Amongst all the IP, the highest BTE was observed with IP of 900 bar. BTE values were lower for EHO than diesel operation for all IP tested. Lower CN, higher viscosity and lower volatility associated with EHO led to poor atomization and slightly inhomogeneous mixture during the ID period which results in a later start of combustion process. At 100% load similar trends were observed with lower values as shown in figure. As the fuel IP increased from 800 bar to 900 bar the peak of the HRR as well as the combustion phasing of EHO advances due to the reduction of the ID through better air entrainment and fuel–air mixing.

Higher IP led to faster ignition of mixture and the peak value of the HRR for EHO were lower compared to that of diesel under the same engine operating conditions. When the IP is increased ID decreased due to smaller sauter mean diameter (SMD), shorter break up length, higher dispersion and better atomization of injected fuel (Puhan, 2009). At higher load condition the mixing process between fuel and air is enhanced by higher IP due to higher charge temperature. More combustible mixture is formed during ID as a result the peak in-cylinder pressure at IP of 900 bar was higher than that of 800 bar injection pressure. Beyond 900 bar IOP there was no significant improvement in BTE. This is probably due to higher IP led to wall wetting. Too high IP (1000bar) led to a delayed injection negating the gain in the performance of CRDI engine.

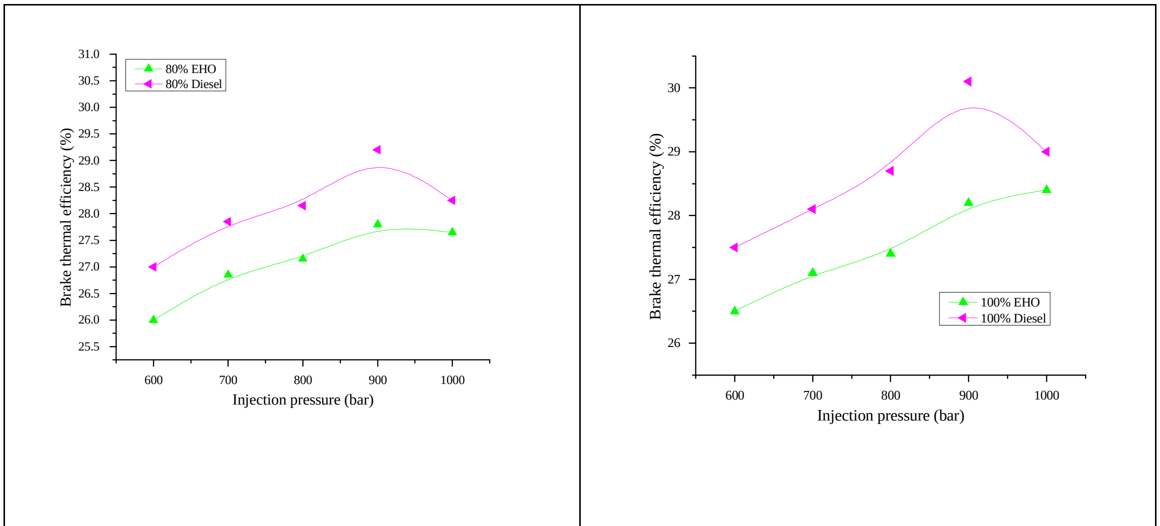


Fig. 10: Effect of IP on BTE at 80% load and 100% load.

Exhaust emissions:

HC and CO emissions

Figures 11 and 12 shows the effect of IP on HC and CO emissions for diesel and EHO at 80% and 100% loads. At higher IP the decreased trend of HC emissions for all fuels used was observed and it might be due to complete combustion prevailing inside the cylinder due to better air-fuel mixing in the CC. CO emissions were affected by in-cylinder gas temperatures and lower CO was observed at higher IP. The HC and CO emissions generally decrease with an increase in IP which could be due to the enhanced atomization ensuring homogeneous fuel-air mixture and better combustion of mixture. Improved ignition qualities and higher oxygen content of the EHO produced much smaller amount of HC and CO emissions but they were comparatively higher than diesel fuel and the lowered BTE of EHO are responsible for the trends reported. The highest IP of 1000 bar led to an increase in the HC emission level probably because of reduction in the BTE. Also a higher IP led to a considerable portion of the combustion of mixture to occur in the diffusion phase on account of the smaller ID.

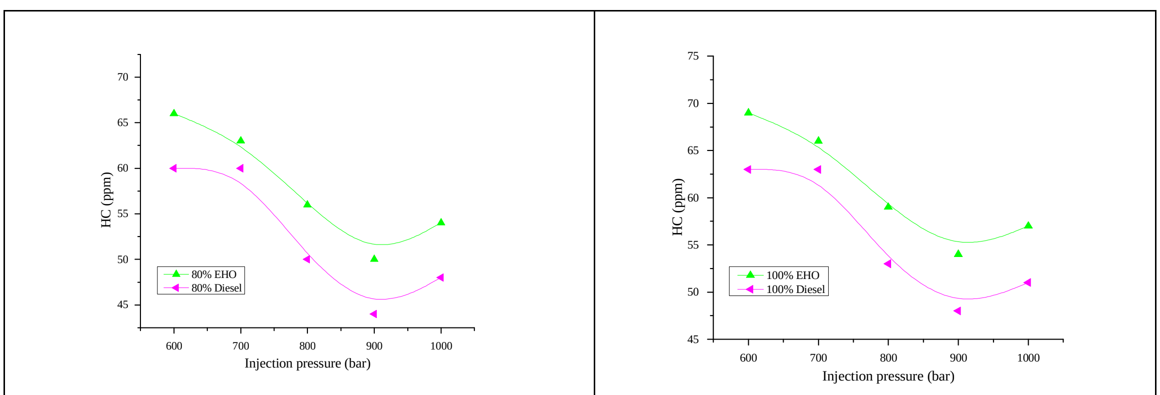


Fig. 11: Effect of IP on HC emission at 80% load and 100% load.

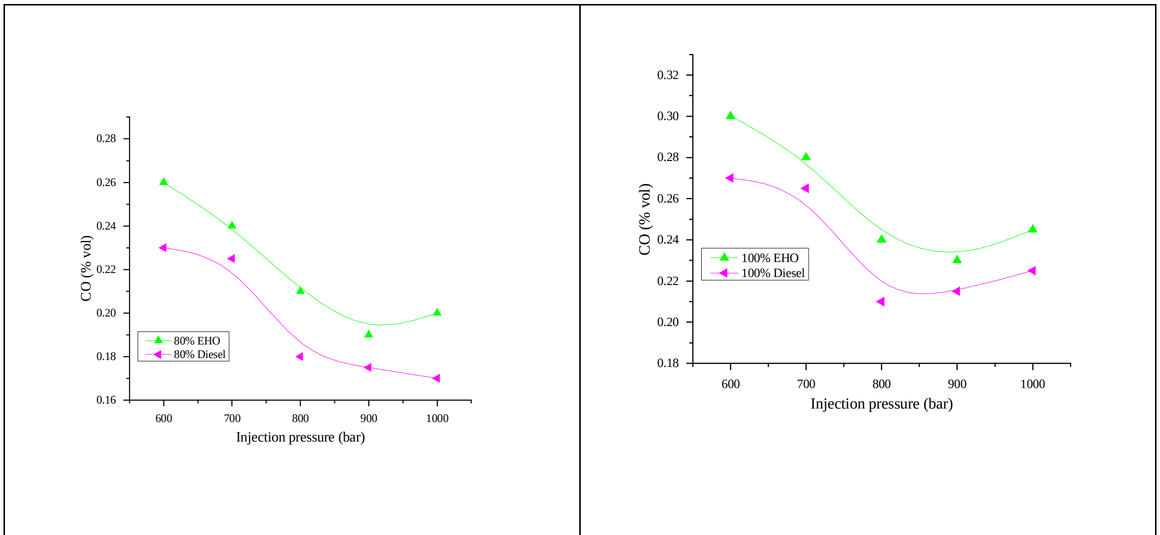


Fig. 12: Effect of IP on CO emission at 80% load and 100% load.

NO_x emissions

NO_x is formed as a result of the oxidation of nitrogen present in the air during burning of the air-fuel mixture in the CC. Its formation is dependent on the flame temperature in the CC. The predominant factors involved in this formation process are the air/fuel ratio and the surrounding temperature. NO_x emission increased with the increases in IP due to faster combustion process and higher gas temperature in the cycle as shown in Fig 13 at 80% and 100% load. Higher IP causes the diesel and EHO spray to vaporize quickly with faster combustion rate resulting in higher cylinder temperature. The earlier SOC and higher heat release peak yields longer residence times and higher in-cylinder temperature that led to increased NO_x emissions of the engine (Charles J 2009). The increased fuel droplet velocity and decreased droplet size due to increased fuel IP that led to better overall mixing of fuel and air and shortened ID (Chang Sik Lee 2005). Higher HRR led to higher in-cylinder temperature, yielding increased NO_xemissions. EHO have short premixed combustion and hence showed comparatively lower NO_xemissions compared to diesel. In case of higher IP, the gas temperature inside the CC increased and consequently more free oxygen atoms of EHO combine with nitrogen resulted in increased rate of NO_xformation. EHO has lower heating value and higher viscosity compared to diesel that led to lower BTE. Lower adiabatic flame temperature and CN of EHO resulted into lower NOx emissions.

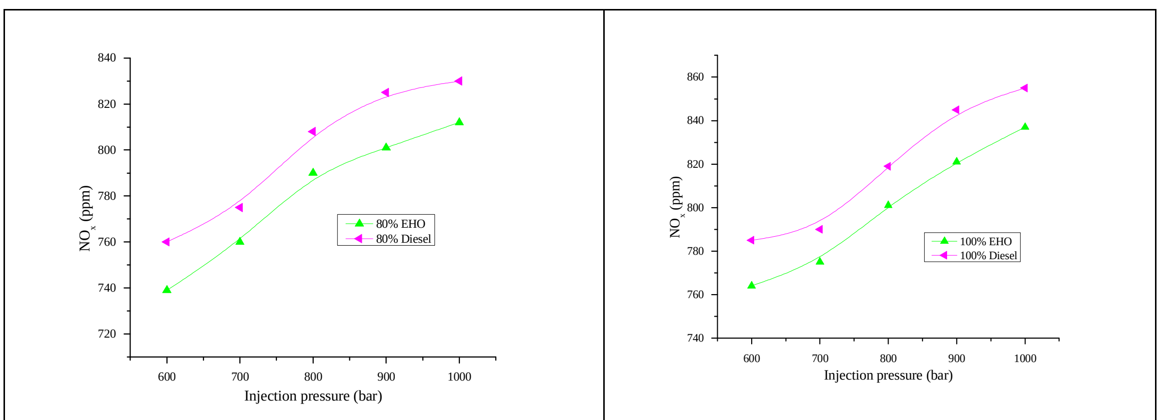


Fig.13: Effect IP on NO_xemission at 80% load and 100% load.

Smoke emissions:

Figure 14 show the effect of IP on smoke emission at 80% and 100% loads respectively. Smoke emission reduced with increase in IP which could be due to enhanced atomization and smaller droplets obtained. The smaller droplets of fuels can improve mixing with air inside the CC resulting in complete combustion of mixture that reduced smoke emission (Yakup 2003). EHO has heavier molecular structure due to higher viscosity compared to petro diesel fuel that resulted into larger fuel droplet size for the same IP. The improper air-fuel mixture achieved in CC resulted into higher smoke emissions compared to neat diesel operation. Lowest smoke level was observed at the IP of 900 bar.

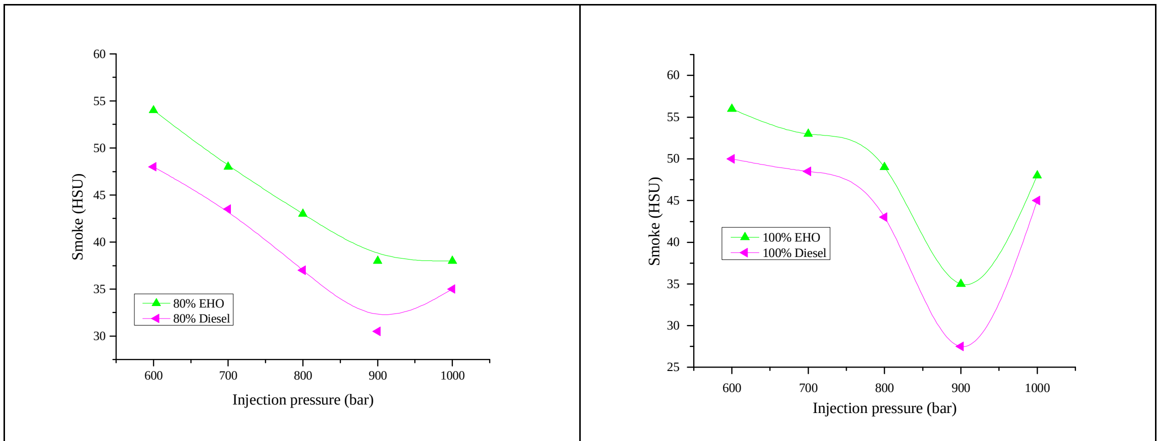


Fig. 14: Effect of IP on smoke opacity at 80% load and 100% load.

Combustion characteristics:

Peak pressure and Heat release rate (HRR) variation:

Figures 15 and 16 shows the effect of IP on variation of pressure and HRR with crank angle for CRDI diesel engine fuelled with diesel and EHO for 100% loading conditions. Increased fuel droplet velocity and decreased droplet size due to increased fuel injection pressure led to better overall mixing of EHO and air. Increased IP with EHO facilitates earlier SOC and higher heat release peak yields longer residence times and higher in-cylinder temperatures (Mueller C J 2009). The combustion of the biodiesel starts slightly later than that of the diesel due to its longer ID compared to diesel and biodiesel has higher viscosity and hence generate higher friction around the injector needle which led to a slow needle-lift movement and longer ID (Wang X 2010). The combustion starts earlier as the fuel IP increased and the in-cylinder pressure peak increased with higher fuel injection pressure. As the fuel IP increased the peak of the HRR as well as the combustion phasing of EHO advanced due to the reduction of the ID through better air entrainment and mixing. Higher IP lead to faster ignition and the peak value of the HRR for EHO but lower compared to that of diesel. Lower CN, higher viscosity and lower volatility of biodiesels lead to poor atomization and mixture preparation with air during the ID period which results in a later SOC. The peak pressure and peak HRR of the EHO are slightly lower than those of the diesel. The peak in-cylinder pressure mainly depends on the combustion rate in the first stage, which is influenced by the fuel taking part in the premixed combustion phase. The amount of fuel delivered during ID period could be increased due to enhanced atomization of fuel at the nozzle outlet with high IP which leads to a more distributed vapour phase and better combustion facilitate increase of premixed HRR especially at high load condition. Similar results were reported in the literature (Labecki, 2012; Kegl, 2006; Ozsezen, 2008; Can, 2004 and Ye, 2010).

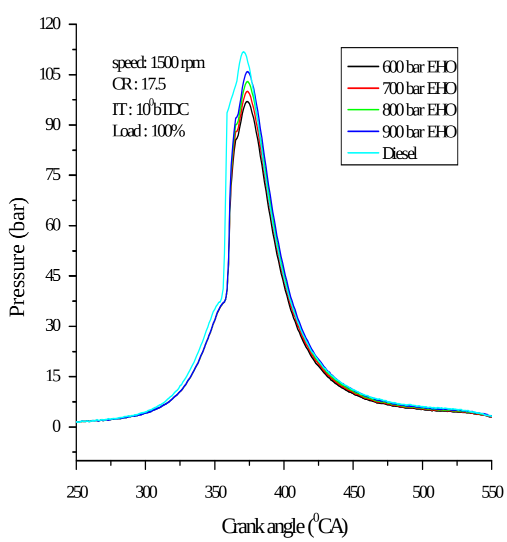


Fig. 15: Effect of IP on Peak pressure at 100% load.

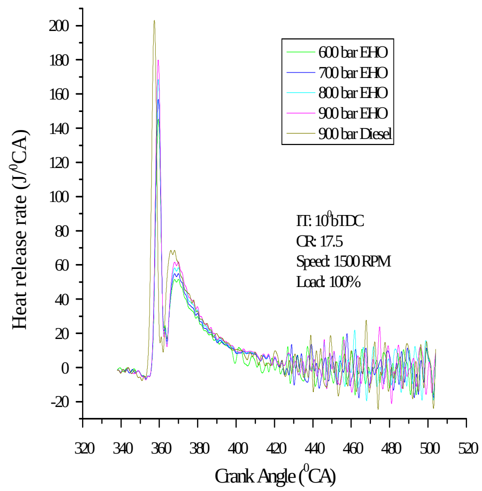


Fig. 16: Effect of IP on HRR at 100% load.

5. Conclusion

The existing single cylinder CI engine was suitably modified to operate on CRDI mode to facilitate varying IT and IP. From the experimental study, the effect of IT and IP on the performance of CRDI engine operated with diesel and EHO the following conclusions were drawn at both 80 % and 100% loads.

- For EHO fuelled CRDI engine the BTE showed increasing trend with retarded IT up to 10^{o}bTDC and beyond this IT BTE reduced. Biodiesel showed poor performance in terms of lower BTEcompared todiesel.
- HC emissions reduced with retarded IT while CO and smoke emissions decreased drastically up to 10^{o}bTDC and increased beyond the said IT. However NOx emissions increased with advanced IT as usual.
- With increased IP, BTE increased up to 900 bar and beyond this pressure the BTE reduced due to system limitation.
- HC and CO emissions showed similar trends for both loads with minimum values at 900 bar. These emissions increased beyond 900 bar.
- NO_x emissions increased with increased IP.
- Higher peak pressure and heat release rates were obtained with advanced IT and higher IP.

On the whole it can be concluded that the developed CRDI single cylinder CI engine operated with EHO worked satisfactorily similar to neat diesel operation. This experimental work showed the capability of EHO to replace diesel which is the need of hour.

Nomenclature

aTDC - after top dead centre
BTE – Brake Thermal Efficiency
CRDI - Common rail direct injection
CO - Carbon monoxide
HC - hydrocarbon
IP – Injector opening Pressure
NOx - Oxides of nitrogen
SOC - Start of combustion
bTDC - Before top dead centre
CC - Combustion chamber
CR - Compression ratio
EHO - Ester of Honge oil
HRR - heat release rate
IT – Injection Timing
PM - Particulate matter

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