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Influence of Injection Timing and Injector Opening Pressure on Combustion Performance and P-θ Characteristics of a CI Engine Operating on Jatropha B20 Fuel

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***Abstract*—**The quest for alternatefuels for a CI engine has become all the more imperative considering its importance in the economy of a nation and from the standpoint of preserving the environment. Reported in this paper are the combustion performance and P-θ characteristics of a CI engine operating on B20 biodiesel fuel derived from Jatropha oil.Itis observed that the twin effect of advancing the injection timing and increasing the injector opening pressure (IOP) up to 220 barhas resulted in minimum brake specific energy consumption and higherpeak pressure. It is also observed that the crank angle of occurrence of peak pressure progressestowards top dead center (TDC) as the timing is advanced and IOP is increased.

***Keywords*—**Crank angle, injector opening pressure, injection timing**,** peak pressure**.**

I. Introduction

COMPRESSION ignition engines, being used in several sectors like transportation,agricultural, stationary power generation etc. play a dominant role in the economy of a nation.Of late there is anacute need for alternate fuels due to the rapid consumption of fossil fuel reserves and resulting raised pollution levels.Among the various alternate fuels identified vegetable oils are being considered as a viable substitute for diesel as they have 90% of the heat content of diesel, environment friendly and are renewable. Experimental studies have reported that using vegetable oils in raw form can cause several operational problems mainly due to their high viscosity and low volatility. These problems include injector coking, piston ring sticking, gumming of fuel lines and filters etc. The problems due to high viscosity can be overcome by different methods such as blending, heating, pyrolysis, micro emulsification and transesterification. Transesterification is the widely used method for chemically modifying vegetable oils to a more engine friendly fuel called biodiesel [1]–[4].

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Biodiesel is usually blended with petroleum diesel to improve the performance of CI engines. Several experimental studies [5], [6] have indicated that 20% volume blend of biodiesel with petroleum diesel (referred as B20 fuel) has resulted in the best performance amongst all other blends.In addition to higher thermal efficiency and lower brake specific energy consumption, there has been substantial reduction in smoke opacity values as well. Biodiesel produced from non-edible oil such as JatrophaCurcas is quite economical considering its cheaper input cost [7].

Several experimental studies have been carried out using jatropha oil either in the raw form or as a blend or as an ester reveal that jatropha is a reasonable substitute for diesel fuel. Forson*et.al.* [8] concluded that the blend of 97.4% diesel/2.6% jatropha oil not only has substantial prospects as a long term substitute for diesel but can also be used as an ignition accelerator additive for pure diesel fuel. Pramanik [9] reports that 50% blend of jatropha oil can be used in a diesel engine without any major operational difficulties but further study is required for the long term durability of the engine. Narayana Reddy and A. Ramesh [10] observed that advancing the injection timing from the base diesel value and increasing the injector opening pressure increase the brake thermal efficiency of a CI engine operating on neat jatropha oil.M. Senthil Kumar *et.al.*[11], carried out experimental comparison of different methods of using jatropha oil and methanol in a compression ignition engine. Their findings statethe methyl esters of jatropha oil (jatropha biodiesel) resulted in brake thermal efficiency higher than neat jatropha oil and comparable to that of petroleum diesel. Similar trend was observed for cylinder peak pressure and peak rate of pressure rise.

According to Richard Stone [12] the power output from a CI engine is greatly dependent on the magnitude and timing of peak pressure. Engine operating variables such as injection timing, injector opening pressure, load, compression ratio etc. greatly influence the same and hence the power output from the engine.Kouremenos*et.al*. [13] Carried out stochastic analysis of cycle by cycle combustion variations in a single cylinder naturally aspirated, four stroke, direct injection, Lister LV1 diesel engine by recording data for 650 successive cycles under different combinations of injection timing and loading conditions. The data was analyzed for peak pressure, peak rate of pressure rise and their respective crank angles of occurrence. Their findings indicate that the pressure data for more than 400 successivecycles forms a safe limit for statistical analysis of cycle by cycle variations.

An attempt is made in this paper to report the effect of engine operating variables such as injector opening pressure and injection timing on brake specific energy consumption and on magnitude and timing of peak pressure in a CI engine operating on B20 fuel derived from jatropha biodiesel.

II. Methodology

Experiments were conducted on a single cylinder, four stroke, naturally aspirated, open chamber, water cooled, 5.2 kW peak output computerized CI engine test rig. The engine was loaded using a directly coupled eddy current dynamometer. The engine and the dynamometer are interfaced to a control panel which is connected to NI USB-6210 hardware and the same can be connected to a computer through a USB port. The specifications of the set up are given in Table I.The test rig can record test parameters such as fuel flow rate, temperatures, air flow rate, load, rpm etc. which are used for calculating different engine performance parameters using the performance analysis software “Enginesoft”. The calorific value and the density of the fuel being tested were fed as input variables to the software.

A PCB Piezotronics Inc. built water cooled piezo electric pressure transducer was installed in the engine cylinder. The sensor was flush mounted and it measured combustion pressure inside the cylinder with 1°crank angle resolution. During the experiments 500 successive cycles of cylinder pressure data for every crank angle were recorded for each loading condition.

The whole set of experiments were carried out at the rated engine speed of 1500 rpm and a compression ratio of 17.5:1. The experiments were conducted at three injection timings of 20°Before Top Dead Center (BTDC), 23°BTDC, 26°BTDC and four IOP’s of 180,200,220and 240 bar.

TABLE I
ENGINE DETAILS

Engine	Four stroke, single cylinder, constant speed, water cooled diesel engine
BHP	7HP (5.2kW) @ 1500 rpm
Bore x Stroke	87.5 x 110 mm
Compression Ratio	17.5:1
Connecting rod length	234 mm
Dynamometer	Eddy current type
Fuel and air measurement	Differential pressure unit
Speed measurement	Rotary encoder
Interfacing with computer	NI-USB 6210 hardware

The static injection timing was varied by changing the gap between the cam and the plunger by removing or inserting shims of different thickness between the fuel injection pump and the cam and by observing the spill cut off of the injection pump. The IOP was set by adjusting the spring of the injector using a nozzle tester.

The methyl ester of jatropha oil blended with petroleum diesel (20% by volume) was directly fed to the fuel tank of the test rig. The properties of B20 fuel derived from jatropha oil and diesel are shown in Table II. Experiments have been carried in the steady state conditions which were ascertained by observing the variations in exhaust gas temperature.

TABLE II
PROPERTIES OF DIESEL AND B20 FUEL

Properties	Diesel	B20
Density at 40ºC (kg/m3)	828	835
Kinematic Viscosity at 40ºC (mm^2/sec)	2.71	3.36
Calorific Value (kJ/kg)	43172	42617
Flash Point (°C)	53	75
Fire Point(°C)	58	86

To statistically analyze such voluminous data, an exclusive computer programhas been writteninVisual Basicwhich uses the pressure crank angle data recorded for 500 cycles as an inputto find the magnitude of peak pressure for each cycle, its respective crank angle of occurrence, to prepare the frequency distribution for the same and to calculate the average value of 500 cycles. The conversion of 500 cycles into a single cycle by averaging the pressure crank angle data was done using Matlab software.

III. Results and Discussions

A. Brake Specific Energy Consumption (BSEC):

Fig. 1 depicts the variation of BSEC with IOP for the three injection timings at full load condition.

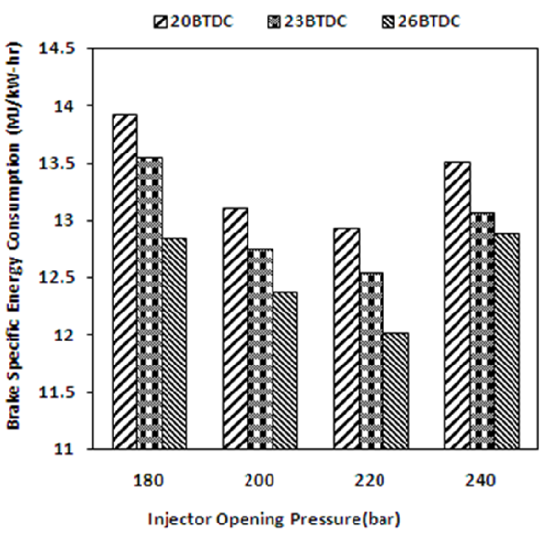

Fig. 1 Variation of BSEC with IOP at full load

As depicted in Fig. 1 the BSEC decreases as the timing is advanced to 26ºBTDC and as the IOP is increased to 220 bar. At these operating conditions the BSEC is 12.01MJ/kW-hr. which is relatively the lowest as compared to the other operating conditions tested.The superior performance at 220 bar may be attributed to two factors. First B20 fuel has higher viscosity as compared to petroleum diesel because of which the spray features are greatly affected since the viscous nature of the fuel minimizes the fineness of atomization. Second direct fuel injection type CI engines are more susceptible to fuel spray characteristics than indirect type CI engines. Hence increasing the IOP from the rated value of 200bar to 220 bar might have resulted in better fuel spray features interms of better cone penetrationleading to proper mixture formation and more or less complete combustion of the mixture as compared to other IOP's tested.However the increase of IOP to 240 bar at 26ºBTDC increases the BSEC. This may be ascribed to the reduced momentum of the fuel droplets to penetrate through the charge resulting from a very fine spray of the injected fuel at higher IOP. It can also be observed from Fig. 1 that among the four IOP's tested 180 bar exhibits higher BSECpossibly due to coarse spray formation and poor atomization leading to poor mixture preparation.

Amongst the 3 injection timings tested the advance timing of 26ºBTDC exhibits consistent and better performance. As stated earlier this may be attributed to the slower nature of combustion of jatropha derived B20 fuel due to its higher viscosity resulting in poor spray features and mixture formation. Hence starting the combustion earlier probably compensates the effect of slow burning nature of the fuel. However the retarded timing of 20ºBTDC exihibits highest BSEC due to sluggish combustion resulting from delayed injection compounded by higher viscosity of the fuel and the same was indeed reflected as higher exhaust gas temperature.

Fig. 2 depicts the relative percentage increases in BSEC for the remaining IOP's as compared to the IOP of 220 bar for the three injection timings testedat full loading condition.The relative percentage increases in BSEC for 20ºBTDC and 23ºBTDC as compared to 26ºBTDC for the four IOP's tested at full loading condition are depicted in Fig.3.

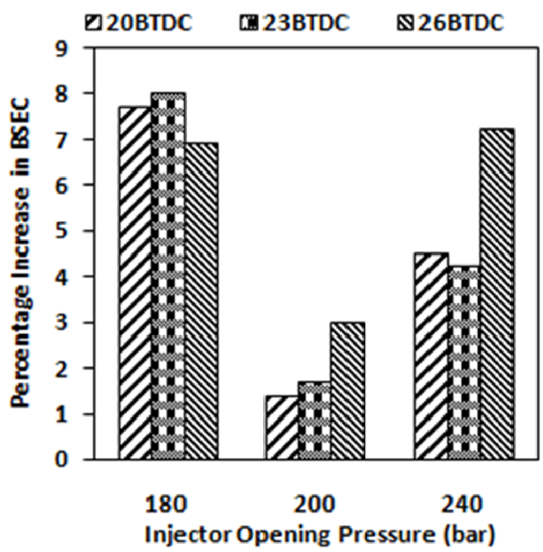

Fig. 2 Percentageincrease in BSEC with respect to 220 bar at full loading condition

As shown in Fig. 2 the relative percentage increase in BSEC is highest for 180bar followed by 240bar and 200bar. This may attributed to the improper degree of atomization of fuel droplets at 180bar and reduced momentum of fuel droplets to penetrate through the charge at 240 bar due to a very fine spray of the injected fuel. The marginal percentage increase in BSEC at 200 bar clearly suggests that combustion is more or less complete at an IOP of 220 bar for B20 fuel. Similarly it can be observed from Fig. 3 that the percentage increase in BSEC is highest for 20ºBTDC followed by 23ºBTDC probably due to incomplete combustion resulting from delayed injection of the fuel. Hence by observing figures 2 and 3 it can be concluded that the ideal operating conditions are 26ºBTDC and 220bar for a CI engine operating on B20 fuel derived from jathropha derived biodiesel.

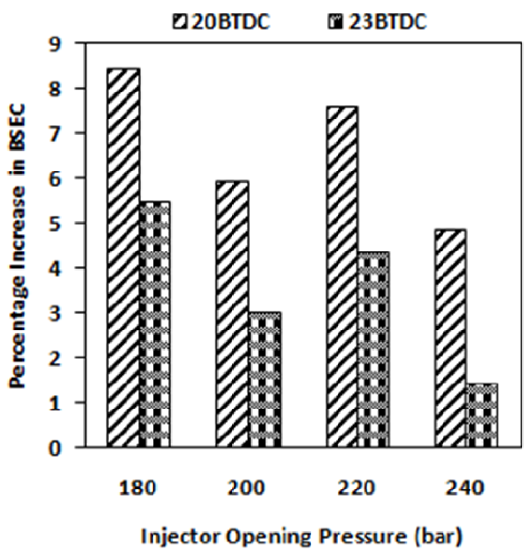

Fig. 3 Percentage increase in BSEC with respect to 26ºBTDC at full loading condition

B. Peak Pressure

Fig. 4 depicts the variation of average value of peak pressure from 500 cycles with IOP for the three injection timings at full load condition. The variation of average peak pressure is in conformity with the behavior of brake specific energy consumption.

The highest average peak pressure occurs at an IOP of 220 bar and for an injection timing of 26ºBTDC with a magnitude of 75.3bar.The average peak pressure is lower at 20ºBTDC and increases with injection advance for the four IOP's tested owing to sufficient time available for mixture formation. Among the four IOP's tested the IOP of 220 bar depicts higher average peak pressure probably due to the better spray characteristics leading to improved atomization and mixture formation which reduces the physical delay period resulting in complete combustion of the fuel.

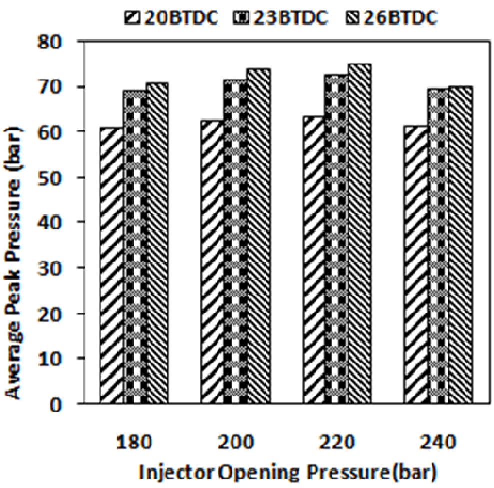

Fig. 4 Variation of average peak pressure with IOP at full load

The pressure – crank angle profile by averaging the pressure data from 500 cycles at 26ºBTDC for the 4 IOP's and at 220 bar for the 3 injection timings at full loading condition are depicted in figures 5and6 respectively.

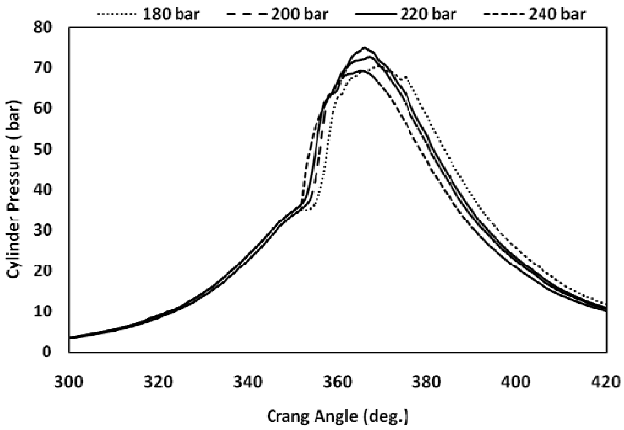

Fig. 5 Pressure – Crank angle diagram at 26ºBTDC for full load

As depicted in Fig.5 the peak pressure for the average pressure- crank angle profile is highest for an IOP of 220 bar followed by 200 bar. Though the combustion starts early at 240 bar the rise in pressure fails to maintain the momentum due to smaller size of the fuel droplets in the later part of the combustion amongst the four IOP's tested. The pressure-crank angle profiles are more or less uniform for IOP's of 200 bar and 220 bar. Combustion to some extent is delayed for an IOP of 180 bar due to poor mixture preparation thereby the pressure- crank angle curve moves away slightlyfrom TDC, indicating that combustion is taking place in the late expansion phase, thereby increasing the exhaust gas temperature. It can also be observed that the crank angle of occurrence of peak pressure for the average pressure- crank angle profile shifts towards TDC as the IOP is increased from 180 bar to 240 bar.

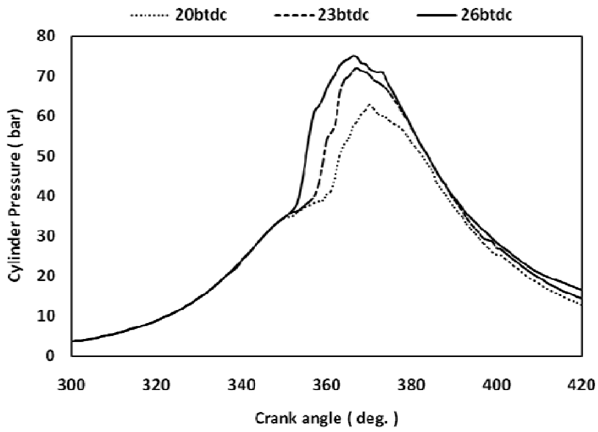

Fig. 6 Pressure – Crank angle diagram at 220 bar for full load

It can be inferred from Fig.6 that the effect of changes in injection timing on peak pressure for the average pressure-crank angle profile is more pronounced as compared to changes in IOP. The peak pressure is highest for an advanced injection timing of 26ºBTDC followed by 23ºBTDC and 20ºBTDC with the crank angle of occurrence shifting away from TDC as the injection is retarded. The retarded timing of 20ºBTDC exhibits lowest peak pressure due to delayed injection leading to improper mixture formation and incomplete combustion and the same has resulted in lower performance.

Figures 7a to 7h depict the frequency distribution for the crank angle of occurrence and magnitude of peak pressure at full loading condition for the three injection timings tested at IOP's of 180 bar, 200 bar, 220 bar and 240 bar respectively. It can be observed from the figures 7a, 7c, 7e and 7g that for the four IOP's tested the crank angle of occurrence of peak pressure moves away from TDC as the timing is retarded. As depicted in Fig. 7a the crank angles of occurrence move away from TDC at 180 bar as compared to the other three IOP's for the three timings tested. This may be attributed to the sluggish nature of combustion due to thelarger size of the fuel droplets since the IOP is lower. Contrary to that they move towards TDC at 240 bar due to rapid combustion as depicted in Fig.7g. They are distributed slightly over a range of 3 to 9º ATDC for IOP's of 200 bar and 220 bar. Further the crank angles of occurrence are distributed over a narrower range for the four IOP's tested at injection timings of 23ºBTDC and 26ºBTDC as compared to 20ºBTDC. They are distributed over a wider range for IOP's of 180 bar and 240 bar at 20ºBTDC probably due to improper mixture formation.

As depicted in figures 7b, 7d, 7f and 7h for the four IOP's tested the rated timing of 23ºBTDC and advanced timing of 26ºBTDC produces higher peak pressure as compared to 20ºBTDC.It is also evident from figures 7a to 7h that the advanced timing of 26ºBTDC produces highest frequency indicating a greater degree of repeatability as most of the cycles are conforming to the same value.

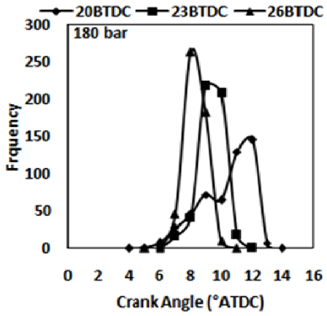

Fig. 7a

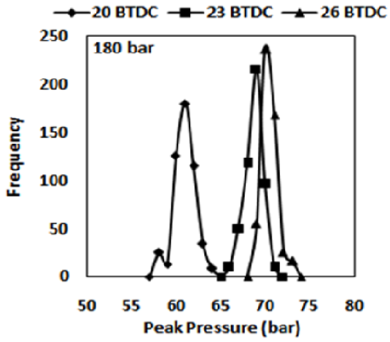

Fig.7b

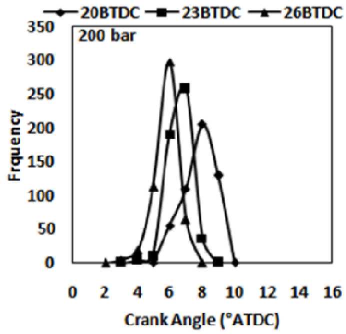

Fig. 7c

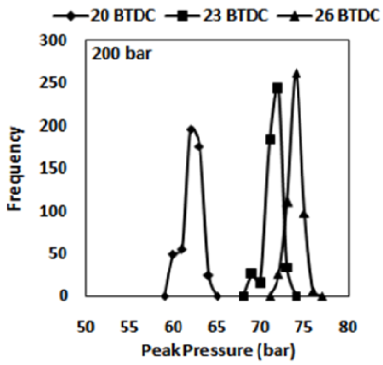

Fig.7d

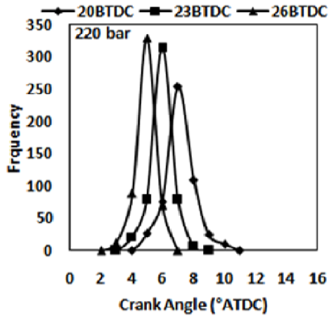

Fig. 7e

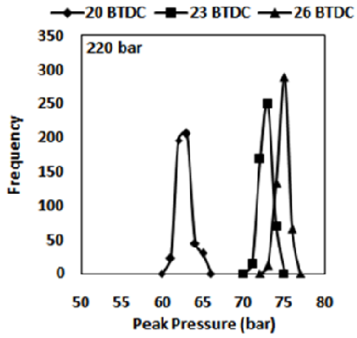

Fig.7f

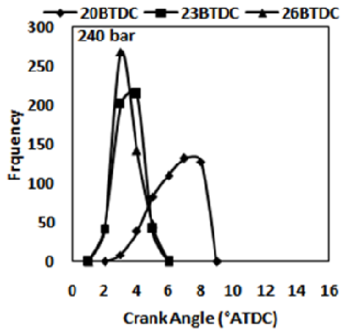

Fig.7g

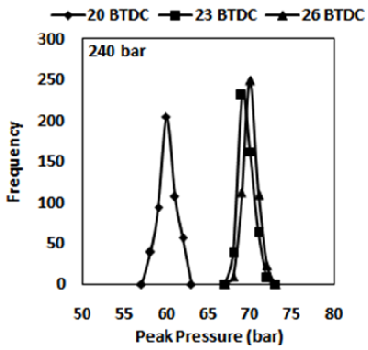

Fig.7h

Fig. 7a-7h Frequency of crank angle of occurrence and magnitude of peak pressure at full load

IV. Conclusion

The following conclusions are deduced from this study:

1. Brake Specific Energy Consumption decreases as the injection timing is advanced to 26ºBTDC and IOP is increased up to 220 bar. The same operating conditions also result in highest average peak pressure
2. The crank angle of occurrence of peak pressure moves away from TDC as the injection timing is retarded to 20ºBTDC and IOP is reduced to 180 bar.
3. Statistically it was observed that advancing the injection timingto 26ºBTDC for all the IOP tested has resulted in a greater degree of repeatability with regard to magnitude and crank angle of occurrence of peak pressure.

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