Investigations on Effect of Fuel Injection Pressure on Performance and Emissions of Linseed Blends in a Diesel Engine

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***Abstract*---Ever increasing demand on fossil fuels and environmental degradation with their use concern the global utilization of internal combustion engines in industrial, automotive and power sectors.An alternate to high pollutant diesel derived from renewable energy sources should be environment friendly, economically cheaper, technically feasible without compromising the engine performance and should provide energy security. Non-edible oils such as linseed oil, karanja, jatropha, and mahua etc., are mostly preferable. In this study, linseed oil derived from flax seed plant is chosen and blended it with diesel in proportions of 10%, 20% and 30%. Performance and emission characteristics of linseed oil blends (L10, L20 and L30) and the diesel are investigated at constant speed in a diesel engine with nozzle opening pressure of 200 bar. The experiment is repeated for different injection pressures (220 and 240 bar) and the results are compared with baseline diesel. Brake specific energy consumption (BSEC) for biodiesel blends is comparable to diesel fuel at all loads and fuel injection pressures (FIPs). Brake thermal efficiency (BTE) is optimum for biodiesel blends at injection pressure of 200 bar. Diesel has shown high mechanical efficiency than biodiesel blends at FIPs 220 and 240 bar. Carbon emissions are less with diesel compared to biodiesel blends.**

Keywords-CI engine, Transesterification, Diesel, Biodiesel blends, FIP, Performance, Exhaust emissions

I. INTRODUCTION

Research predicts that the energy crisis and rapid degradation of environment in future concern the compression ignition (CI) engines which solely depend on the non-renewable sources and threaten environment through their exhaustion. On the other hand, CI engines are advantageous in fuel economy, durability and cheaper maintenance. Today, CI engines are part of the mechanized world which play key role in industry, transport and energy sectors. However, in view of environmental consciousness and scarcity of primary fuel reserves, scientists from across the globe have been motivated towards new alternative as well as renewable energy forms. This alternative to mineral diesel should be eco-friendly, technically feasible, economical and provide energy security [1]. Vegetable oils and animal fats from the feed stocks of biological sources are suitable for diesel engines without compromising to the performance and it requires no hardware modifications to the engine. In diesel engines, vegetable oils in direct use will create operational and durability problems due to their polyunsaturated character, high viscosity and extremely low volatility which leads to high spray jet penetration, large droplet size and poor fuel atomization [2], [3]. As a result, the jet tends to be a solid stream instead of a spray of small droplets which further leads to poor combustion accompanied by loss of power and economy [4].

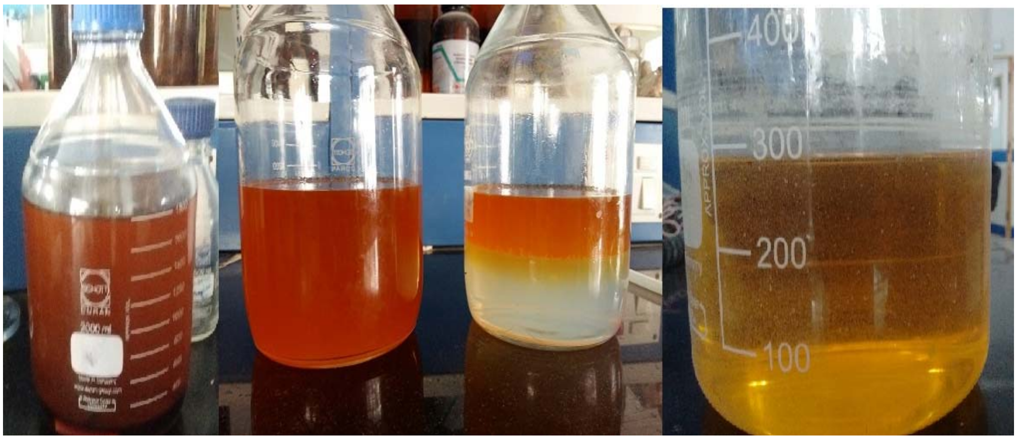
Literature clearly shows that transesterification is the best way to reduce the high viscosity as well as high density of vegetable oils by converting them into methyl esters commonly known as biodiesel [5]. In view of literature, diesel and biodiesel possess approximately same fuel characteristics and contains similar molecular structure [6], [7]. However, biodiesel still has higher density and viscosity than diesel. Biodiesel has bio-degradability, non-toxicity and excellent lubricity and has a higher cetane number compared with petroleum diesel fuel. Combustion characteristics of the engine are good with biodiesel as it is rich oxygenated fuel (10-12% oxygen by weight) which significantly reduces oxides of carbon (CO and CO_2), sulphur oxides (SO_x), particulate matter (PM) and unburned hydrocarbon (UHC). However, many researchers have reported increased oxides of nitrogen (NO_x) emissions with biodiesels [8], [9]. Various stringent emissions control norms are imposed on the vehicle manufacturers to build light-duty and heavy-duty diesel engines to reduce the exhaust emissions. Research has been directed towards achieving the high performance and low emissions which depend on the factors of combustion, performance and emissions characteristics like fuel injection pressure (FIP), start of injection (SOI), multipoint injection (MPI), exhaust gas recirculation (EGR), design of combustion chamber and nozzle spray patterns. In CI engines, ignition delay during combustion increases due to lower FIPs which results in larger droplet diameters. This will also increase cylinder pressures, which further results in higher NO_x

emissions. This may be the probable reason for higher NO_x in the case of biodiesel as the high viscosity, density and surface tension are the dominating effects which lead to higher mean droplet size of biodiesel. On the other hand, spray droplet diameter reduces with higher FIPs so that fuel-air mixture improves as a result of superior mixing during ignition delay and thus increases rate of combustion and reduce smoke and CO emission. Hence, it is concluded that the best solution to decrease emission and to improve fuel atomization is to inject the biodiesel at higher pressures [10], [11]. Shehata et al. carried out a series of tests on DI engine using corn and soybean fuel blends in the ratio of 20% biodiesel at different engine speeds, loads and injection pressures of 180, 190 and 200 bar and obtained better results regarding BSFC (15% decrease) at increased injection pressure of 200 bar when compared to original injection pressure (180 bar) [12]. Sastry et al. investigated experimentally the performance and emission characteristics of direct injection (DI) diesel engine fueled with diesel-biodiesel blends in which isobutanol and ethanol were added 5-10% by volume as additives. BTE and fuel economy were improved when the nozzle opening pressure was increased to 250bar. Also, CO and emission opacity was reduced significantly and NO_x emissions reduced marginally in some blends [13].In an attempt to improve the combustion quality of biodiesel blends with mineral diesel, higher fuel injection pressures are maintained in the current investigation. Biodiesel has been produced from the raw linseed oil and is blended with mineral diesel in concentrations of 10%, 20% and 30% (v/v). Effect of linseed biodiesel blends on performance and emission characteristics of CI engine by varying loads at constant speed have been experimentally investigated. Performance and emissions curves are analyzed from the recorded data and it is compared with the mineral diesel.

II. MATERIALS AND METHOD

A. *Transesterification*

One-and-a-half liter of raw linseed oil is heated up to 55°C in a constant water bath to thin it. On the other hand, a mixture of methanol (320 ml i.e., approx. 20% v/v) and sodium hydroxide, a catalyst (6.3gm i.e., approx. 0.4% of raw linseed oil) is stirred well for 15 minutes to form sodium methoxide [14]. Now, heated raw linseed oil is added to this mixture and the entire mixture is stirred continuously using a magnetic stirrer for one hour. Later, the whole is allowed to settle down under gravity for 15-24 hours as shown in Fig. 1(a). The upper layer in Fig. 1(a) is methyl ester and lower layer is glycerol which is a by-product of transesterification reaction. The separated methyl ester is mixed with water at 75°C and allowed it to settle down for some time and again the top layer is collected as shown in Fig. 1(a). This process is repeated for two more times in order to remove the excess catalyst in the ester [15]. For the third time it is allowed to settle down under gravity for 10-15 hours. Now the methyl ester is separated from water and heated at 105°C for about an hour to remove the water traces and finally biodiesel is obtained as shown in Fig. 1(b). The viscosity of raw linseed oil is reduced after transesterification but still it is more compared to diesel and also the heating value has been increased slightly because of presence of alcohol. The yield of biodiesel from transesterification process is found to be 84.6%. The properties of the linseed methyl ester after transesterification are shown in Table I.



(a) (b)

Fig. 1.(a) Transesterification process, (b) pure biodiesel L100

B. *Blending*

From previous investigations, it is found that transesterification is a simple chemical process which helps to utilize vegetable oils in CI engines. Also, it strengthens the energy security since it depends on the locally grown feed stocks. However, it increases the cost of production since logistics are required to chemically process the vegetable oils although variety of vegetable oils readily available in local areas. In addition to that, after transesterification biodiesel has still high viscosity than diesel. Blending of biodiesel with diesel is an attractive way to reduce the viscosity and the biodiesel-diesel bends are easily handled in diesel engines without operational and durability problems [16]-[18]. In the present study, blending of linseed biodiesel with diesel has been done in various concentrations like L10, L20 and L30 (%v/v) and L10 indicates a blend including 10% linseed biodiesel whereas L100 represent pure biodiesel. Fig. 2 shows the fuels (diesel and L100) used for blending along with biodiesel-diesel blends.

TABLE I. Fuel properties [19]

Properties	**Diesel**	**Linseed Methyl Ester (L100)**	**ASTM standards**
Density (kg/m^3)	850	875	…
Kinematic viscosity (cSt)	2.049	4.336	1.9-6.0
Calorific value (kJ/kg)	42000	38896.2	>33000
Flash point (°C)	78	154	>130
Fire point (°C)	83	160	>53
Cloud point (°C)	<10	-2	-3-12
Pour point (°C)	-6	-6	-15-10
Carbon residue (%)	0.0214	0.0179	<0.05
Ash content (%)	0.02	0.02	0.02% (max)
FFA (%)	…	0.0705	<2.5
pH	…	7.7	…

Fig. 2.Inside picture biodiesel-diesel blends (L10, L20 and L30) shown in the middle, mineral diesel and pure biodiesel are shown at the ends

C. *Experimental setup*

The engine test rig used for this study as shown in Fig. 3 is a single cylinder, four stroke, vertical, water cooled, constant speed, naturally aspirated, direct injection diesel engine. It has a rated output of 3.68 kW at 1500 rpm. An electrical dynamometer is coupled to the engine is used as a loading device. The load and speed can be varied on the dynamometer and thereby on the engine by switching on or off the load resistances [16]. The change in voltage and current at respective loads has been observed using sensors placed at appropriate locations. The flow rate of fuel is calculated by means of a burette and a stop watch. A digital tachometer is used to record the engine speed. The fuel injection system used is with fuel injector operated at nozzle opening pressure of 200bar. The fuel injection pressure can be increased or decreased by rotating the screw clockwise or anticlockwise respectively located on the top of the injector and one complete rotation of screw in clockwise direction increases the pressure by 40bar. The calibrated pressure has been checked before conducting experiment using a pressure gauge [20]. Experiments were carried out at three different injection pressure values 200, 220 and 240bar. The performance and emission tests were conducted on engine with different biodiesel blends and mineral diesel subjected to altered fuel injection pressures. All the tests were conducted at three different engine loads along with no load in terms of mean effective pressure. The engine ran without any visible problem throughout the tests and it didn’t show any starting difficulties when fueled with biodiesel-diesel blends. All the data were collected after the engine was stabilized. This data was analyzed through the graphs which include BSEC, BTE, indicated thermal efficiency (ITE), mechanical efficiency and exhaust emissions for all the fuels at different FIPs. The technical specifications of the engine are shown in Table II.

Table II. Specifications of the test engine

Engine parameters	**Specifications**
Manufacturer and model	Kirloskar India, AV1
Engine type	4-stroke, vertical, single cylinder, direct injection, CI engine
Maximum power output	3.68 kW
Rated speed	1500 rpm (constant)
Bore × stroke	80 mm × 110 mm
Compression ratio	16 :1
Type of cooling	Water cooled
Dynamometer	Electrical dynamometer
Brake mean effective pressure @ 1500 rpm	5.31 bar

III. RESULTS AND DISCUSSION

The experiments were conducted on the engine for different test fuels at nozzle opening pressure of 200 bar. Later tests were repeated twice changing FIPs to 220 and 240 bar. Performance and emission curves represent the resulted experimental data are used for analysis.

A. *Performance*

Fig. 4 represents the variation of BSEC from different test fuels at varying engine loads expressed in terms of BMEP at three FIPs. Since the calorific values and densities of test fuels are different, BSEC is a more reliable parameter than BSFC to compare them [18]. Fig. 4(a) shows the curves for BSEC in decreasing trend when the engine load increases. BSEC is slightly higher for blend L30 when compared to other test fuels at FIP 200 bar. BSEC is almost similar at all loads for the test fuels when FIP is 220 bar as shown in Fig. 4(b). At higher FIP i.e., 240 bar, BSEC is comparable at all loads for all the test fuels as shown in Fig. 4(c). Among all the three FIPs, the BSEC is moderate and similar for all the fuel samples when injected at 220 bar. If diesel is considered, FIP of 200 bar is optimum which have shown least BSEC and for biodiesel blends almost similar BSEC is recorded at all the loads and FIPs.

(a) (b)

Fig. 3.(a) Experimental setup, (b) Engine with fuel injector operating at 200, 220 and 240 bar

Fig. 5 shows the variation of BTE for biodiesel blends at varying engine loads and FIPs in relation to mineral diesel. Except L30 blend, other blends traced the same trend as the mineral diesel at all the loads as shown in Fig. 5(a) when 200 bar injection pressure is maintained. Blend L30 has showed least performance at all loads at FIP 200 bar. BTE of diesel lessened with increase in FIP to 220 bar as shown in Fig. 5(b). However, all the biodiesel blends performed well and have shown similar BTE at all the loads. Blending concentrations have no effect on the BTE at all loads when biodiesel blends were injected at 220 bar. When we increased FIP further to

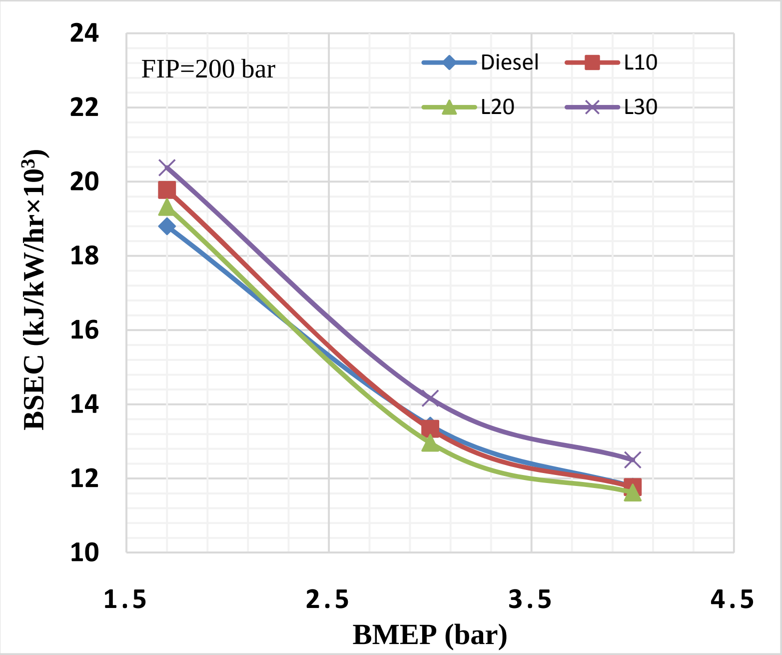
240 bar, it is seen from Fig. 5(c) that the effect of FIP on BTE has resulted in decrease of BTE for all the test fuels except L30 when compared to other FIPs. The significant characteristics of higher FIPs are seen at FIP 220 bar when the engine fueled with biodiesel blends.

The amount of power developed in the cylinder or the power exerted on the piston defines indicated power and the ratio of indicated power to fuel power gives ITE. Fig. 6 describes the variation of ITE for different test fuels at varying loads and FIPs. At FIP 200 bar, mineral diesel showed highest ITE than biodiesel blends at all varying loads followed by L20, L10 and L30 respectively as shown in Fig. 6(a). On the other hand, when FIP is increased to 220 bar, the diesel showed least ITE than biodiesel blends at all the loads. Fuel power is well converted into indicated power for the blends L10 and L20 which resulted in higher ITE as shown in Fig. 6(b). Similar trend is seen in Fig. 6(c) i.e., in case of 220 bar, diesel have shown least ITE among all test fuels. For FIP 240 bar also, L10 resulted in highest ITE at all the loads. It is observed that for blend L20, ITE decreases as the load increases.

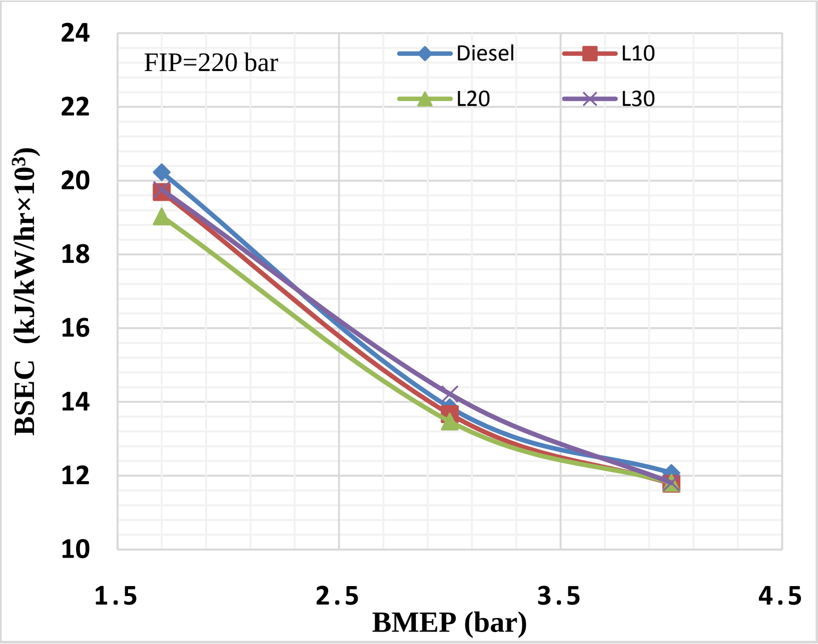
Mechanical efficiency is the measure of effectiveness of a machine which converts energy and power as input into the force and movement of a device as output. Fig. 7 shows the variation of mechanical efficiency from different fuels at varying BMEPs, at three FIPs. Mechanical efficiency is higher at all BMEPs for the blend L30 than any other fuel as shown in Fig. 7(a). This is the significant contribution of blending the biodiesel with mineral diesel. Blends L10 and L20 have shown similar as well as more mechanical efficiency than diesel when injected at 200 bar. From Fig. 7(b), it is seen that diesel showed higher mechanical efficiency than biodiesel blends when the FIP is increased to 220 bar. Mechanical efficiency of L30 is slightly less compared to diesel and it is more when compared to L10 and L20. L10 and L20 blends also showed here same mechanical efficiency at all loads but it is less when compared to other test fuels. Mineral diesel continued to show higher mechanical efficiency at all loads when it is injected at 240 bar. The similar trend of mechanical efficiency is observed at all loads for L20 and L30 blends but it is less when compared to diesel. When higher FIPs are used, L10 has shown less mechanical efficiency amongst all other test fuels as shown in Fig. 7(c). Diesel has delivered higher mechanical efficiency at all varying loads when FIP is of 220 bar. The increase in FIP on biodiesel blends lead to decrease in mechanical efficiency.

B. Exhaust emissions

The emissions from the CI engines such as CO, CO_2 and O_2 were measured and analyzed. Fig. 8 shows the variation of CO with BMEP. It is observed from Fig. 8 that the CO emissions are more for blend L30 than other test fuels at all injection pressures. CO emissions are less for blend L10 when compared to other fuels at all loads and injection pressures. Fig. 9 shows the variation of CO_2 with BMEP at all varying loads and injection pressures. CO_2 emissions are fewer for diesel at all varying loads and FIPs. At higher FIPs 220 and 240 bar, L10 and L20 have almost released same amount of CO_2 at all varying loads. Fig. 10 shows the variation of O_2 with BMEP. O_2 release content is more with biodiesel blends L10 and L20 and it is less with L30 when compared to L10 and L20 but it was released same amount at all loads and followed same trend at all FIPs.



(a)



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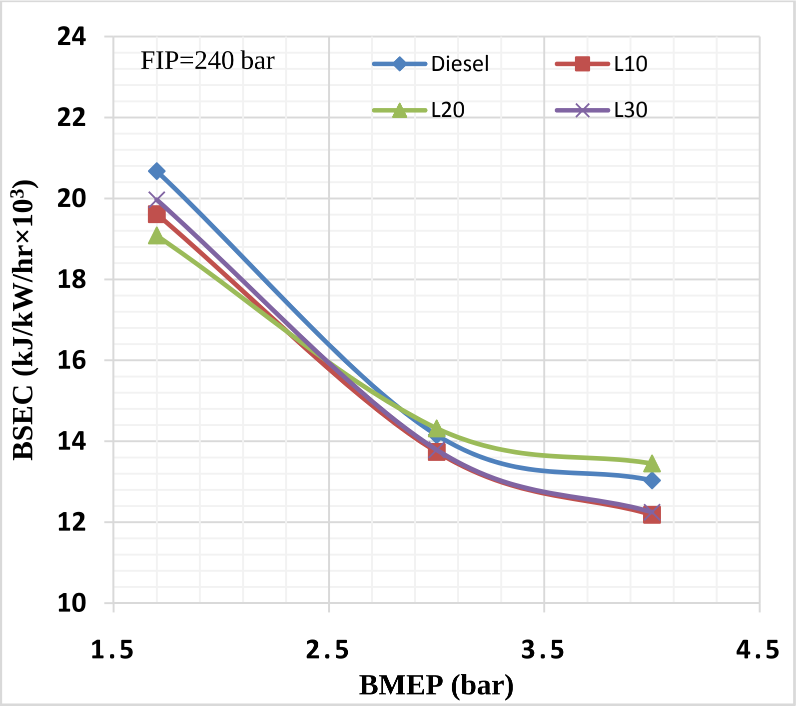
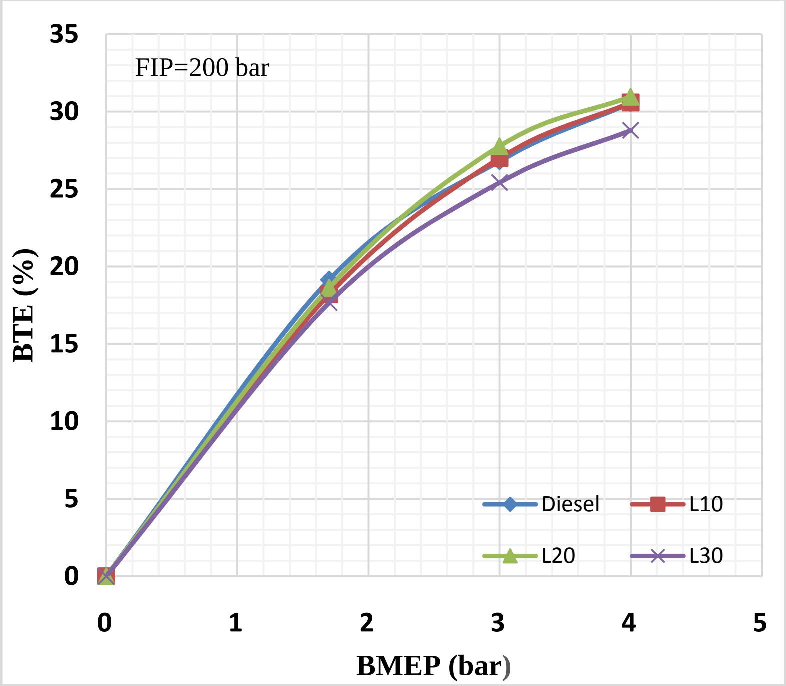
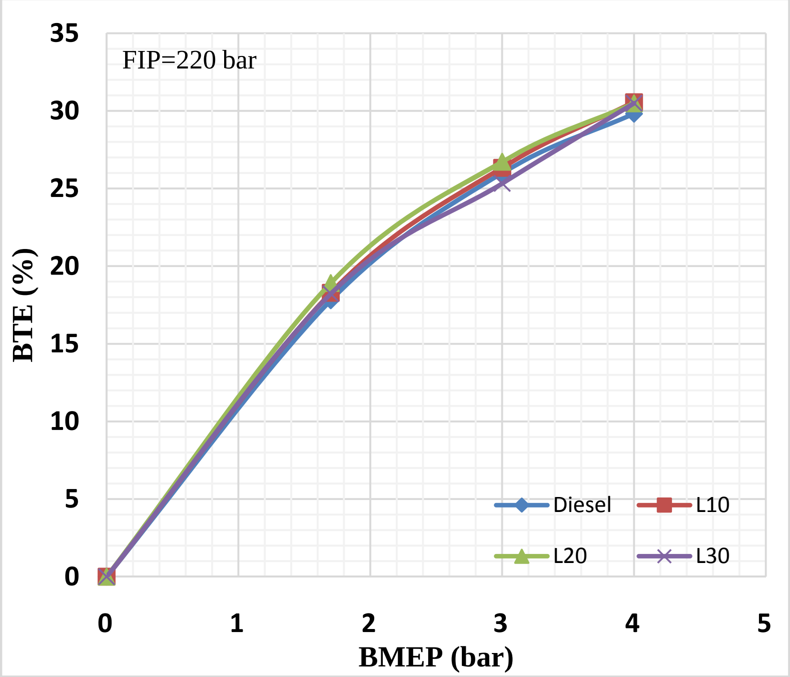


(c)

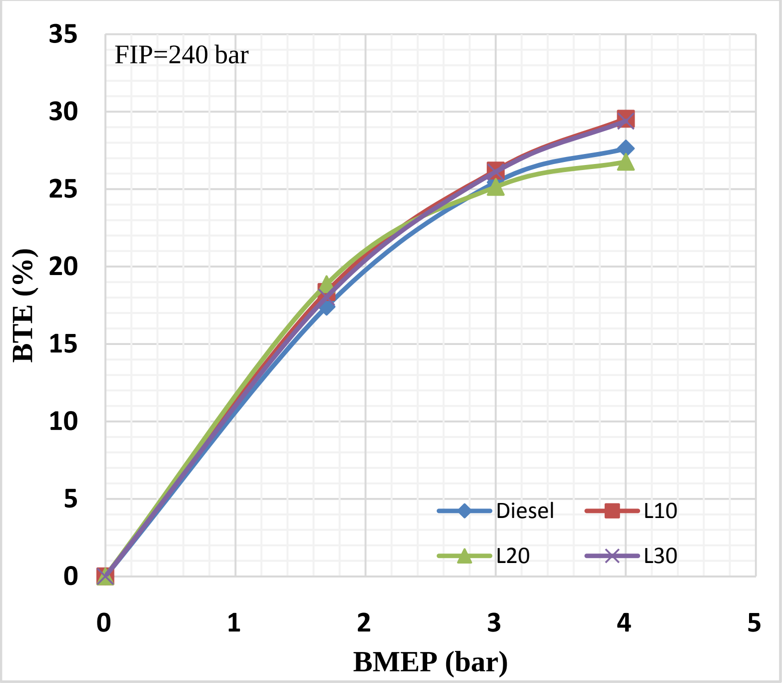
Fig. 4.BSEC variation with increased BMEP for the test fuels (a) at FIP 200 bar, (b) at FIP 220 bar, (c) at FIP 240 bar


FIP=200 bar
BTE (%)
BMEP (bar)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
Diesel
L10
L20
L30

(a)

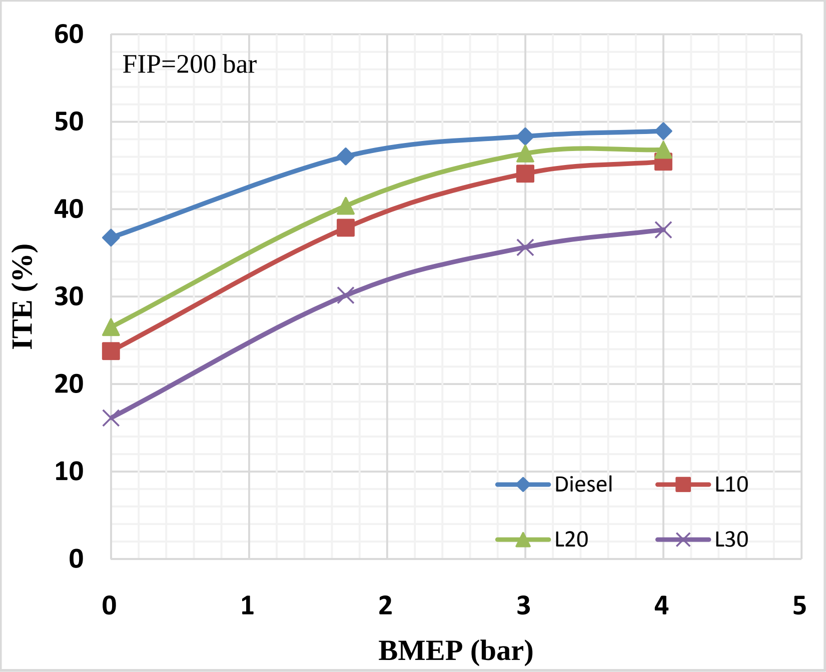

FIP=220 bar
BTE (%)
BMEP (bar)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
Diesel
L10
L20
L30

(b)

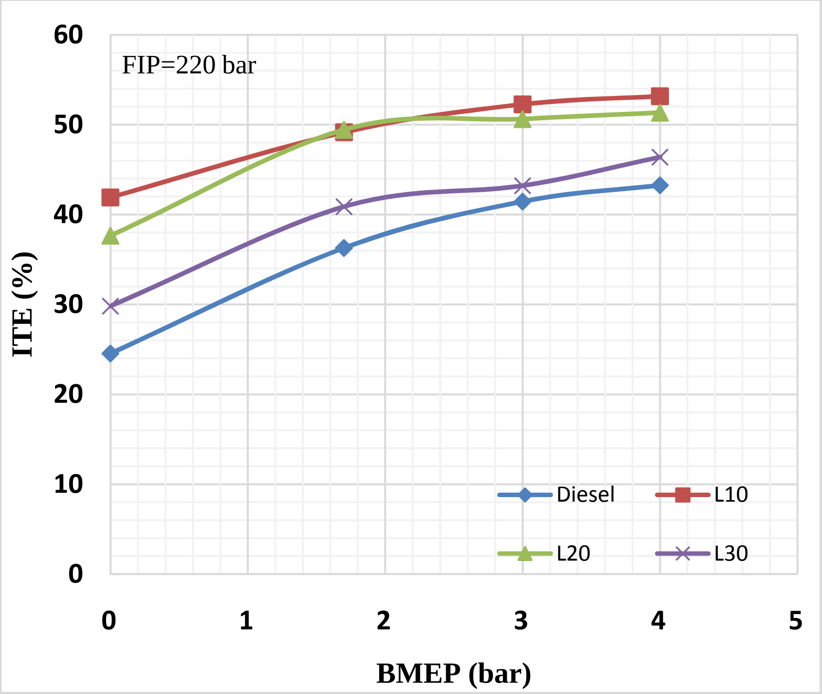


(c)

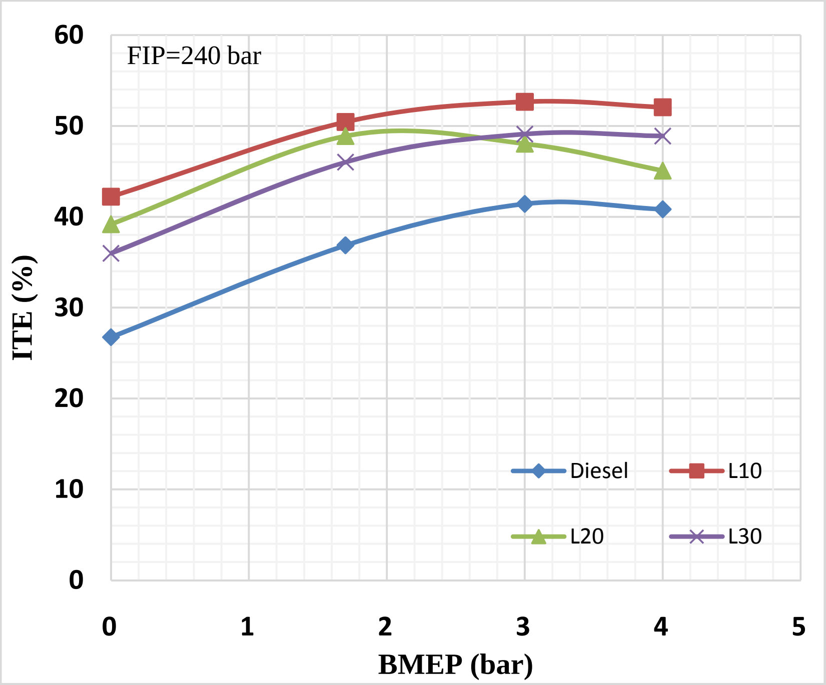
Fig.5.Variation of BTE with engine load for the test fuels (a) at FIP 200 bar, (b) at FIP 220 bar, (c) at FIP 240 bar



(a)

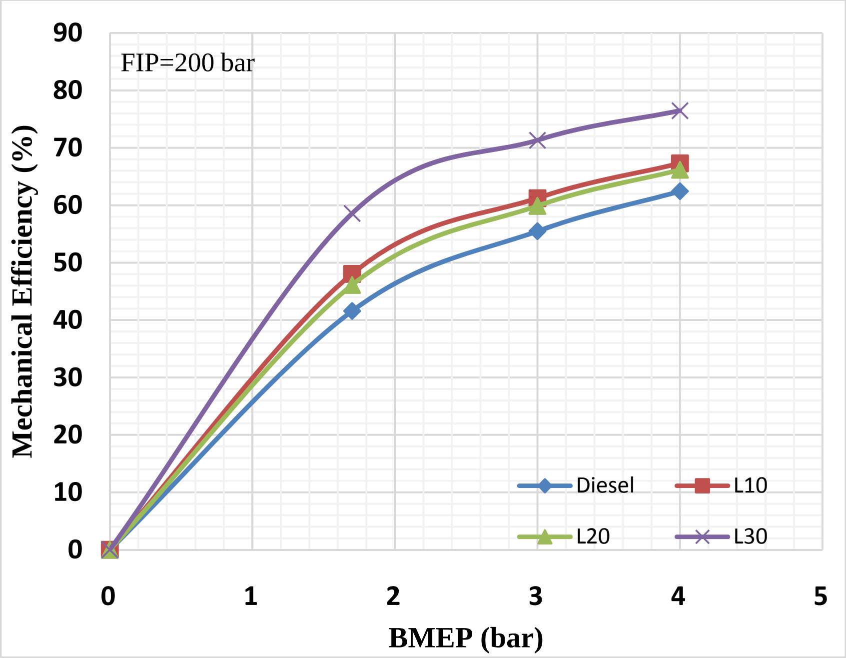


(b)

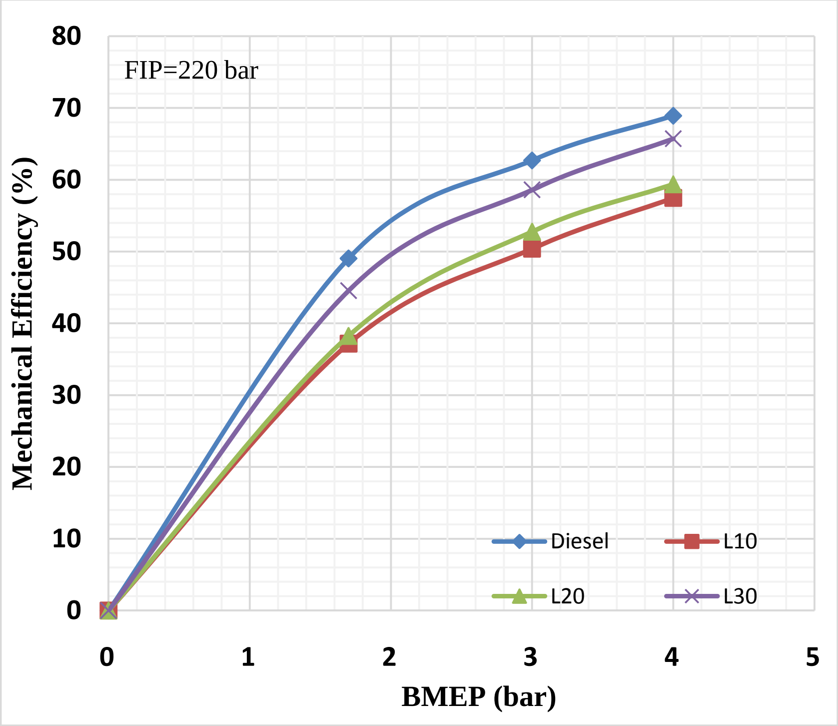


(c)

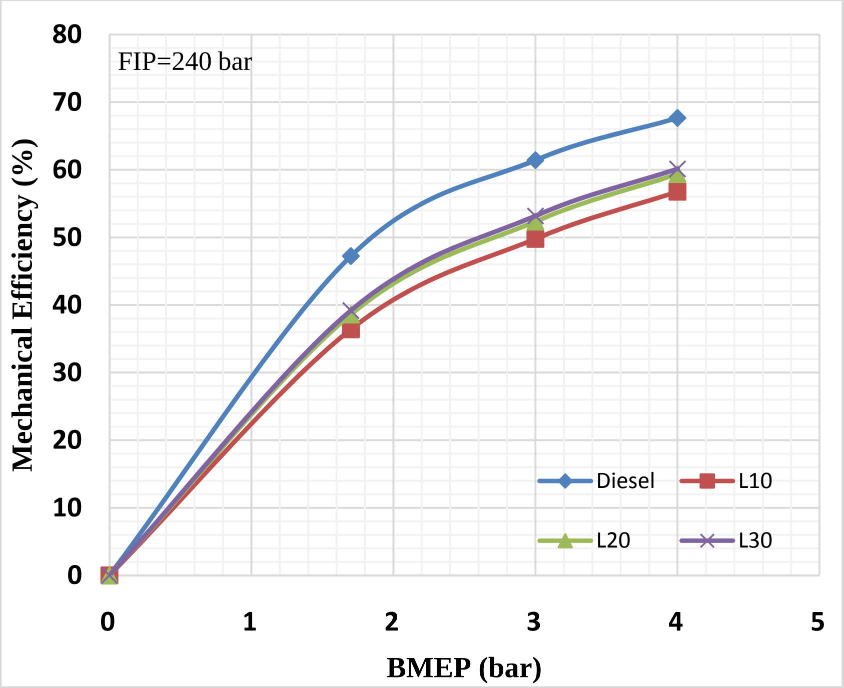
Fig. 6.Variation of ITE with BMEP for the test fuels (a) at FIP 200 bar, (b) at FIP 220 bar, (c) at FIP 240 bar


FIP=200 bar
Mechanical Efficiency (%)
BMEP (bar)
0
10
20
30
40
50
60
70
80
90
0
1
2
3
4
5
Diesel
L10
L20
L30

(a)

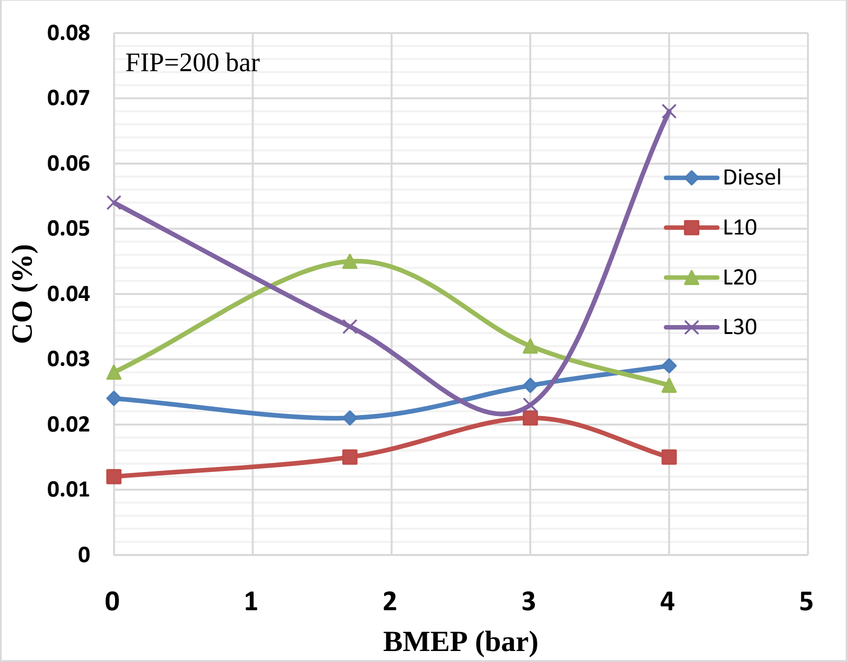

FIP=220 bar
Mechanical Efficiency (%)
BMEP (bar)
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
Diesel
L10
L20
L30

(b)

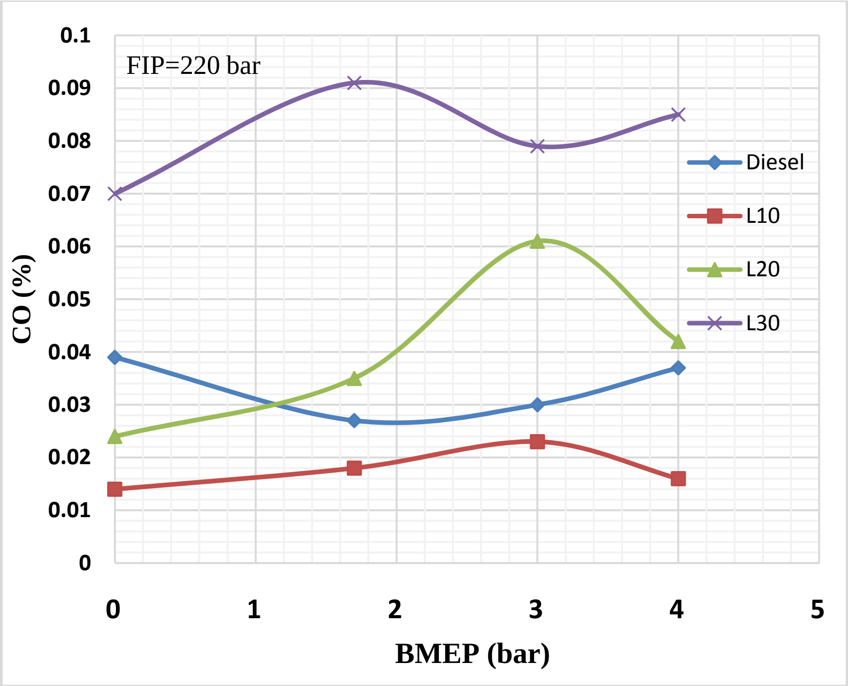


(c)

Fig. 7.Mechanical efficiency obtained at different BMEPs for the test fuels (a) at FIP 200 bar, (b) at 220 bar, (c) at 240 bar



(a)



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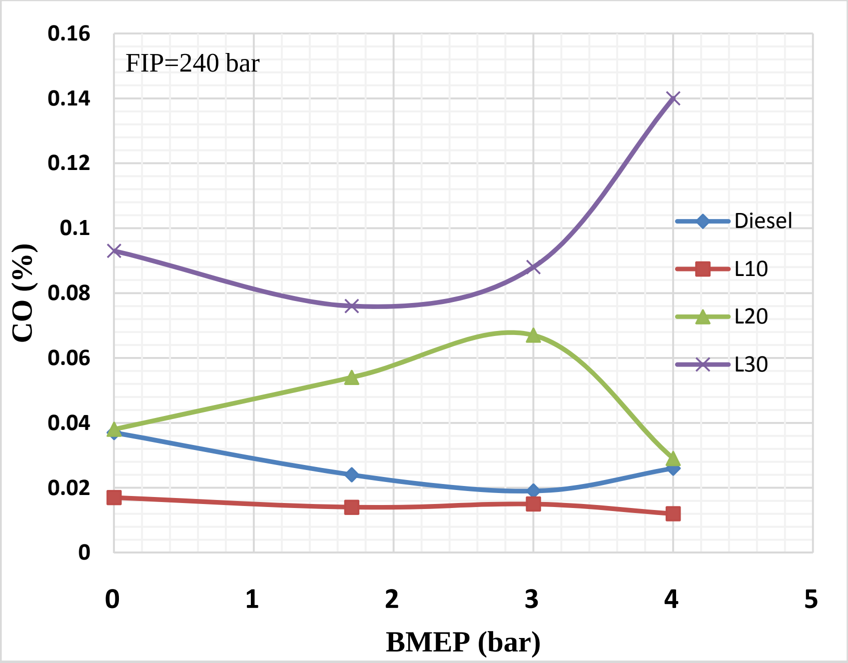
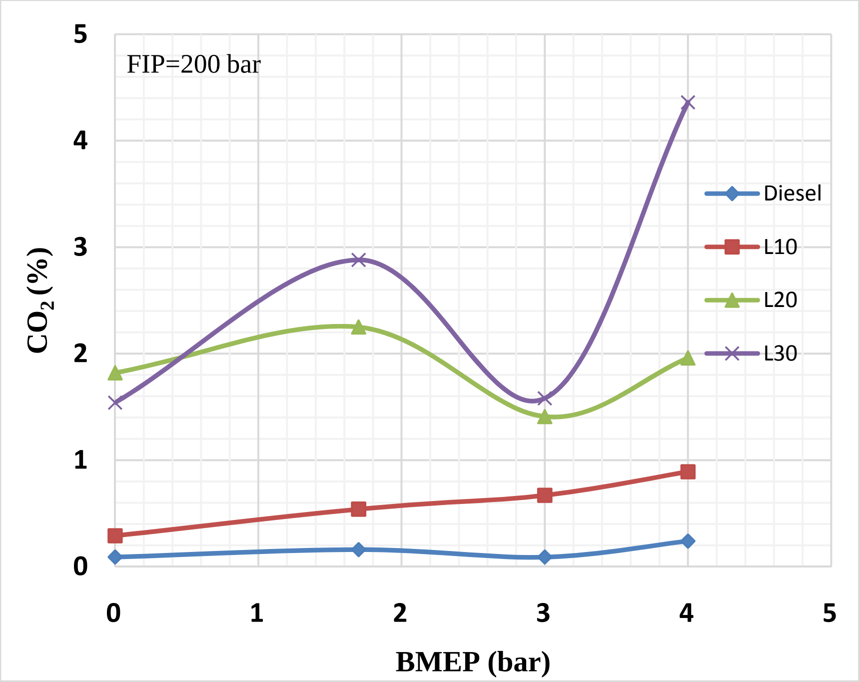
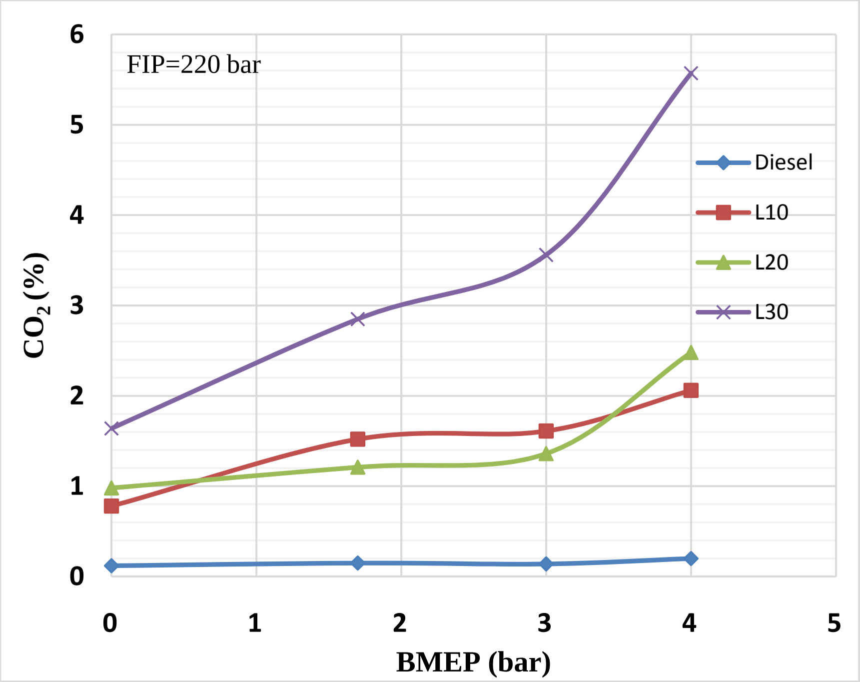


(c)

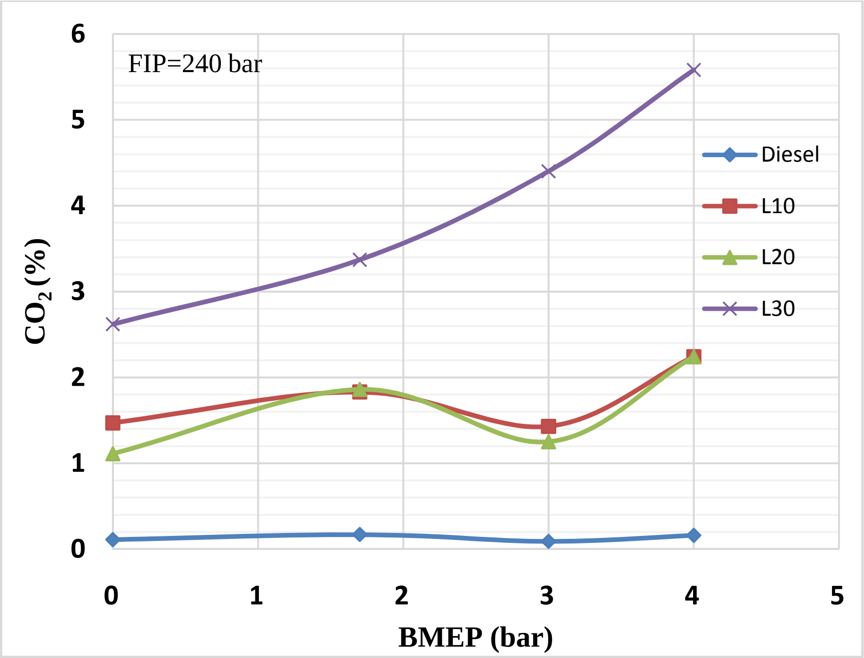
Fig. 8.CO emission values for the diesel and biodiesel blends with trend lines (a) at FIP 200 bar, (b) at FIP 220 bar, (c) at FIP 240 bar


FIP=200 bar
CO2 (%)
BMEP (bar)
0
1
2
3
4
5
Diesel
L10
L20
L30

(a)

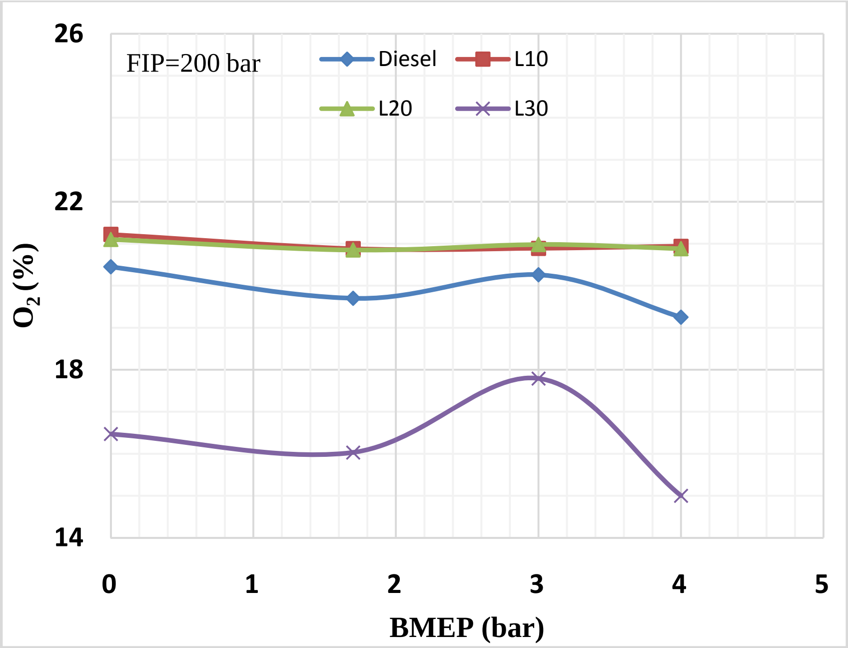

FIP=220 bar
CO2 (%)
BMEP (bar)
0
1
2
3
4
5
6
Diesel
L10
L20
L30

(b)

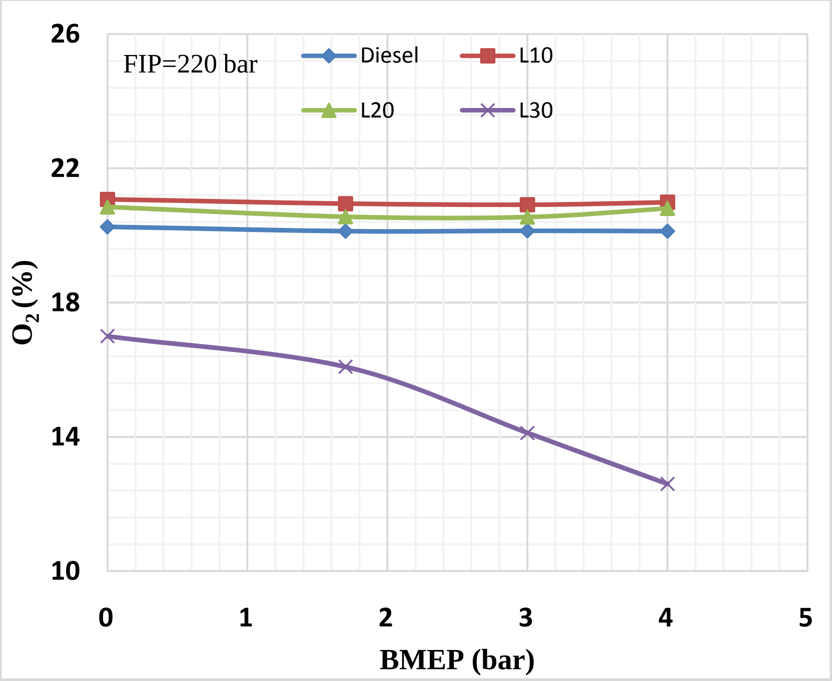


(c)

Fig. 9.CO_2 emission values for the diesel and biodiesel blends with trend lines (a) at FIP 200 bar, (b) at 220 bar, (c) at 240 bar



(a)



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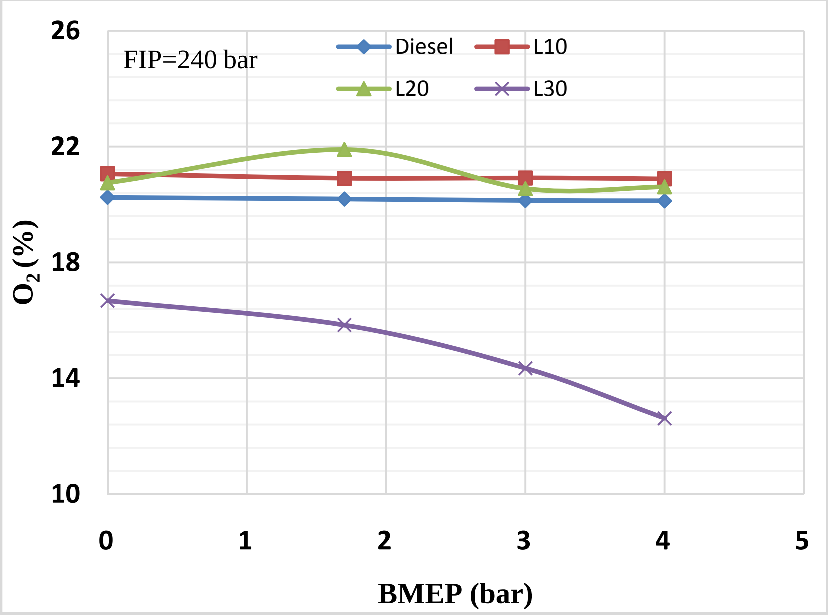

(c)

Fig. 10.O_2 emission values for the diesel and biodiesel blends with trend lines (a) at FIP 200 bar, (b) at 220 bar, (c) at 240 bar

IV. CONCLUSION

In this study, biodiesel was prepared from raw linseed oil through transesterification process and it was blended with mineral diesel in three concentration ratios of 10%, 20% and 30% (v/v). Later the effect of fuel injection pressure on the performance and exhaust emissions of a CI engine were experimentally investigated when the engine was fueled with biodiesel-diesel blends. The experimental data was compared with baseline mineral diesel. The important findings are as follows: BSEC for biodiesel blends is comparable to diesel fuel at all loads and injection pressures. At lowest FIP, diesel has shown least BSEC when compared to other test fuels. Highest FIP has led to decrease in BTE for all the test fuels except for L30. BTE is optimum for biodiesel blends at FIP 220 bar. For FIP 220 bar, L10 and L20 blends showed good ITE next to diesel. Diesel has shown highest mechanical efficiency at FIPs 220 and 240 bar. L30 has shown better mechanical efficiency at FIP 200 bar. Diesel is the least contributor of CO and CO_2 emissions when compared to biodiesel-diesel blends. Overall, the optimum FIP is found to be 220 bar and regarding blend wise L30 is considered to be better in getting mechanical efficiency.

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