Combustion and Emission Characteristics of a Compression-Ignition Engine fuelled with Transesterified-Jatropha Biodiesel-Diesel Blends

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Abstract- *Jatropha-curcas* biodiesel has recently been identified as a potential renewable energy source on the Asian continent. *Jatropha-curcas* biodiesel has similar properties to diesel oil. It can be produced from non-edible *Jatropha-curcas* to oil through the transesterification process. The paper experimentally investigates the combustion, performance, and exhaust emissions characteristics of a direct-injected compression-ignition engine fuelled with 25% (BD25), 50% (BD50), and 100% (BD100) volume basis *Jatropha-curcas* biodiesel with diesel. The experimental results showed that the Ignition Delay and Heat Release Rate during combustion were lower for *Jatropha-curcas* biodiesel and their blends than for diesel. *Jatropha-curcas* biodiesel and its blends also exhibited lower Brake Thermal Efficiency and Exhaust Emissions than diesel, except for Nitrogen-Oxides and Brake Specific Fuel Consumption. It was observed that the blend containing 25% *Jatropha-curcas* biodiesel (BD25) was the best alternative for diesel, based on the overall performance in terms of engine emissions and performance. Therefore, BD25 could be considered as a potential alternative fuel for compression-ignition engines.

Keywords *Jatropha-curcas;* Biodiesel; Diesel Engine; Thermal Efficiency; Emissions.

1. Introduction

The deepening fuel crisis, global warming, and related environmental issues have raised significant interest in the scientific community that has triggered the need to search for environment-friendly fuels, such as biofuel or vegetable oil, to sustain the high-quality fuel. Out of these, biodiesel holds the most potential owing to its similarity to mineral diesel oil [1]. Biofuels could be indirectly or directly extracted from various biomass sources. Biomass sources exist in the form of solid, liquid or gas. Moreover, biodiesel is mainly derived from fatty acid alkyl esters, edible or non-edible vegetable oils or waste greases [2].

Biodiesel molecules or methyl-esters contain a relatively high amount of oxygen, approximately 10-11% (by weight)) that is involved in the combustion process. These oxygenated biodiesel fuels can effectively improve combustion and reduce various emissions, such as unburned hydrocarbons (HC), particulate matter (PM), and carbon-monoxide (CO), in four-stroke compression-ignition (4S-CI) engines. Although these oxygen-rich fuels improve combustion temperature, they also lead to minor increase in NO_x emissions [3-4].

CI engines can be run on biodiesel with no or minor modifications. Biodiesel can be used both in pure form as well as in conjugation with the fossil fuels [5]. However, with respect to CI engines, biofuel imparts an advantage over conventional diesel, since it can be used both solo and as an additive without the requirement of any engine modifications [6]. Although, vegetable oil-derived fuels have high viscosity and low cetane number, volatility, and boiling point, the characteristics that are important for CI engines. Such properties of these fuels lead to incomplete combustion, engine deposits, higher exhaust emissions, and engine oil contamination, restricting the direct use of biofuels in CI engines [7-8].

There has been extensive research on combustion, emission, and performance of conventional 4S-CI engines when fuelled with raw or pure as well as the ethyl or methyl esters of vegetable oils derived from *Jatropha* [9-10], *Palm* [11-13], *Mahua* [14], *Karanja* [15-16], *Soybean* [17-19], and *Rapeseed* [20]. However, pure vegetable oils as fuels have been discouraged by various studies. The fuels spray pattern and atomization are adversely affected by high viscosity and low volatility of vegetable oils, causing incomplete fuel combustion, leading to several problems, such as carbon deposition, injector coking, fuel pump failure, and piston ring sticking. Previous studies have proposed various techniques that decrease the vegetable oil viscosity, such as blending, transesterification, and pyrolysis [21]. Among them, transesterification is most effective to produce biodiesel and lower the viscosity of vegetable oil [1].

Jatropha biodiesel has attractive potential and advantages because it has the same characteristics as diesel fuel and is environmental-friendly. Previous literature has shown that biodiesel decreases the carbon monoxide, particulate matter, and hydrocarbon emissions in CI engines; however, it increases NO_x emissions. However, high oxygen levels in biodiesel raises the combustion temperature causing higher NO_x emissions [22-23].

According to Puhan et al. [14], the use of *mahua* oil ethyl-ester biodiesel led to an increase in BSFC than when diesel was used. In addition, with a mild increase of 0.22% in BTE, the HC, NO_x, Smoke, and CO emissions decreased by 63%, 12%, 70%, and 58%, respectively. While using the animal fat-ethanol blends [24-25] and *methanol* [26] blends of Jatropha biodiesel oil in CI engine under high loading conditions, Kerihuel et al. reported that the HC, Smoke, and CO emissions decreased significantly compared to when pure fat or diesel was used.

Nursal et al. [27] performed experimental investigations with three kinds of biodiesels, *Jatropha-curcas* oil (JCO), *crude palm* oil (CPO), and *waste cooking* oil (WCO), in a direct-injected CI engine. Studies were carried out at 5% blending ratios under 0%, 50%, and 90% loading conditions at engine speeds of 800, 1200, 1600, and 2000 rpm. Studies showed that *Palm* and *Jatropha* biodiesel increased, and WCO decreased overall engine performance. Moreover, compared to diesel, fuel economy and brake thermal efficiency improved mildly, and exhaust emissions reduced. In addition, CPO reduced CO_2, HC, and CO emissions, JCO mildly increased NO_x, CO_2, and HC emissions, and WCO increased CO_2, NO_x, and CO emissions.

Nayyar et al. [28] tested various blends of diesel and n-butanol on CI engine employed in agricultural applications. Also, optimization was carried out using the Taguchi method for blends of diesel and n-butanol in the ratio (10–20% by volume) and compression ratio varying between 17.5-19.5, injection pressures varying between 200-220 bar and injection timing from 21 to 25 crank angle btdc. Subsequently, optimized results were verified with experiments; improved performance and emission level were recorded with increasing compression ratios. Further, reduction in NO_x, CO and Smoke were reported to be 13.68%, 49.03% and 5.88%, respectively in comparison with diesel. However, an increase of 11.76% was found in HC as opposed to diesel.

Patel et al. [29] performed experiments on biodiesels such as *Jatropha*, *Karanja* and *Waste cooking* oil for operating conditions with varying loads and a constant speed of 1500 rpm. *Waste cooking* oil resulted in the increased rate of release of thermal energy as compared to other biodiesels. Reduction in HC and NO_x emission was noticed in biodiesels as compared to mineral diesel oil.

Thus, biodiesel has shown a high potential for 4S-CI engines, but further in-depth analysis of engine performance is still needed. However, very limited literature is available on the combustion performance of the engine. Therefore, this research focuses on the investigation and performance evaluation of CI engine run on *Jatropha-curcas* biodiesel.

2. Methods and Materials

In India, approximately 200,000 metric tons of *Jatropha-curcas* biodiesel are produced each year. It grows well in barren mountains and wastelands. It is an excellent renewable energy source with high seed oil productivity. To elucidate the potential of *Jatropha* oil, thermal release rate of a diesel engine running on *Jatropha-curcas* oil needs to be studied [28][30]. The *Jatropha* biodiesel is produced from raw seeds using transesterification. It has been widely accepted worldwide for the production of biodiesel. *Jatropha* kernel possesses about 63.16% oil content [26], which is higher compared to the oil contents in *Palm* Kernel (44.6%), *Linseed* (33.33%), and *Soybean* (18.35%) [31]. Hence, *Jatropha-curcas* biodiesel could be the most viable biodiesel, being more economical with respect to chemical composition or oil content. The fuel properties of diesel, *Jatropha-curcas* biodiesel, and their blends have been determined as per ASTM standards and procedures, which are tabulated in Table 1. Density, cloud point, and pour point of *Jatropha-curcas* biodiesel is found higher than diesel oil. Higher cloud reflects the unsuitability of *Jatropha-curcas* biodiesel as diesel fuel in cold climatic conditions. The flash point of biodiesel is relatively high compared to diesel. Hence, *Jatropha-curcas* biodiesel is highly safe to handle.

Table 1. Properties of Diesel, Jatropha-curcas biodiesel, and their blends

Test Fuel	Kinematic viscosity (cSt)	Density (kg/m^3)	Calorific value (MJ/kg)	Flash Point (°C)	Cloud Point (°C)
D	2.9	850	44	76	6.5
BD25	3.12	851	43.78	85	6.8
BD50	3.59	857	43.33	113	7.3
BD100	4.18	873	42.73	148	10.2

2.1. Transesterification Process

Some basic tests, such as free fatty acid content, iodine value, and moisture content, were performed prior to the transesterification process. This was achieved to ensure that the biodiesel yield was of high quality after the reaction. The biodiesel was produced using standard materials and under standard conditions, resulting in a trouble-free process. Transesterification refers to the reaction between an alcohol and a vegetable oil that leads to the formation of alkyl esters along with glycerol as a by-product. The reaction is catalyzed by a catalyst, e.g. potassium hydroxide or sodium hydroxide. Here, transesterification was used to produce biodiesel from *Jatropha* oil. *Jatropha* biodiesel was produced by reacting *Jatropha* oil (one litre) with methanol (0.2 liter) in the presence of potassium hydroxide (6.90 gram). This process focuses on the two stage synthesis of biodiesel from higher fatty acid *Jatropha-curcas* oil, its purification using organic adsorbents and some natural adsorbents.

3. Test Equipment

For this study, we used a Kirloskar-make, vertical, single-cylinder, naturally aspirated four-stroke, direct-injection, air-cooled, constant speed, compression-ignition engine. Figure 1 and Figure 2 show the experimental test-setup and schematic diagram of the 4S-CI test-setup, respectively. An Eddy Current type dynamometer (Model-AG10) was attached to the test-setup. The thermocouple monitored the exhaust gas temperature. This type of CI engine widely is used in the agriculture field in India. Table 2 list the detailed specifications and working conditions of the test-setup.

Fig. 1. Photograph of 4S-CI test-setup

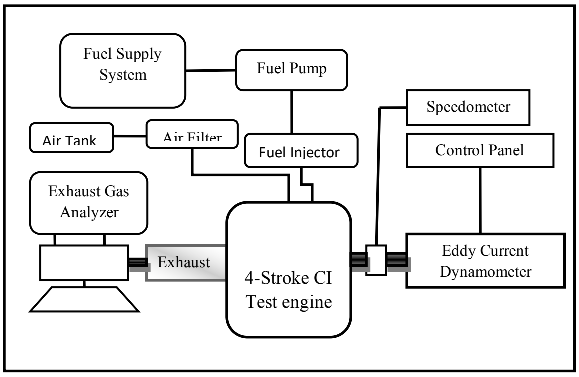

Fig. 2. Schematic diagram of 4S-CI test-setup

Table 2. Engine Specification

Type of Engine, Make	4-Stroke, Direct-injected, Kirloskar Diesel Engine
Mode of cooling	Air-Cooled
Engine Rated Power and Speed	6 HP, at 1500 rpm
Cylinder Number	1
Compression Ratio	17.5:1
Cylinder Bore	87.5 mm
Cylinder Stroke	110 mm
Injection Pressure	21 MPa
Nozzle Hole Diameter	0.28 mm
Injection Timing	23 °BTDC
Dynamometer	Eddy Current Type

4. Test Procedures

Engine emission and performance tests were conducted using *Jatropha* biodiesel and its blends at various load conditions. The engine was operated on standard conditions set by recommended manufacturers. All test fuels were injected at injection timing and pressure 23°BTDC and 21MPa, respectively. These emission and performance values were defined as baseline values during the experiment compared to the results obtained from tests with different test fuel and load conditions. Engine tests were conducted at a constant engine speed of 1500 rpm under varying loads of 0%, 25%, 50%, 75%, and 100%. The exhaust gas temperature was measured using the thermocouple. HC, NO_x, and CO emissions were monitored using the AVL-make CDS-250) exhaust gas analyzer. The smoke intensity was analyzed using the Bosch smoke meter, in which the smoke sample was collected via a smoke sampling pump using a filter paper.

5. Results and Discussion

5.1. Effect of Engine Load on Brake Thermal Efficiency (BTE)

Brake thermal efficiency refers to the work output generated by the engine at the expense of fuel-mediated chemical energy [32]. Figure 3 shows the variation in BTE against brake power in the presence of various *Jatropha* biodiesel and diesel blends. The presence of oxygen in fuel improves combustion properties but reduces the calorific value of the fuel. *Jatropha* biodiesel has approximately about 90% calorific value compared to diesel. BTE was lower in the presence of pure BD100 and its blends as compared to BTE in the presence of diesel at all load conditions.

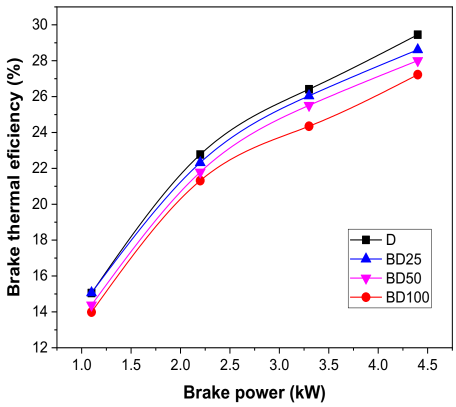

Fig. 3. Effect of engine load on BTE using CI engine in different test fuels

Highest BTE was observed at 4.4 kW power with diesel fuel. BTE for BD25 blend was comparable to BTE for diesel. At full load, the brake thermal efficiencies for BD25, BD50 and BD100 were lower by 2.84%, 4.89% and 7.54%, respectively, compared to diesel. These observations could be attributed to higher viscosity and density and lower calorific values of *Jatropha* biodiesel. Also, Avinash et al. [7] confirmed this observation.

5.2. Effect of Engine Load on Brake Specific Fuel Consumption (BSFC)

The ratio of consumed fuel mass to power of the brake is referred to as the BSFC [32]. BSFC indicates an engine's fuel efficiency. Figure 4 depicts the BSFCs for different fuels. The results showed that BSFC reduced as the brake power increased. BD25 had the lowest BSFC compared to that of BD50. However, it was 7.14% higher than that obtained with diesel. Pure BD100 exhibited the highest BSFC compared to its blends and was about 21.43% higher than the BSFC of pure diesel. For full load, BSFCs of BD25, BD50 and BD100 were 0.30 kg/kW-h, 0.32 kg/kW-h and 0.34 kg/kW-h, respectively, whereas it was 0.28 kg/kW-h for diesel. This result could be due to the lower calorific value of biodiesel blends; the same is also confirmed by Kumar et al. [26].

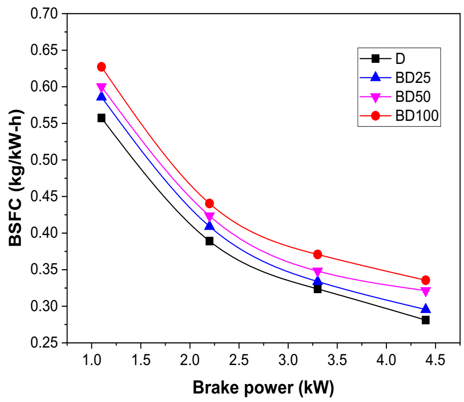

Fig. 4. Effect of engine load on BSFC using CI engine in different test fuels

5.3. Effect of Engine Load on Hydrocarbon (HC) Emission

Hydrocarbons are produced by the incomplete combustion processes that may occur during the working of an IC engine. The engine load effect in the presence of various fuels on HC emissions is shown in Figure 5. The results indicated that higher load led to a higher HC emission for all fuels due to fuel-rich mixtures. For lower load, higher *Jatropha* biodiesel content in the blends led to increased HC emission. These results were attributed to lower viscosity and wider dispersion in the combustion chamber for blends with higher *Jatropha* biodiesel content. For full load, the use of diesel led to maximum HC emission, and the use of BD25, BD50 and BD100 led to a reduction in HC emissions of 18.5%, 48.2%, and 57.7%, respectively. An increase in the *Jatropha* biodiesel level of blend significantly decreased the emission of unburned HC, which could be due to higher oxygen levels in biodiesel, leading to a higher combustion temperature that triggers HC oxidation. The lowest HC emissions were observed in the presence of pure BD100.

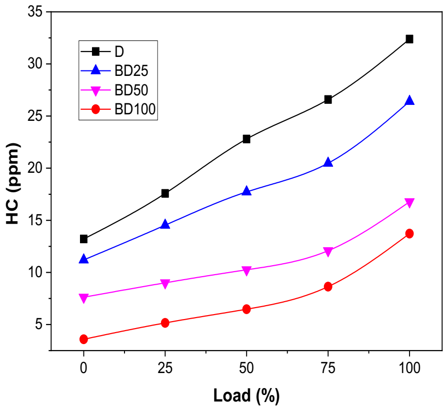

Fig. 5. Effect of engine load on HC emission using CI engine in different test fuels

5.4. Effect of Engine Load on Carbon Monoxide (CO) Emission

Carbon monoxide is an air pollutant that is produced when carbon-containing fuels are incompletely combusted. CO is a strong respiratory irritant. The quality of the combustible fuel determines the CO formation. The high enriched mixture produces high CO, while the lean fuel mixture produces low CO emission. In a diesel engine, combustion is accompanied by a lean mixture and contains a lot of oxygen, which lowers CO emission [33].

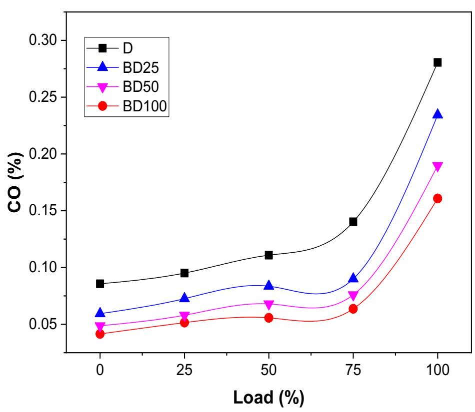

Fig. 6. Effect of engine load on CO emission using CI engine in different test fuels

The effect of load on CO emission due to various fuels is shown in Figure 6. For all load conditions, CO emission decreased with increase in the *Jatropha* biodiesel content. The least CO emissions were observed in the presence of pure BD100, and the highest CO emissions were observed in the presence of pure diesel. The use of BD25, BD50 and BD100 led to a decrease in CO emissions by 16.5%, 32.4%, and 42.7%, respectively.

5.5. Effect of Engine Load on Emission of Nitrogen Oxides (NOx)

A diesel engine operates at a higher temperature and pressure as compared to a petrol engine, which promotes NO_x formation. The duration and volume of the hottest part of the flame determines the level of NO_x, due to which diesel engine produces more NO_x as compared to petrol engines. The high temperature of combustion chamber also contributes to the generation of NO_x [32]. The effect of engine load on NO_x emission in the presence of various fuels is shown in Figure 7. As shown in the figure, NO_x emission increased with increase in *Jatropha* biodiesel content. The NO_x emissions in the presence of BD25, BD50 and BD100 fuel blends increased by 4%, 19% and 26%, respectively, than that in the presence of diesel. These observations could be due to the higher oxygen level in the biodiesel, which causes rapid combustion leading to the rapid increase in in-cylinder pressure and temperature. This leads to higher NO_x emission.

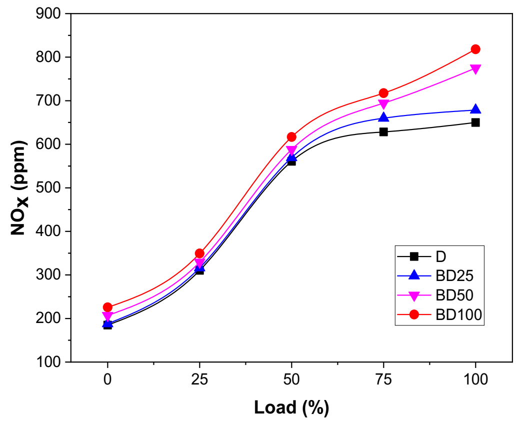

Fig. 7. Effect of engine load on NO_x using CI engine in different test fuels

5.6. Effect of Engine Load on Smoke Intensity Emission

The carbon in the exhaust gases refers to smoke. Figure 8 depicts the smoke emissions due to various fuels with respect to increasing load. For all load conditions, higher *Jatropha* biodiesel levels in the fuel led to reduced smoke emissions. At full load, smoke emissions in the presence of BD25, BD50 and BD100 decreased by 21%, 47.2%, and 57%, respectively, than that in presence of diesel. The least smoke emission was observed in the presence of pure BD100 at full load conditions. *Jatropha* biodiesel and its blends significantly reduced smoke emission at all load conditions, due to better combustion of these fuels.

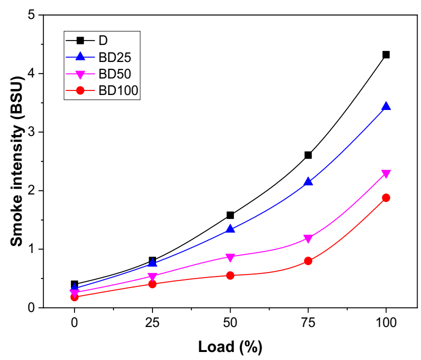

Fig. 8. Effect of engine load on smoke intensity emission using CI engine in different test fuels

5.7. Effect of Engine Load on Ignition Delay

Ignition delay of fuel determines the knocking properties of the CI engine. Ignition delay is directly dependent on the fuel's cetane number, the indication of its self-ignition ability. Biofuels have high cetane number leading to a decreased ignition delay than conventional diesel. Ignition delay has been observed to be inversely proportional to its cetane number. In turn, an engine's combustion performance is affected by such ignition delay. Hence, engine performance can be improved by optimizing the ignition delay [34-35]. Figure 9 shows ignition delay due to various fuels. The ignition delay period due to *Jatropha* biodiesel and its blends was much shorter than that in presence of diesel. Increase in *Jatropha* biodiesel content in the blends, as well as increased loads, lead to lower ignition delay periods. At full load, ignition delays due to BD25, BD50 and BD100 were 1.95 °CA, 3.15 °CA and 5.67 °CA shorter, respectively, than that due to conventional diesel. This could be because the methyl-esters in the fuel split into smaller compounds while entering into the combustion chamber, leading to wider spray angles and, in turn, more rapid ignition. Thus, *Jatropha* biodiesel and its blends had higher cetane numbers compared to diesel.

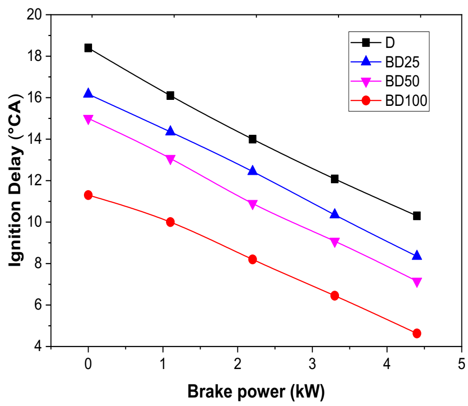

Fig. 9. Effect of engine load on ignition delay period due to different test fuels

Furthermore, the ignition delay is also affected significantly by engine load. Increase in engine load raises the in-cylinder gas temperature that lowers the ignition delay period. This result was attributed to lower exhaust gas dilution and higher combustion chamber wall temperature at greater loads.

5.8. Effect of Engine Load on Exhaust Gas Temperature

The exhaust gas temperature is directly related to how well the engine itself is working. Gasoline and diesel fuel-powered vehicles have specific temperature ranges that the exhaust must remain within for the components to function correctly. Figure 10 shows exhaust gas temperature variation against load in presence of different *Jatropha* biodiesel blends. With increase in *Jatropha* biodiesel level, the exhaust gas temperature increased. These results could be attributed to higher oxygen level of *Jatropha* biodiesel that enhances combustion, which increases exhaust gas temperature. The exhaust gas temperatures for diesel, BD25, BD50, and BD100 were 408.93 °C, 412.18 °C, 424.23 °C and 447.69°C, respectively, at full load.

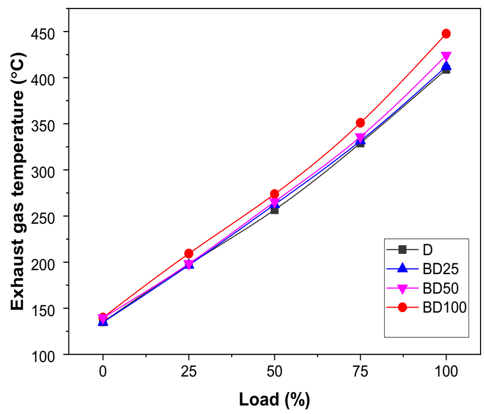

Fig. 10. Effect of engine load on exhaust gas temperature variation due to different test fuels

5.9. Heat Release Rate (HRR)

Figure 11 shows the heat release rate (HRR) per degree of crank angle. HRR decreased with increase in *Jatropha* biodiesel content. These results could be due to higher cetane number and lower ignition delay period of *Jatropha* biodiesel. The highest heat release rate (90.72 J/degCA) for diesel was observed at 6 °bTDC, while for BD25, BD50, and BD100, HRRs were 79.24, 75 J/degCA and 68.35at 8 °bTDC, respectively. Higher *Jatropha* content in blends led to a decreased HRR at an increased crank angle.

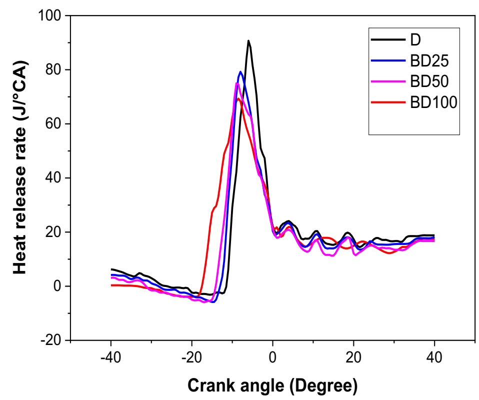

Fig. 11. Heat release rate due to different test fuels

5.10. Peak Cylinder Gas Pressure

As shown in Figure 12, the higher load led to a higher peak cylinder gas pressure because with increase in load, higher amount of fuel needs to burn. Furthermore, for all load conditions, the peak pressure increased mildly with increase in *Jatropha* biodiesel content of blends. For full load, diesel, BD25, BD50 and BD100 exhibited peak pressures of 61.97 bar, 62.23 bar, 63.22 bar, and 64 bar, respectively. The results could be attributed to higher oxygen level in *Jatropha* biodiesel, leading to lower ignition delay with an increase in *Jatropha* content.

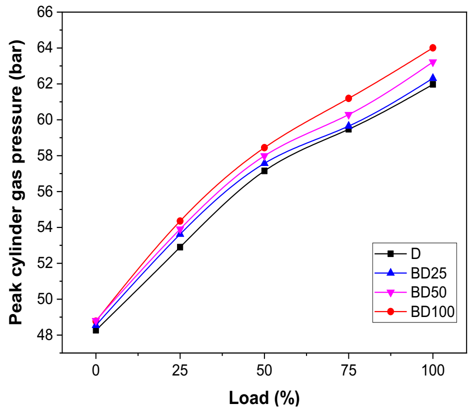

Fig. 12. Peak cylinder gas pressure due to different test fuels

4. Conclusions

A comprehensive experimental study was carried out to compare, analyze and evaluate the combustion characteristics, exhaust emissions and performance of *Jatropha* biodiesel blends with diesel in a 4S-CI engine. The major conclusions of this research are as follows:

➢ Increasing the Jatropha biodiesel content reduces BTE. The maximum BTE has been observed at full load conditions using only diesel. At full load, BTE is found 8.16 % higher than pure BD100 in diesel and 2.16% higher than BD50 in BD25.

➢ Increasing the Jatropha biodiesel content increases BSFC. BSFC is found 16.2% lower than pure BD100 in diesel and 8.02% higher than BD50 in BD25. BSFC of BD25 was comparable to that of pure diesel.

➢ The use of Jatropha biodiesel and the blends led to a lower ignition delay and lower heat release rate. At full load, the ignition delay is found 55.05% lower than diesel in pure BD100 and 16.78% higher than BD50 in BD25. Also, the heat release rate is found 24.66% lower than diesel in pure BD100 and 5.66% higher than BD50 in BD25.

➢ The exhaust gas temperature and peak cylinder gas pressure are considerably improved with the increase in Jatropha biodiesel content compared to the diesel at all load conditions. At full load, exhaust gas temperature is found 9.49% higher than diesel in pure BD100 and 2.83% lower than BD50 in BD25. In addition, the peak cylinder gas pressure is found 3.28% higher than diesel in pure BD100, and 1.43% is lower than BD50 in BD25 at full load.

➢ Higher Jatropha biodiesel content led to a decreased level of unburned HC emission. HC is found 57.64% higher than pure BD100 in diesel and 57.36% higher than BD50 in BD25 at full load.

➢ Higher Jatropha biodiesel content led to a decreased level of CO emission. CO is found 42.7% higher than pure BD100 in diesel and 19.05% higher than BD50 in BD25 at full load.

➢ Higher Jatropha biodiesel content led to a decreased level of Smoke emission. Smoke intensity is found 56.54 % lower than diesel in pure BD100 and 48.87% higher than BD50 in BD25 at full load.

➢ Higher Jatropha biodiesel content in the blends led to an increase in NOx emission. NOx is found 25.88% higher than diesel in pure BD100 and 12.43% lower than BD50 in BD25 at full load. In addition, for all fuels, the CO, HC, and NOx emissions as well as the Smoke levels, increased with higher engine load.

➢ These above results indicated that the Jatropha biodiesel and its blends are suitable for the engine operation. Consequently, the Jatropha biodiesel blends BD25 can be considered as a possible alternative fuel without major engine modifications.

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