Chapter 4

Experimental Study

An experimental study is conducted to evaluate the thermal performance and emission constituents and combustion analysis of a Karanja biodiesel fuelled variable compression ratio diesel engine. Section 4.1 includes the procedure for evaluation of thermal performance emission constituents and combustion analysis. The results and discussions are presented in Section 4.2. A brief of summary of the experimental investigations is given in section 4.3. In the discussions to follow Diesel, diesel refers to Diesel oil only as fuel.

4.1 Experimental Procedure

The experimental procedure followed in the present study is divided into three different programs viz. thermal performance evaluation, emission characteristics evaluation and Combustion Analysis. The experimental procedure followed for thermal performance evaluation is explained in Section 4.1.1 which is followed by emission characteristic evaluation in Section 4.1.2. The procedure followed for conducting combustion analysis is dealt in Section 4.1.3. Sections 4.1.1 and 4.1.2 are further subdivided into three sections which include the procedures for validation of the test set up using Diesel oil alone as fuel, followed by the procedures using Karanja biodiesel , blends of Karanja biodiesel and Diesel oil as fuels. Section 4.1.3 consists of two more sections which explain procedures for Combustion Analysis using first Diesel oil and then using Karanja biodiesel as fuels. Readings are recorded with repeat trials to ensure the accuracy of the data recorded.

4.1.1 Thermal Performance

Thermal Performance Evaluation is carried out in three different experimental programs:

1. With Diesel oil as fuel at different preset compression ratios, Loads and injection pressures each time keeping any two of the parameters a constant and varying the other.
2. With Karanja biodiesel as fuel following similar condition as in 1.

3. With blends of Karanja biodiesel and diesel as fuel following similar conditions as in 1. The blend proportions used to conduct the experiments are B20, B40, B60 and B80. B20 corresponds to a blend with 20% of Karanja biodiesel and 80% Diesel oil by volume. The blends are prepared by direct mixing of both the fuels in required proportions.

The first experimental program is a validation test(for ensuring the preparedness of the experimental test setup). The experimental procedure undertaken for conducting the validation test, thermal performance evaluation using Karanja biodiesel and blends of Karanja biodiesel with diesel are explained in detail in Sections 4.1.1.1, 4.1.1.2 and 4.1.1.3 respectively. The Diesel oil and Karanja biodiesel used during the study are obtained from the same lot acquired for the purpose and from the same source to ensure consistency in their properties.

4.1.1.1 Validation Test

A validation test is conducted using Diesel oil as fuel. The following step by step procedure is adopted for the test:

1. Check the lubrication, cooling and fuel systems of the engine for their adequacy.
2. Switch ON the electric supply and ensure that all digital and electric instruments are ON.
3. Start the engine and run under idling condition (no load) for 10 minutes to ensure warm and steady operating conditions.
4. Set the compression ratio at a selected value (say 14) using the tilting block arrangement for the engine.
5. Set the injection pressure at a selected value (say 150 bar) using the nut provided on the cylinder head near fuel injection line.
6. Record all the thermal performance parameters for no load condition through a data acquisition system interfaced with the computer. A commercial software, "Enginesoft LV" is used to interface, record and analyze the data.
7. Adjust the load for 3kg using the loading unit dimmerstat and wait for 3 minutes for engine to get stabilized. Repeat step 6 to ensure correctness & reliability/ repeatability of the data recorded.
8. Repeat step 6 for different loads viz. 6kg, 9kg and 12kg.
9. Repeat the steps 4 to 8 for different compression ratios viz. 15, 16, 17, 17.5 and 18.

10. Repeat the steps 4 to 9 for different injection pressures viz. 200 bar and 250 bar.
11. After all readings are recorded, bring down the loading condition to 'no load' before stopping the engine. The water is allowed to circulate for about 5 minutes for engine cooling and then the pump is stopped.

4.1.1.2 Karanja Biodiesel

The procedure followed for conducting the experiment using Karanja biodiesel is the same as explained in Section 4.1.1.1 except that Karanja biodiesel is to replace Diesel oil as fuel. The Karanja biodiesel used to conduct the experiments is commercially procured from MINT BIOFUELS, Pune. The properties of the Karanja biodiesel provided by the manufacturer are shown in Table 4.1. It compares the properties of Karanja biodiesel with different standards. It is clear that the properties of Karanja biodiesel used for the present study confirm to the different set standards. Various methods used to synthesize biodiesels developed by various investigators are explained in Appendix VI.

Table 4.1 Properties of Karanja Biodiesel (Courtesy Mint Biofuels)

Property	Unit	Value	ASTM D 6751 – 09 Standards	EN Standard	BIS Standards
Kinematic Viscosity @ 40 ^{0}C	Cst	5.21	1.9 - 6.0	3.5 – 5	2.5 – 6
Flash point	^{0}C	160	130 min	120 min	120 min
Density @ 15 ^{0}C	Kg/cu m	874	Not mentioned	860 – 900	860 – 900
Water and sediments	% volume	< 0.05	0.05 max	0.05 max	0.05 max
Free Glycerin	% mass	0.012	0.02 max	0.02 max	0.02 max
Total Glycerin	% mass	0.18	0.24 max	0.25 max	0.25 max
Copper strip corrosion		Class 1	No 3 max	Class 1	Class 1
Carbon Residue (100%) Sample	% mass	0.028	0.05 max	0.3 max	0.05 max
Acid Number	mgKOH/gm	< 0.5	0.5 max	0.5 max	0.5 max
Calorific Value	kJ/kg	38874 – 39710	Not Mentioned	Not mentioned	Not mentioned
Cetane number		55*	47 min	Not mentioned	Not mentioned

No definite colour for biodiesel is specified by International standards. Colour is feed dependent.
*Cetane number for Diesel oil is 47.

4.1.1.3 Blends of Karanja Biodiesel and Diesel

The procedure followed for conducting the experiment using blends of Karanja biodiesel and diesel is same as explained in Section 4.1.1.1 except that blends of Karanja biodiesel and diesel is to replace Karanja biodiesel as fuel. The blends selected for the experimental study are B20, B40, B60 or B80. Table 4.2 gives the properties of different tested fuels.

Table 4.2 Properties of Different Tested Fuels

Tested fuels	Calorific Value (kJ/kg)	Density (kg/cu m)
Diesel oil	42000	830
B20	41458	839
B40	40917	847
B60	40375	856
B80	39834	865
B100	39292	874

Properties for Diesel oil are measured and for B100 are given by the supplier of biodiesel. Other properties of blends are determined using a mixture rule model.

4.1.2 Emission Characteristics

The experimental evaluations of emission characteristics are conducted in following three programs:

1. With Diesel oil as fuel at different preset compression ratios ,Loads and injection pressures each time keeping any two of the parameters a constant (Validation Test).
2. With Karanja biodiesel as fuel following similar condition as in 1.
3. With blends of Karanja biodiesel and diesel as fuel following similar conditions as in 1.

The first experimental program is a validation test . The experimental procedure for conducting the validation test, emission characteristic evaluation using Karanja biodiesel and blends of Karanja biodiesel with diesel are explained in detail in Sections 4.1.2.1, 4.1.2.2 and 4.1.2.3.

4.1.2.1 Validation Test

A validation test is conducted using Diesel oil as fuel. The following step by step procedure is adopted for the test:

1) Repeat the steps 1 to 5 as in Section 4.1.1.1.
2) Record all the constituents of exhaust gas for no load condition using the exhaust gas analyzer and smoke meter.
3) Adjust the load at 3kg using the loading unit (dimmerstat) and wait for 3 minutes for engine to get stabilized. Repeat step 2.
4) Repeat step 2 for different loads viz. 6kg, 9kg and 12kg.

5) Repeat the steps 1 to 4 for the different compression ratios viz. 15, 16, 17, 17.5 and 18.
6) Repeat the steps 1 to 5 for different injection pressures viz. 200 bar, 250 bar.
7) After all readings are recorded, bring down the loading condition to 'no load' before stopping the engine. The water is allowed to circulate for about 5 minutes for engine cooling and then the pump is stopped.

4.1.2.2 Karanja Biodiesel

The procedure followed for conducting the experiment using Karanja biodiesel is the same as explained in Section 4.1.2.1 except that Karanja biodiesel is to replace Diesel oil as fuel.

4.1.2.3 Blends of Karanja Biodiesel and Diesel

The procedure followed for conducting the experiment using blends of Karanja biodiesel & diesel is the same as explained in Section 4.1.2.1 except that blends of Karanja biodiesel and diesel is to replace Karanja biodiesel as fuel.

4.1.3 Combustion Analysis

The Combustion Analysis is conducted in following two programs:

1. With Diesel oil as fuel at full Load, at different preset compression ratios and at standard preset injection pressure.
2. With Karanja biodiesel as fuel at full load, at different preset compression ratios and at standard preset injection pressure.

The experimental procedures undertaken for conducting combustion analysis using Diesel oil as fuel and Karanja biodiesel as fuel are explained in detail in Sections 4.1.3.1 and 4.1.3.2 respectively.

4.1.3.1 Diesel oil

The procedure followed for conducting the experiment using Diesel oil as fuel for combustion analysis is as follows:

1) Repeat the steps 1 to 5 given in Section 4.1.1.1.

2) Adjust the load for 12kg using the loading unit dimmerstat and wait for 3 minutes for engine to get stabilized.
3) Set compression ratio at a selected value (say 14) using the tilting block arrangement for the engine.
4) Set the injection pressure to 200 bar using the nut provided on the cylinder head near fuel injection line.
5) Record all the parameters of combustion for full load (12 kg) condition and set compression ratio. Commercial software, "Enginesoft LV" is used to interface, record and analyze the data.
6) Repeat step 5 for other compression ratios viz. 16 and 18
7) After all readings are recorded, bring down the loading condition to 'no load' before stopping the engine. The water is allowed to circulate for about 5 minutes for engine cooling and then the pump is stopped.

4.1.3.2 Karanja Biodiesel

The procedure followed for conducting the experiment using Karanja biodiesel as fuel is the same as explained in Section 4.1.3.1 except that Karanja biodiesel is to replace Diesel oil as fuel.

4.2 Results and Discussions

The results obtained from the experiments conducted for thermal performance evaluation, emission characteristics evaluation and combustion analysis are interpreted in this section. Before carrying out the series of experiments, the engine's readiness for the test is validated by running the engine with Diesel oil alone as fuel and is presented in Section 4.2.1. The interpretations to the results of thermal performance parameters and emission characteristics evaluation are explained in Sections 4.2.2 and 4.2.3 respectively. Sections 4.2.2.1, 4.2.2.2 and 4.2.2.3 include the interpretations of the variation of thermal performance parameters with respect to, different preset compression ratios, different loads and different injection pressures. Similar studies are carried out with respect to emission constituents in Section 4.2.3 where emission constituents are studied at different preset compression ratios, Loads and injection pressures. Section 4.2.4 presents the interpretations for analysis of combustion parameters.

The uncertainties for maximum and minimum loads for the thermal performance parameters are represented in Table 4.3. The calculations of uncertainty analyses are given in Appendix VII.

Table 4.3 Uncertainty of Performance Parameters at Maximum and Minimum Loads

Quantity	Uncertainty at Maximum Load (%)	Uncertainty at Minimum Load (%)
Brake Mean Effective Pressure	4.4	4.1
Brake Thermal Efficiency	2.3	4.1
Brake Specific Fuel Consumption	2.2	4.2
Volumetric Efficiency	1.5	1.5
Heat Equivalent of Brake Power	2.1	3.8
Heat Equivalent of Exhaust Gas Temperature	1.0	1.8

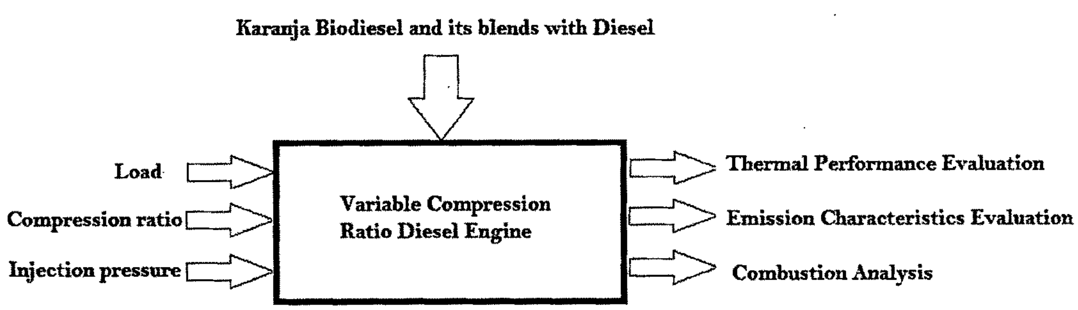

Figure 4.1 Input and Output Variables of the Engine System

Figure 4.1 indicates the Input (Control) variables and Output (Response) variables for the engine system.

4.2.1 Validation Test

The validation test is conducted for thermal performance evaluation of the engine running on Diesel oil alone as fuel. The tests are conducted at different loads (from 0kg to 12kg in steps of 3kg), at different preset compression ratios (CR) (14, 15, 16, 17, 17.5, 18) and injection pressure (IP) of 200bar. The thermal performance parameters considered for validation of the engine setup are Brake Thermal Efficiency (BTHE) and Brake Specific Fuel Consumption (BSFC). Similar tests are also considered for evaluation of emission constituents to capture a baseline data using Diesel oil alone as fuel for comparison with Karanja biodiesel-diesel blends for further studies. The emission constituents considered validation of the engine setup are Unburnt Hydrocarbon (HC), Oxygen (O_2) and Oxides of Nitrogen (NO_x).

Figures 4.2 and 4.3 give the comparison of effect of the variation of load on selected thermal performance parameters such as BTHE and BSFC respectively. The test is conducted at a rated CR of 17.5, IP of 200bar and at different loads. Although the standard IP is 210 bar, the pressure setting varied close to 190-210 bar and the mean i.e. 200bar is taken as standard value of IP. The trends of the results closely match with that of Jindal et al. [66] for load variation at standard settings of the engine. The results of Jindal et al. [66] are considered for comparison since the engine used in the present study is of the same type as that used by them. The magnitudes of BTHE and BSFC may not match on comparison as properties of and quality of Diesel oils used for the studies may vary from region to region. Further, the aging of the engine also matters.

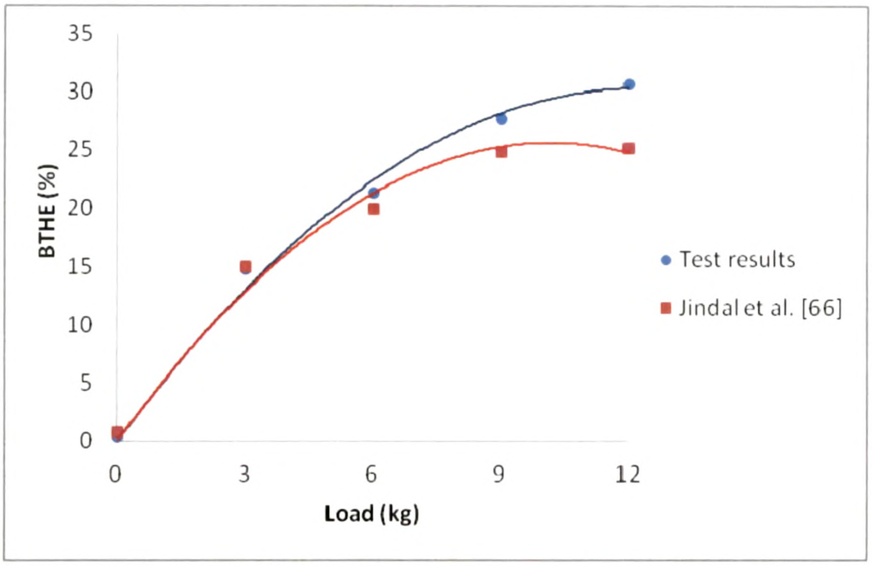

Figure 4.2 Comparison of Variation of BTHE with Load at CR of 17.5 and IP of 200bar

The validation test is needed to be conducted at different preset CRs and IPs to ascertain the preparedness of the engine. Since there appears to be no valid reference available in literature for variation of BTHE and BSFC with CR, the value of BTHE and BSFC at rated load (full load), CR of 17.5 and IP 200 bar from the present study is compared with results of Jindal et al. [66] at the same conditions in Figure 4.4 and Figure 4.5.

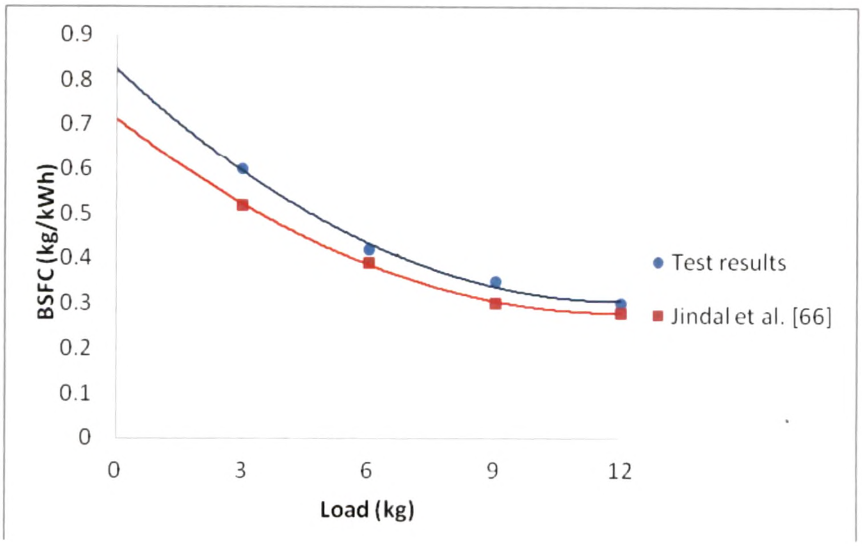

Figure 4.3 Comparison of Variation of BSFC with Load at CR of 17.5 and IP of 200bar

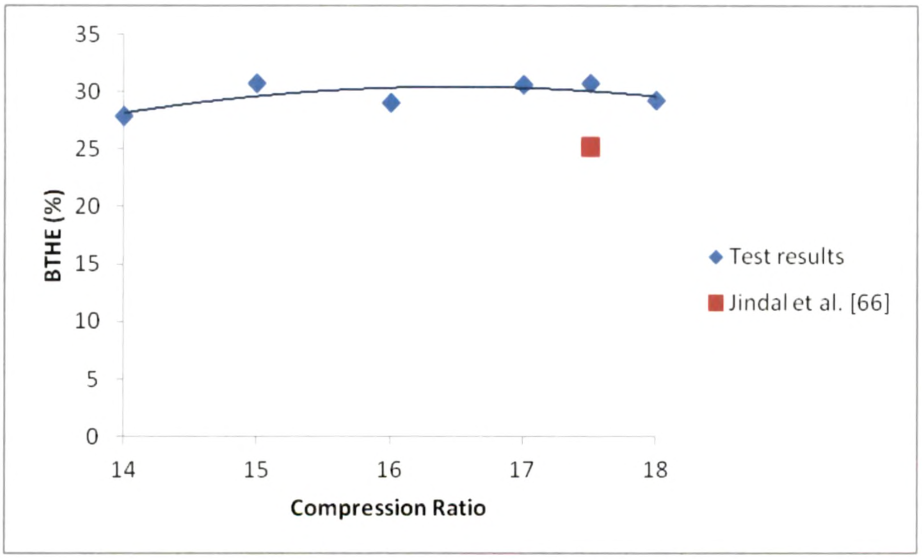

Figure 4.4 Comparison of BTHE at Rated Load, CR of 17.5 and IP of 200bar

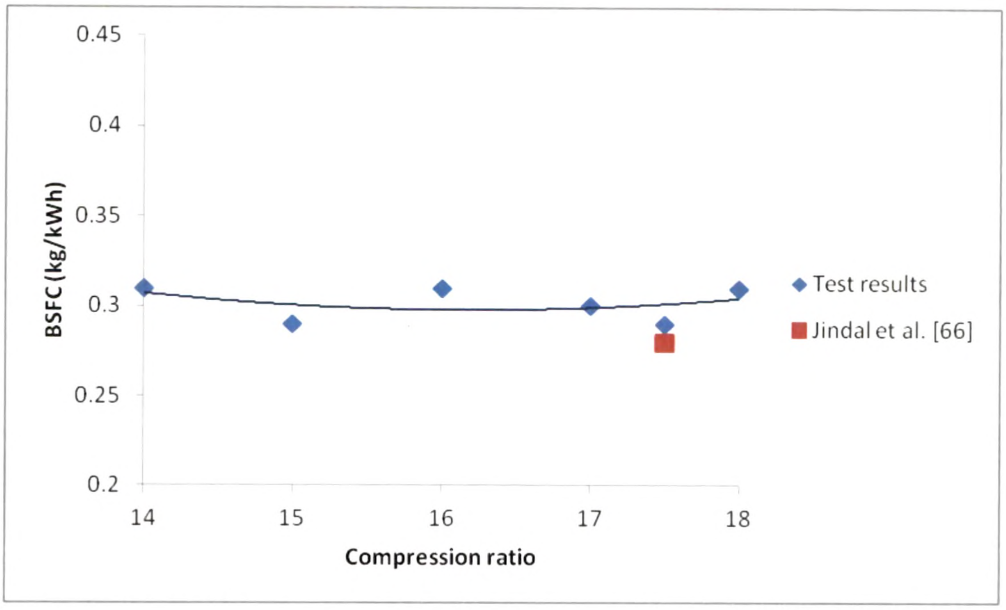

Figure 4.5 Comparison of BSFC at Rated Load, CR of 17.5 and IP of 200bar

From the comparisons made in Figures 4.4 and 4.5, it is observed that the values of BTHE and BSFC at rated load, CR of 17.5 and IP 200 bar are in close agreement with each other. Since, the comparisons made in Figures 4.2-4.5 are at an IP of 200 bar, the preparedness of the engine at varying IPs is ascertained.

The engine tests are conducted to capture emission characteristics at different loads (0 to 12kg in steps of 3kg), different preset CRs (14, 15, 16, 17, 17.5, 18) and different IPs (150, 200, 250bar) keeping any two of them a constant each time. Figures 4.6 to 4.14 give the effect of the variation in load, compression ratio and injection pressure on selected emission constituents such as HC (ppm), NO_x (ppm) and O_2 (%). It should be noted that the emission test carried out are standardized with respect to Diesel oil as fuel on the engine where experimental studies are proposed to be carried out and this is taken as baseline data for further comparisons of various emissions with other tested fuel combinations. Also, the quality of Diesel varies from region to region and hence validation of emissions is not possible.

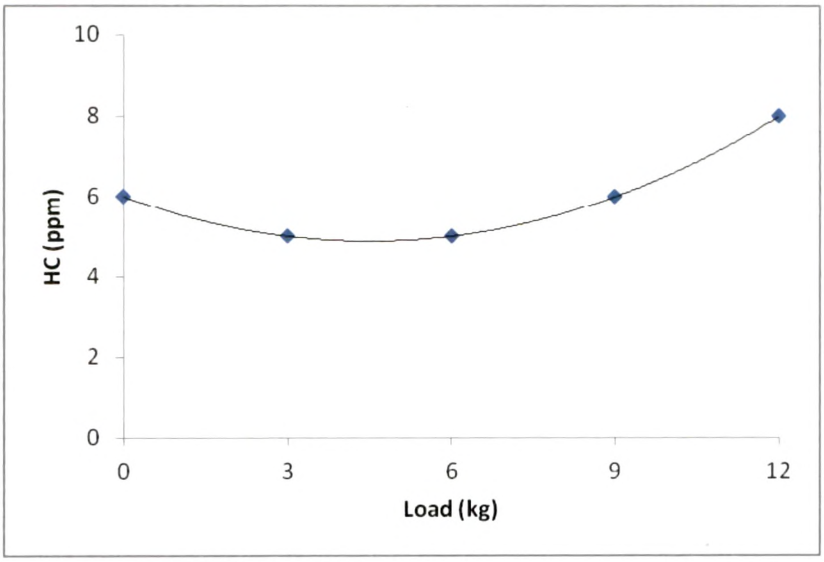

Figure 4.6 Variation of HC with Load at CR of 17.5 and IP of 200bar

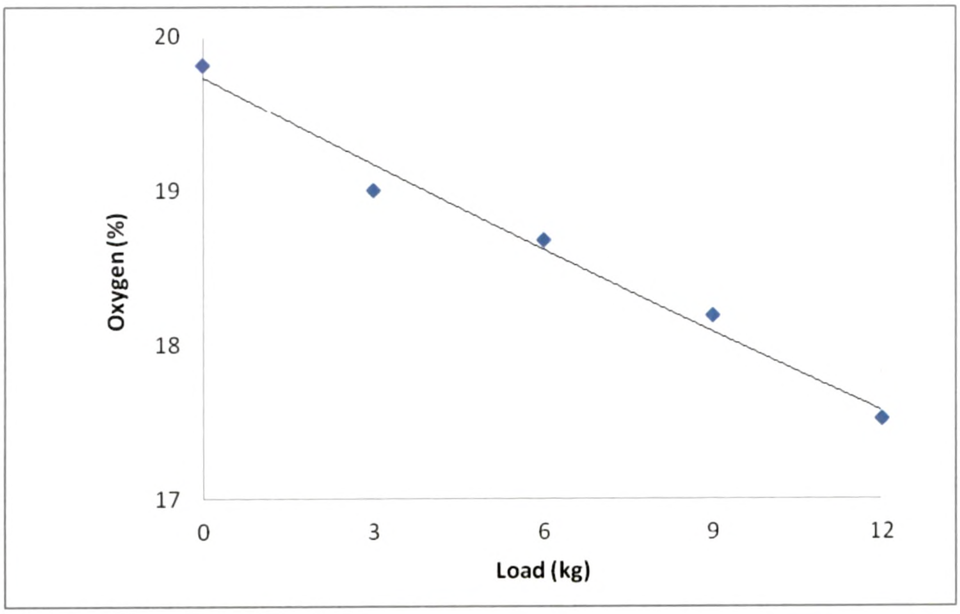

Figure 4.7 Variation of O_2 with Load at CR of 17.5 and IP of 200bar

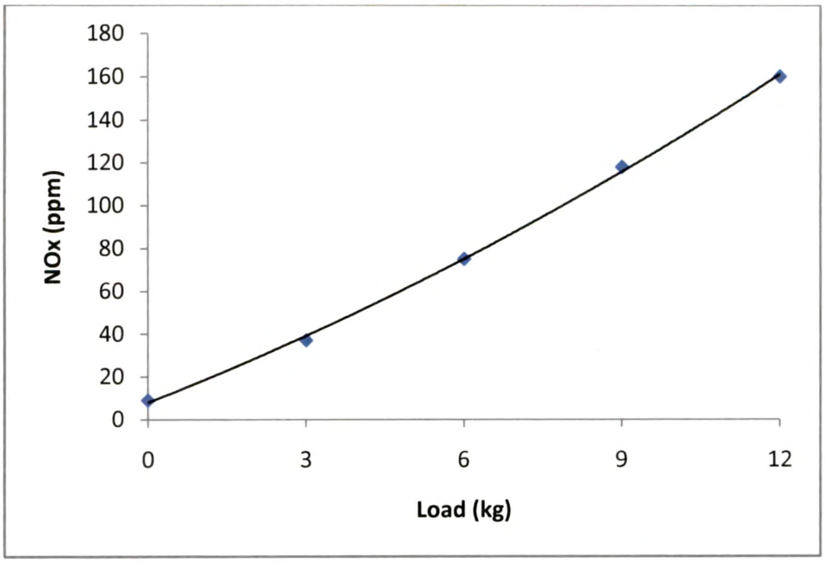

Figure 4.8 Variation of NO_x with Load at CR of 17.5 and IP of 200bar

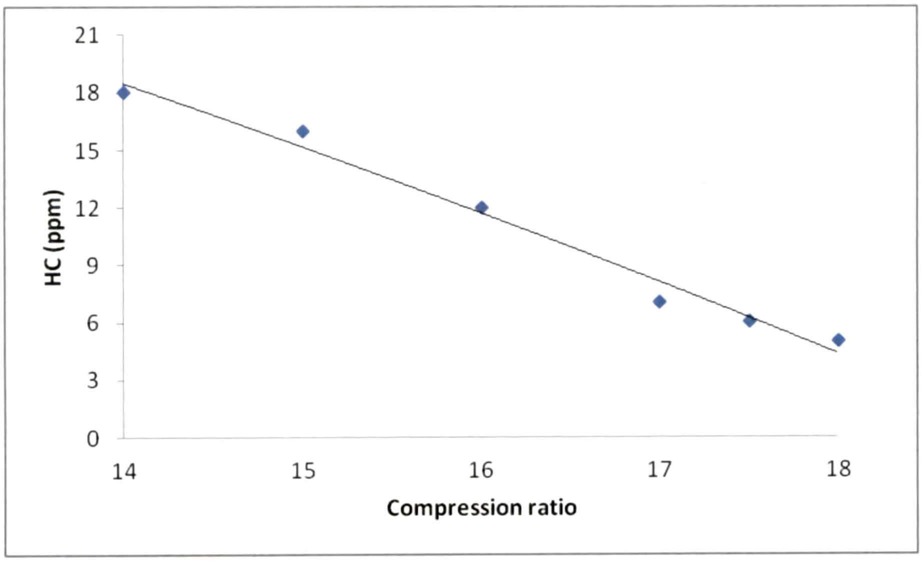

Figure 4.9 Variation of HC with CR at Load of 12kg and IP of 200bar

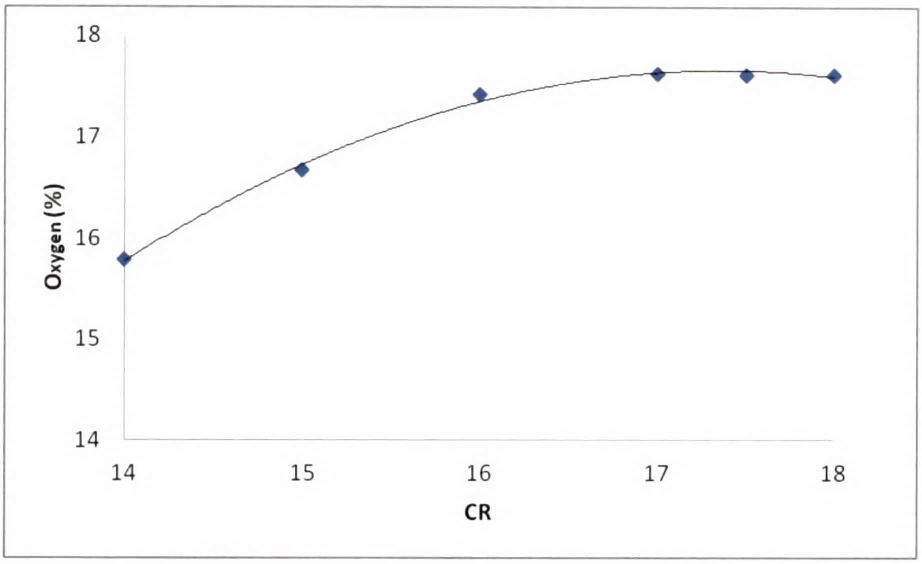

Figure 4.10 Variation of O_2 with CR at Load of 12kg and IP of 200bar

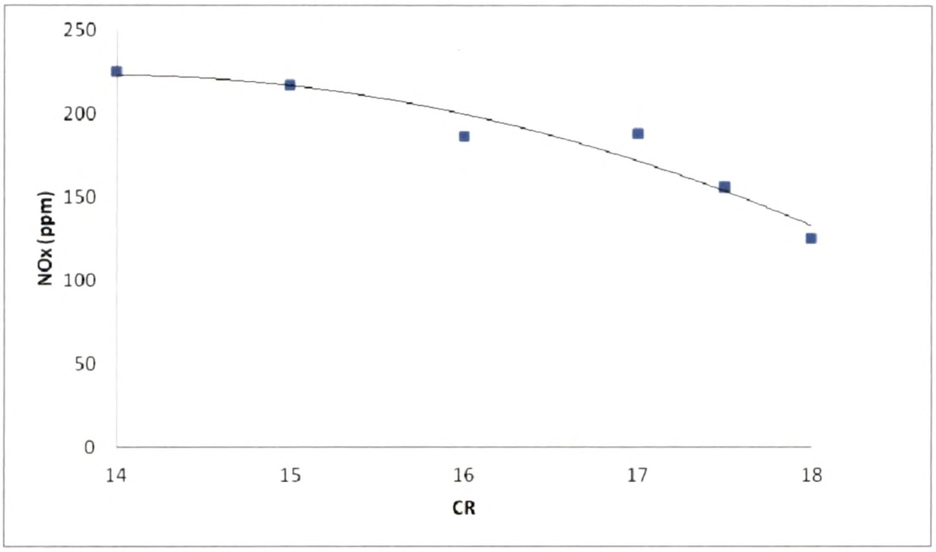

Figure 4.11 Variation of NO_x with CR at Load of 12kg and IP of 200bar

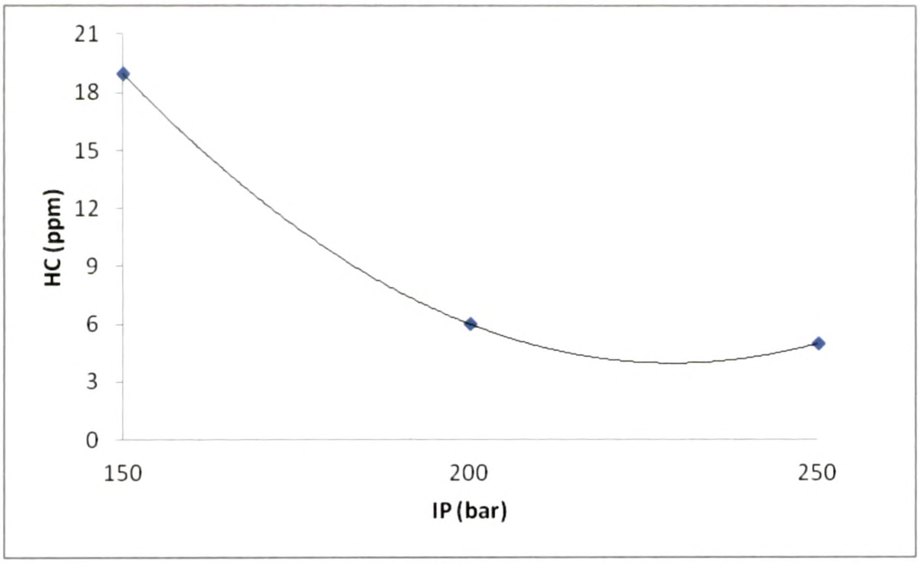

Figure 4.12 Variation of HC with IP at Load of 12kg and CR of 17.5

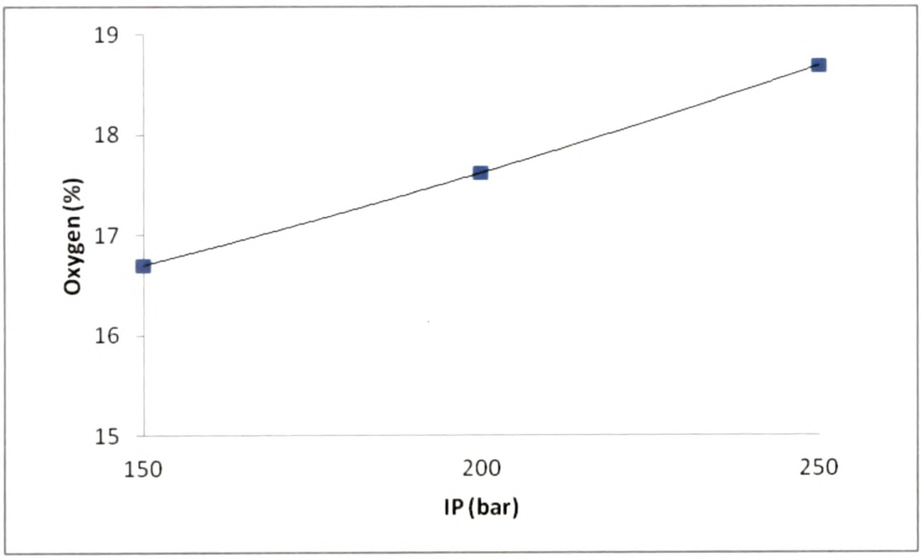

Figure 4.13 Variation of O_2 with IP at Load of 12kg and CR of 17.5

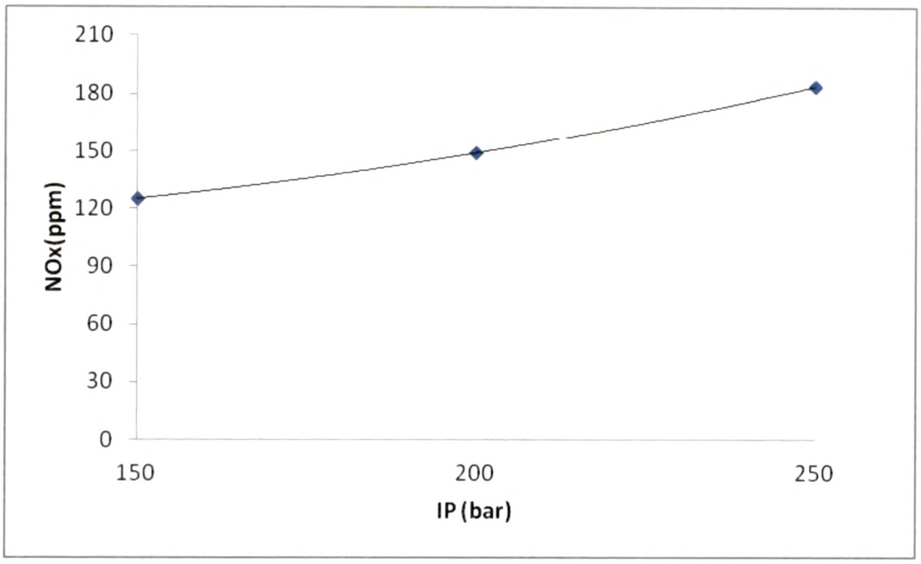

Figure 4.14 Variation of NO_x with IP at Load of 12kg and CR of 17.5

4.2.2 Thermal Performance

The thermal performance parameters considered in the present study are BTHE BSFC, EGT, Brake Mean Effective Pressure (BMEP), Volumetric Efficiency, Heat Equivalent of Brake Power (HBP), Heat Equivalent of Exhaust Gas (HGas). The variations of the performance parameters with CRs, Load and IPs are presented in three different sections i.e., 4.2.2.1, 4.2.2.2 and 4.2.2.3 respectively. Section 4.2.2.1 describes the results of the experiment carried out on the thermal performance parameters when CR is varied at values of 14, 15, 16, 17, 17.5 and 18. The purpose of this study is to find out whether the rated CR of 17.5 is or not to be selected for further analysis with Karanja biodiesel and its blends. For each of the parameters, the variations in the performance for Diesel oil, Karanja biodiesel and blends of Karanja biodiesel with Diesel are superposed and compared.

4.2.2.1 Compression Ratio

The variations of thermal performance parameters at different values of CRs at 14, 15, 16, 17, 17.5 and 18 with a constant rated load of 12kg and IP of 200bar is presented in Figures 4.15 to 4.23.

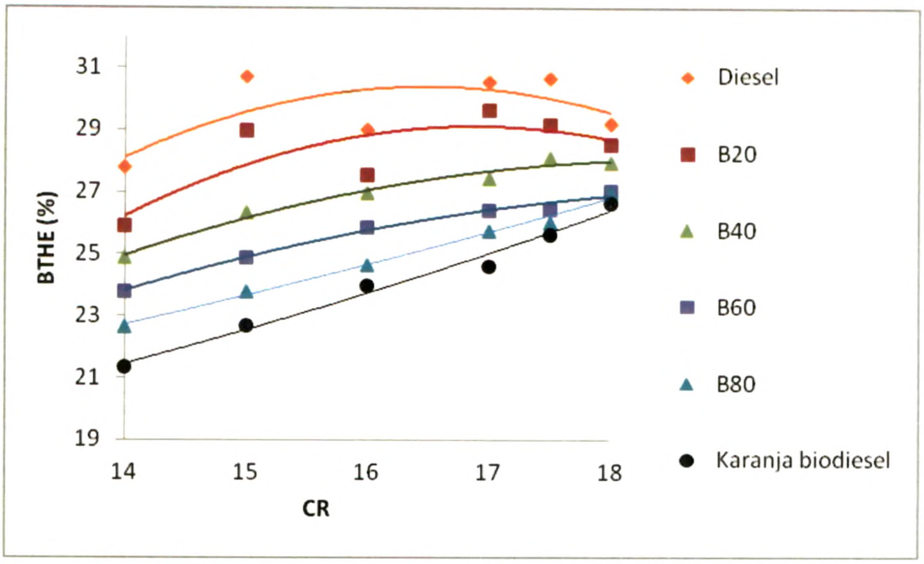

Figure 4.15 Comparison of Variation of BTHE with CR at a Load of 12kg and IP of 200bar

A comparison of the variation of BTHE with CR for Karanja biodiesel and its blends with Diesel oil at a load 12kg and IP of 200bar is presented in Figure 4.15. It can be observed that BTHE increases continuously with increase in CR for all the fuels tested except for B20 and Diesel oil. The increasing trend is due to higher air temperature achieved at higher CR which results in better combustion of fuel. It is also observed that BTHE is decreased with increase in biodiesel content in the blend at a constant CR. The decrease may be due to higher viscosity of biodiesel which hinders the fuel evaporation due to poor atomization during combustion process.

With the increase in CR from 14 to 18, the BTHE increased upto 6% for all fuels. The values of BTHE at full load (12kg) and 18CR are 26.64%, 26.98%, 27.03%, 27.95%, 28.54% and 29.2% for Karanja biodiesel, B80, B60, B40, B20 and Diesel oil respectively.

It can be observed in Figure 4.15 that with the increase in CR the performance with Karanja biodiesel and its blends with diesel approaches that of Diesel oil. At 18 CR the BTHE of the engine operated with Karanja biodiesel is 9.6% less than Diesel oil. Due to this reason CR of 18 is selected for comparison of variation of other thermal performance parameters with load and IP for further analysis.

A comparison of the variation of BSFC with CR for Karanja biodiesel and its blends with Diesel oil at a load 12kg and IP of 200bar is shown in Figure 4.16. It can be observed that as the CR of the engine increases, there is a decrease of 5% to 13% in the fuels as expected. The BSFC is found to be the least at 18CR because at higher CRs complete combustion of fuel takes place due to high heat (temperature) of compressed air. The complete combustion produces higher brake power. Therefore, load demand is met with less fuel consumption.

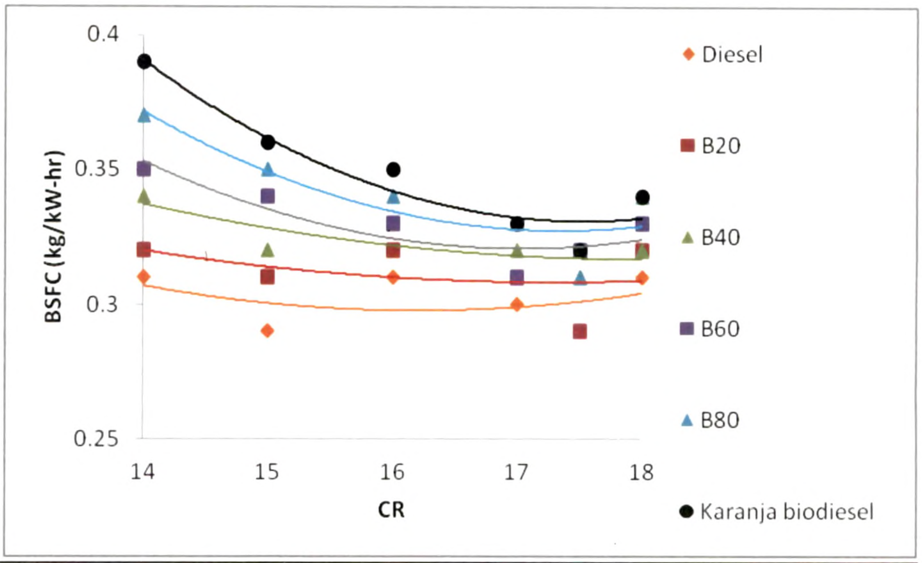

Figure 4.16 Comparison of Variation of BSFC with CR at a Load of 12kg and IP of 200bar

It is also seen that BSFC increases with the increase in percentage of Karanja biodiesel in the blend. This may be due to the reason that fuel burning rate required is more with Karanja biodiesel because of its lower calorific values. The reduced delay due to higher cetane number during injection accounts for increased rate of fuel injection.

As CR increases from 14 to 18, BSFC decreases by about 5% to 13% for biodiesel blends B40, B60, B80 and B100. It is seen that the consumption of pure Karanja biodiesel is about 25% more at CR of 14 while that at CR of 18 is about 10% more. At CR of 18 the thermal performance of Karanja biodiesel is close to that of Diesel oil. The values of BSFC for Karanja biodiesel at CRs of 14, 15, 16, 17, 17.5 and 18 are 0.39, 0.36, 0.35, 0.33, 0.32 and 0.31 kg/kWh respectively.

Figure 4.17 shows the comparison of variation of BTHE and BSFC with CR at a load of 12kg and IP 200bar of the present study with that of earlier investigations of Sureshkumar et al. [52], Banapurmath et al. [44], Jindal et al. [66], Raheman & Ghadge [40] and Raheman & Phadatare [17].

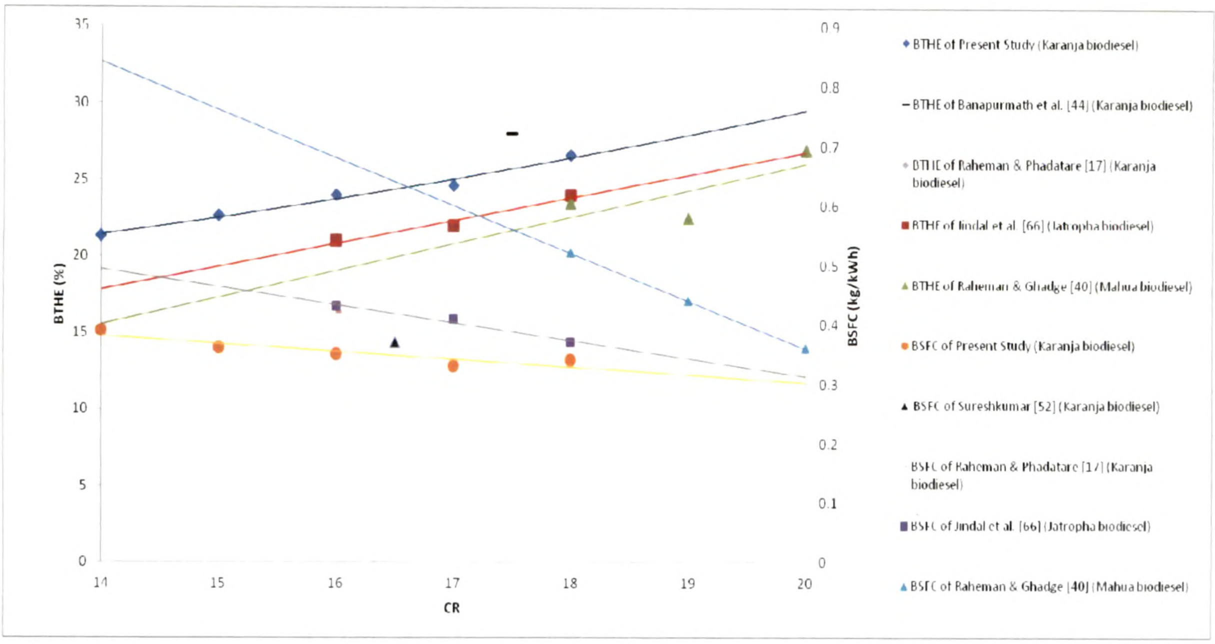

Figure 4.17 Comparison of Variation of BTHE and BSFC with CR at a Load of 12kg and IP of 200bar with Earlier Studies

Similar increasing trends of BTHE with CR as found in the present study are observed by Jindal et al. [66] and Raheman & Ghadge [40] while using Jatropha and Mahua biodiesels respectively. It is seen that the value of BTHE at 18 CR is less by 10% for Jatropha and 12% for Mahua as compared to that of Karanja biodiesel used in the present study. It should be noted that the values of BTHE with Karanja biodiesel are available only at a given single value of CR from the earlier studies. Banapurmath [44] has reported a 10% higher value of BTHE at a constant CR of 17.5 while 12% lesser BTHE has been reported by Raheman and Phadatare [17] at a constant CR of 16 using Karanja biodiesel as compared to the present study.

Similar decreasing trends of BSFC with CR as found in the present study are observed by Jindal et al. [66] and Raheman & Ghadge [40] while using Jatropha and Mahua biodiesels respectively. It is seen that the value of BSFC at 18 CR is more by 9% for Jatropha and 52% for Mahua as compared to that of Karanja biodiesel used in the present study. It should be noted that the values of BSFC with Karanja biodiesel are available only at a given single value of CR from the earlier studies. Sureshkumar [52] has reported a 3% higher value of BSFC at a constant CR of 16.5 while 21% more BSFC has been reported by Raheman and Phadatare at a constant CR of 16 using Karanja biodiesel as compared to the present study.

Figure 4.18 shows a comparison of the variation of BMEP with CR for Karanja biodiesel and its blends with Diesel oil at a load of 12kg and IP of 200bar. Brake Mean Effective Pressure (BMEP) is the external shaft work per unit volume displacement of the engine. From the figure, it can be observed that CR does not have a significant effect on BMEP.

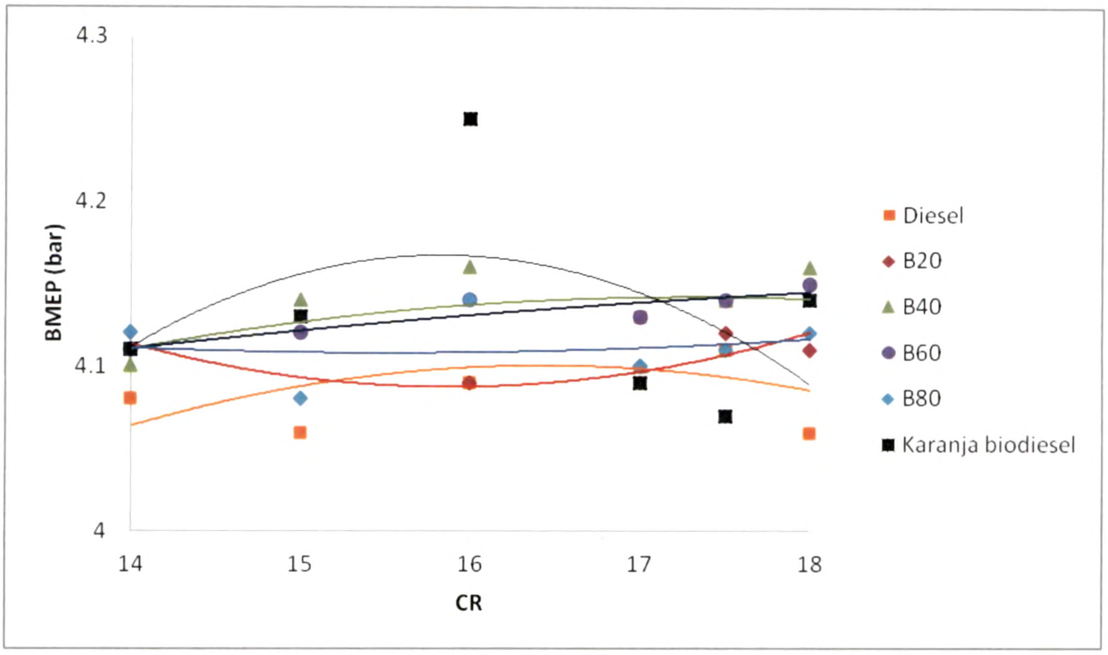

Figure 4.18 Comparison of Variation of BMEP with CR at a Load of 12kg and IP of 200bar

It is also observed that the use of different Karanja biodiesel-diesel blends does not have much effect on BMEP. Hence, it is inferred that though the cylinder peak pressure attained is slightly less with biodiesel, the effective pressure on the engine piston remains fairly the same. It may probably be due to complete burning of the fuel of biodiesels in the premixed combustion phase which takes place during the diffusion phase with Diesel oil combustion.

A comparison of the variation of volumetric efficiency with CR for Karanja biodiesel and its blends with Diesel oil at a load 12kg and IP of 200bar is presented in Figure 4.19. The volumetric efficiency is an important performance parameter which is also referred to as the breathing capacity of engine. It is basically a mass ratio and not a volume ratio because it is the ratio of the mass of charge actually admitted into the cylinder to the mass of the charge corresponding to the swept volume. It is desirable to maximize the volumetric efficiency since the amount of fuel that can be burnt and power produced for a given engine displacement are maximized with higher rate of air inflow at suction conditions. Although it does not influence in any way directly the thermal efficiency of the engine, it will influence the efficiency of the system since the fuel economy will go up with an engine having higher volumetric efficiency (Heywood [96], Ferguson & Kirkpatrick [98]).

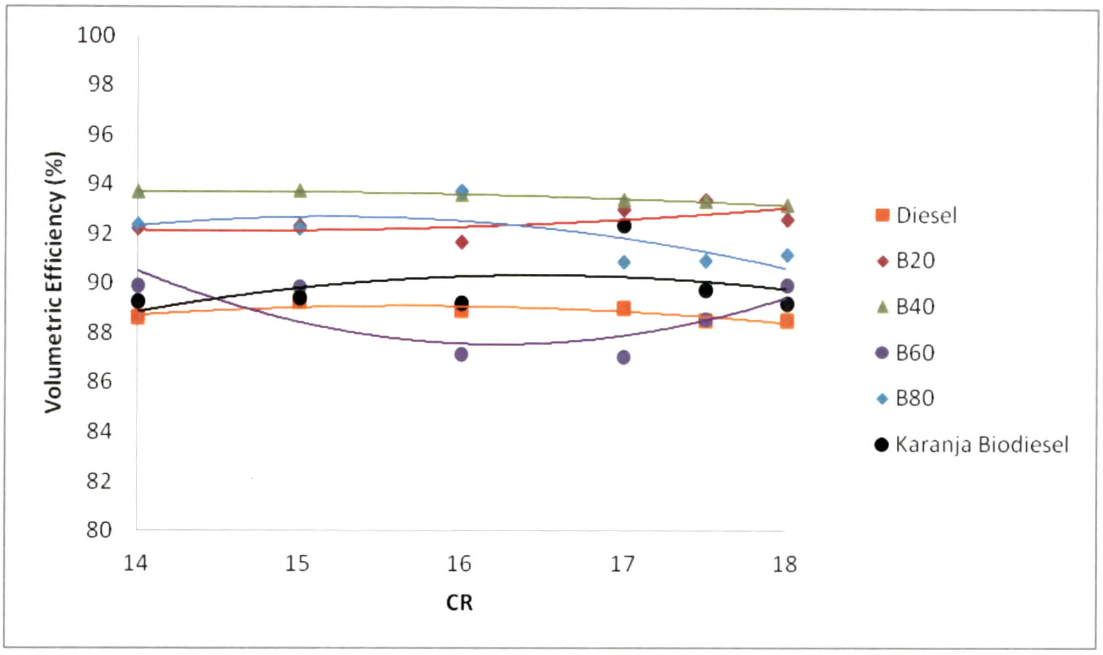

Figure 4.19 Comparison of Variation of Volumetric Efficiency with CR at a Load of 12kg and IP of 200bar

It is observed that change in CR does not affect the volumetric efficiency of the engine (Figure 4.19). Therefore, the engine could be operated at any CR without hampering the volumetric efficiency of the engine. It can also be noted that volumetric efficiency does not depend on blend proportion. However, it is marginally higher for Karanja biodiesel than Diesel oil. For Karanja biodiesel, the volumetric efficiencies at tested CRs are 89.23%, 89.41%, 89.2%, 92.34%, 89.76% and 87.6%.

Figure 4.20 shows the comparison of variation of HBP with CR for Karanja biodiesel and its blends with Diesel oil at a load 12kg and IP of 200bar. HBP represents the amount of input percent thermal energy associated with the useful power output of an engine. It is evident from the figure that the HBP increases with increase in CR for all the fuels tested. The trend observed is due to higher brake power at higher CR resulting in better combustion of fuel which in turn is due to high heat of compressed air. It is observed that HBP decreases with increase in content of Karanja biodiesel in the blend at constant CR. The trend is due to lower calorific value of Karanja biodiesel. It can also be noted that the increase in HBP with CR is continuous for Karanja biodiesel while it increases up to CR of 16 then remains almost constant upto CR of 17 and subsequently decreases for other tested fuels. Therefore, it can be inferred that combustion is better at CR of 16 for the blends and at CR of 18 for Karanja biodiesel.

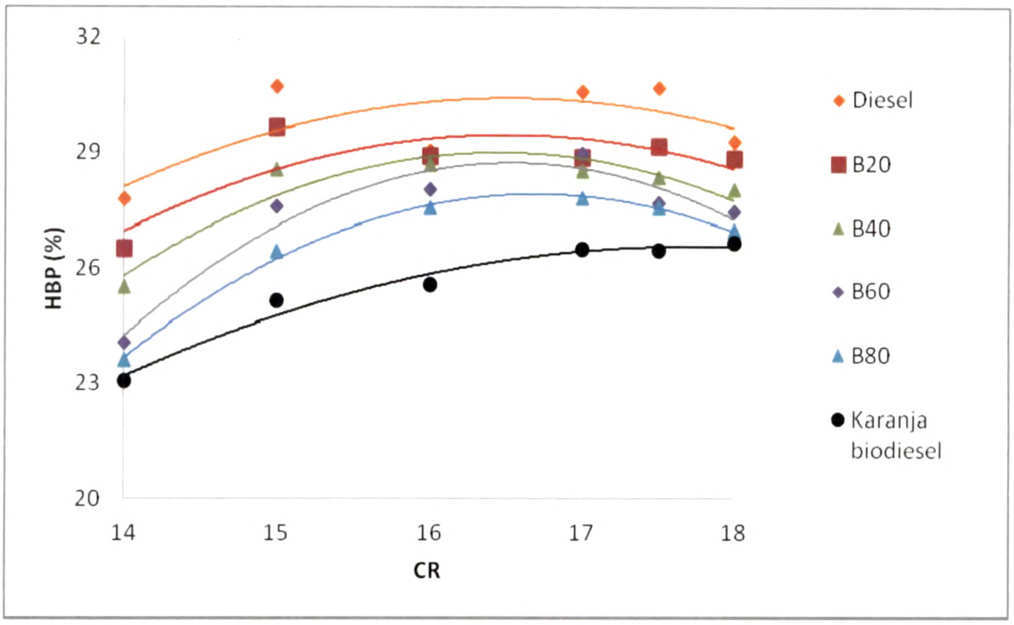

Figure 4.20 Comparison of Variation of HBP with CR at a Load of 12kg and IP of 200bar

The values of HBP for Diesel oil for the respective tested CRs are 27.76%, 30.69%, 29.01%, 30.56%, 30.66% and 29.29% and the same for Karanja biodiesel are 23.04%, 25.13%, 25.57%, 26.48%, 26.46% and 26.64%. It can be noted that HBP for Karanja biodiesel is closer to that of Diesel oil particularly at higher CRs.

Figure 4.21 presents the comparison of variation of HGas with CR for Karanja biodiesel and its blends with Diesel oil at a load of 12kg and IP of 200bar. HGas represents the amount of total thermal energy carried with the engine exhaust. Higher exhaust temperature represents the effectiveness of combustion but greater heat loss and hence the attainment of lesser value of thermal efficiency. It can be observed from the figure that the change in CR does not have much effect on the HGas of the engine. It can also be observed that there is no specific trend of variation of HGas with Karanja biodiesel content in the blend. However, at most of the CRs it is less for Karanja biodiesel than Diesel oil. The trend may be due to lower heat released during combustion of Karanja biodiesel which probably may be due to its lower calorific value.

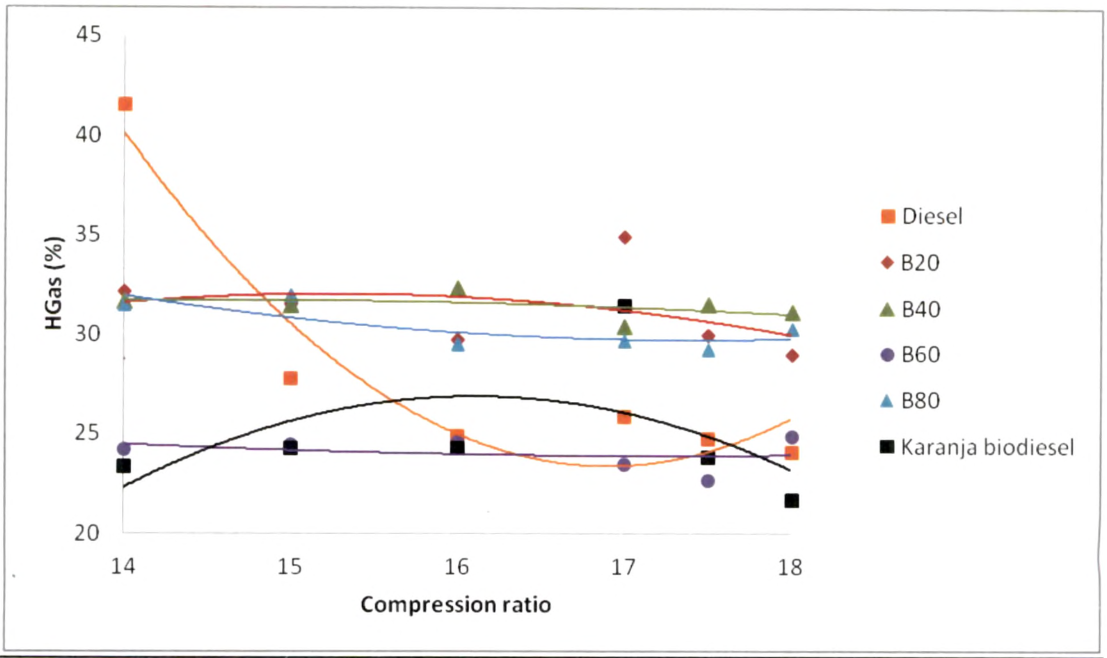

Figure 4.21 Comparison of Variation of HGas with CR at a Load of 12kg and IP of 200bar

It can also be noted that at a CR of 14, the HGas for Diesel oil is higher compared to that of Karanja biodiesel-diesel blends. It may be due to a fact that at lower CR combustion is incomplete due to less heat of compressed air. Therefore, higher calorific value of Diesel oil results in higher HGas. The values of HGas for Diesel oil at various tested CRs are 41.57%, 27.8%, 24.92%, 25.92%, 24.79 and 24.08% and for Karanja biodiesel are 23.39%, 24.31%, 24.32%, 31.48%, 23.87% and 21.71%.

A comparison of the variation of EGT with CR for Karanja biodiesel and its blends with Diesel oil at a load of 12kg and IP of 200bar is given in Figure 4.22. EGT represents the temperature of flue gases that come out of the engine and indicates the effectiveness of combustion and engine thermal energy conversion. Lower EGT is always desirable for any engine. It can be seen from the figure that EGT decreases with the increase in CR for all the fuels tested. The reduction in EGT can be attributed to high temperature of compressed air inside the cylinder at higher CRs due to which the fuel is burnt more completely.

It is observed that EGT reduces with the increase in blend proportion. Also, the rate of EGT drop is almost the same at different CRs for all fuels tested. The EGT reduces upto 18% for all fuels as the CR increases from 14 to 18. At CR of 18, the values of EGT for Karanja biodiesel, B80, B60, B40, B20 and Diesel oil are found to be

343.77^{0}C, 346.99^{0}C, 347.25^{0}C,345.67^{0}C, 347.96^{0}C and 350.75^{0}C respectively indicating that EGT at higher CRs for blends are closer to Diesel oil.

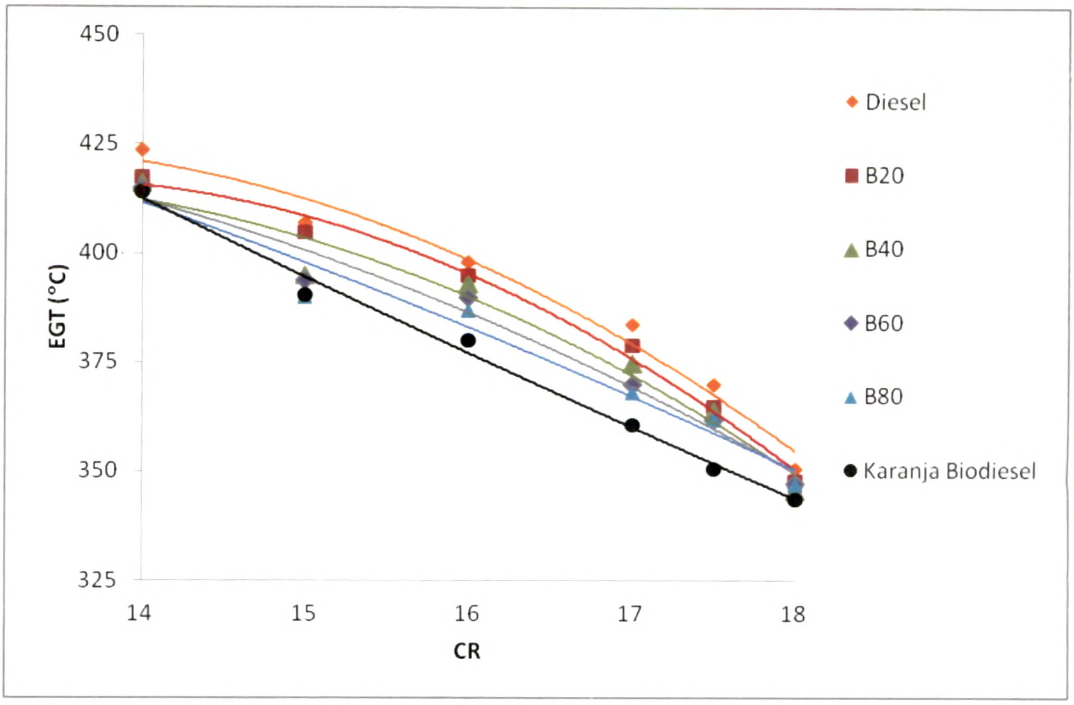

Figure 4.22 Comparison of Variation of EGT with CR at a Load of 12kg and IP of 200bar

Figure 4.23 shows the comparison of variation of EGT with CR of the present study at a load of 12kg and IP of 200bar with that of earlier investigations of Sureshkumar [52], S. Jindal et al. [66] and Raheman & Ghadge [40]. The fuels used by the investigators are Karanja biodiesel, Jatropha biodiesel and Mahua biodiesel respectively. It can be seen that, similar decreasing trend of EGT with CR as found in the present study is observed by Raheman & Ghadge [40] while an opposite trend is seen by Jindal et al. [66]. Further it is observed that the value of EGT at 18 CR is less by 4% (Raheman & Ghadge [40]) and more by 17% (Jindal et al. [66]) as compared to that of the present study. It is also observed that the value of EGT for the study of Sureshkumar [52] with Karanja biodiesel at a constant CR of 16.5 is not comparable with that of the present study. It can however be noted that the EGT values lie in range of 350-400^{o}C for the present study and Jindal et al [66].

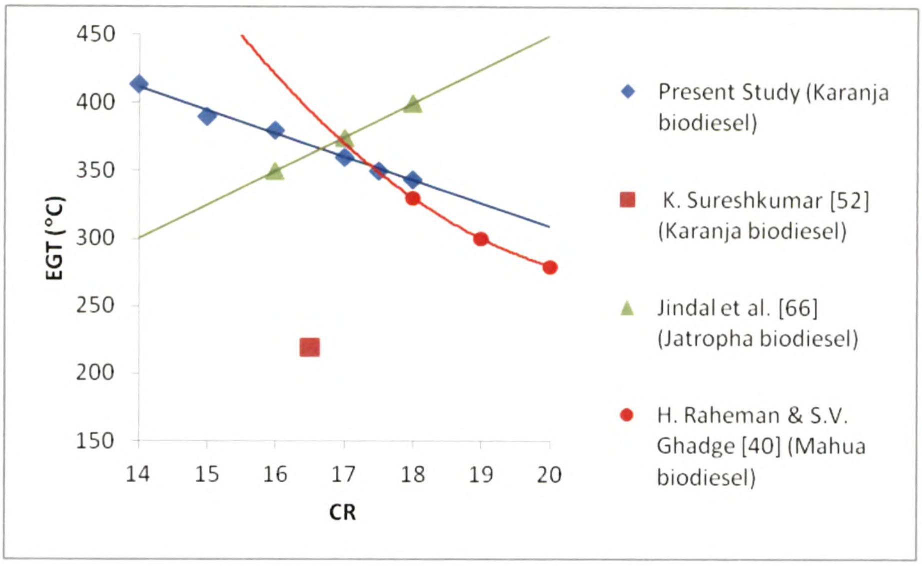

Figure 4.23 Comparison of Variation of EGT with CR at a Load of 12kg and IP of 200bar with Earlier Studies

4.2.2.2 Load

The variations of thermal performance parameters at different loads from 0kg and 12kg in steps of 3kg are presented in Figures 4.24 to 4.32. The load is varied maintaining a constant CR and IP at 18 and 200bar respectively.

Figure 4.24 presents the comparison of variation of BTHE with load for Karanja biodiesel and its blends with Diesel oil at CR of 18 and IP of 200bar. It is observed that BTHE increases significantly with increase in load for all the blends tested. The trend may be due to the reason that relatively less portion of power is lost with increasing load. It can be observed that BTHE decreases with the increase in blend proportion at constant load. The reduction in BTHE can be attributed to lower heating value of the blends. Also, the higher viscosity of the blend may result in slightly reduced atomization and poorer combustion. The early initiation of combustion for Karanja biodiesel and significant early pressure rise before TDC contributes to increased compression work and heat loss resulting in a decrease in BTHE.

At full load (12kg), BTHE for Karanja biodiesel is lower by 8% as compared to Diesel oil. The values of BTHE at full load are 28.65%, 28.75%, 29.32%, 30.05%, 30.5% and 31.25% for Karanja biodiesel, B80, B60, B40, B20 and Diesel oil respectively which indicate that BTHE for Diesel oil and Karanja biodiesel are close to each other.

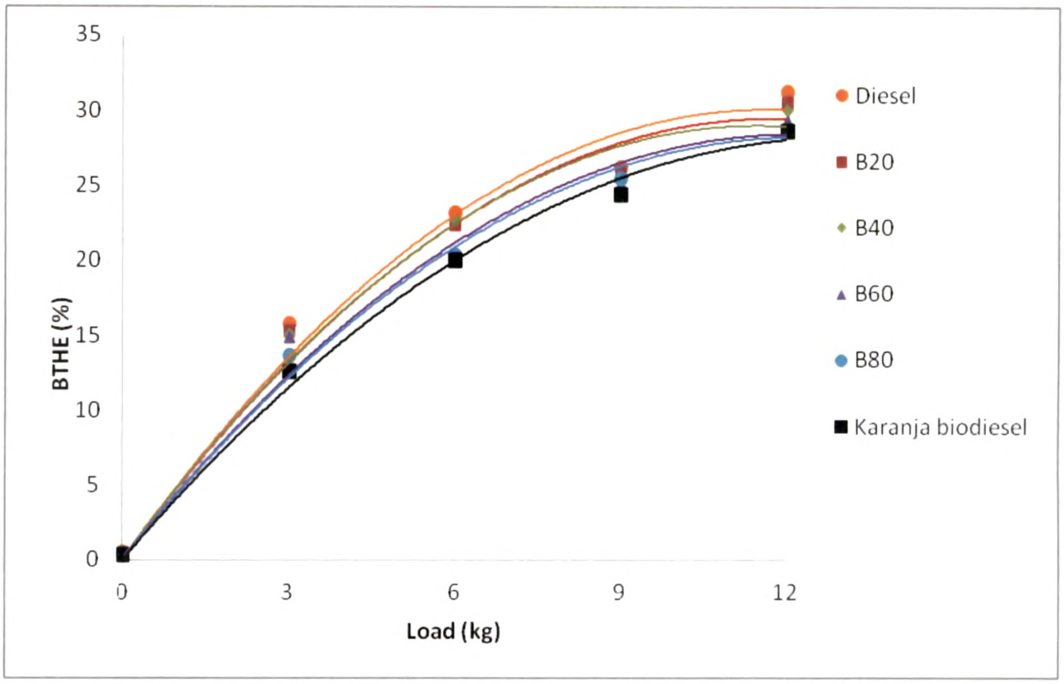

Figure 4.24 Comparison of Variation of BTHE with Load at a CR of 18 and IP of 200bar

The comparison of variation of BSFC with load for Karanja biodiesel and its blends with Diesel oil at CR of 18 and IP of 200bar is shown in Figure 4.25. It is observed that BSFC decreases significantly with the increase in load for all blends as expected. The trend observed may be attributed to the percent increase in fuel required to operate the engine is less than the percent increase in brake power due to relatively less portion of the heat losses at higher loads. It can also be due to increase in fuel consumption with load because the mixture must be enriched beyond stoichiometric. BSFC is higher at low loads because the friction becomes a larger portion of the indicated work and engine starts on rich mixture (Ferguson and Kirkpatrick [98]).

It can be observed that BSFC increases with increase in blend proportion at constant load. The trend observed may be due to lower heating value and relatively higher viscosity of blends due to which the fuel consumption rate is higher. It is observed that BSFC for Karanja biodiesel and its blends are close to that of Diesel oil.

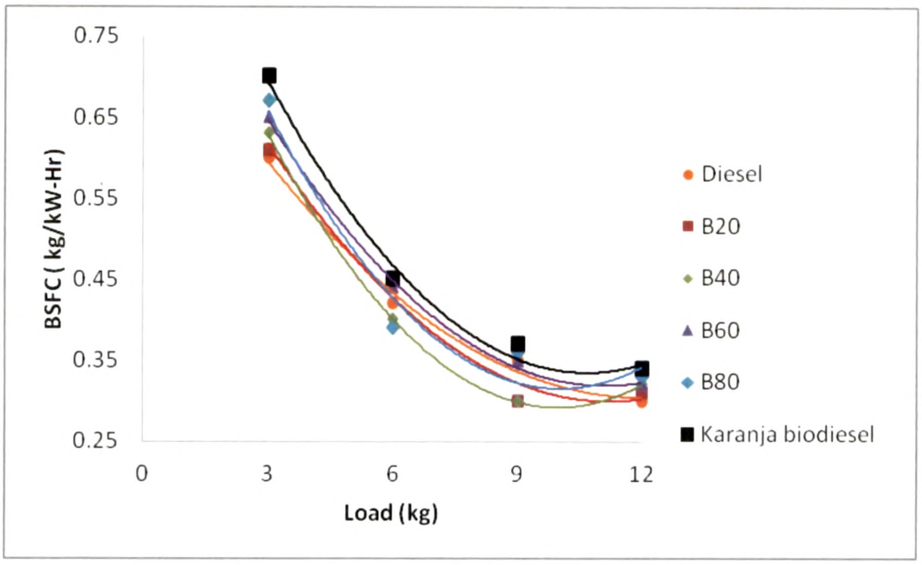

Figure 4.25 Comparison of Variation of BSFC with Load at a CR of 18 and IP of 200bar

At full load, BSFC for Karanja biodiesel is higher by about 18% as compared to Diesel oil. At full load, BSFC for Diesel oil, B20, B40, B60, B80 and Karanja biodiesel are 0.3, 0.31, 0.32, 0.32, 0.33 and 0.34 kg/kWh respectively.

Figure 4.26 shows the comparison of variation of BTHE and BSFC with load at a CR of 18 and IP of 200bar of the present study with that of earlier investigations of Sureshkumar et al. [52], Banapurmath et al. [44], Jindal et al. [66], Raheman & Ghadge [40] and Raheman & Phadatare [17]. Banapurmath et al. [44] and Raheman & Phadatare [17] used Karanja biodiesel and Jindal et al. [66] and Raheman & Ghadge [40] used Jatropha and Mahua biodiesels respectively.

Similar increasing trends of BTHE with load as found in the present study are observed by Banapurmath et al. [44] and Raheman & Phadatare [17] using Karanja biodiesel and Jindal et al. [66] and Raheman & Ghadge [40] using Jatropha biodiesel. At a constant load of 12 kg, preset CR of 18 and IP of 200bar, it is seen that Banapurmath et al. [44] reported a 3% higher value of BTHE while that reported by Raheman & Phadatare [17] was 26% lower as compared to that of present study. Further, the performance in terms of BTHE at a constant load of 12kg, CR of 18 and IP of 200bar when compared using different biodiesel, is found to be 30% and 39% less for Jatropha and Mahua biodiesel respectively with Karanja biodiesel used in the present study.

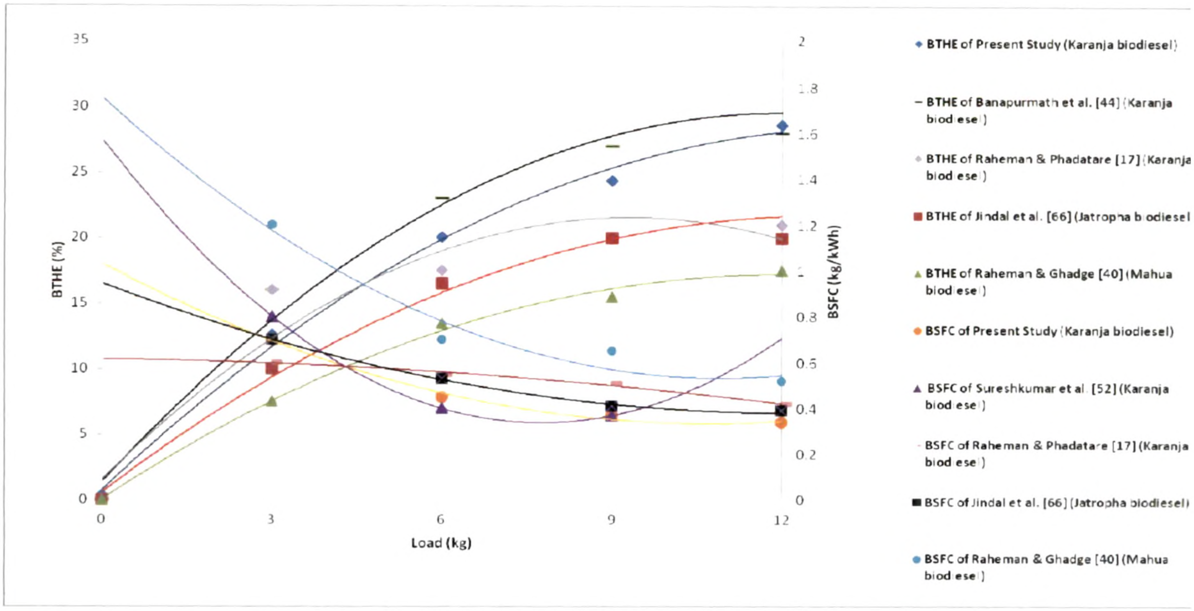

Figure 4.26 Comparison of Variation of BTHE and BSFC with Load at a CR of 18 and IP of 200bar with Earlier Studies

Similar decreasing trends of BSFC with load as found in the present study are observed by S. Banapurmath et al. [44], Raheman & Phadatare [17], Sureshkumar et al. [52], Jindal et al. [66] and Raheman & Ghadge [40]. Sureshkumar et al. [52] used Karanja biodiesel has reported almost same value of BSFC at a load of 9kg as that of the present study. 24% more BSFC as compared to the present study has been reported by Raheman & Phadatare [17] at a load of 12kg using Karanja biodiesel. It is seen that the value of BSFC at a load of 12kg is more by 14% and 50% for Jatropha and Mahua biodiesels respectively as compared to that of Karanja biodiesel used in the present study.

The comparison of variation of BMEP with load for Karanja biodiesel and its blends with Diesel oil at CR of 18 and IP of 200bar is shown in Figure 4.27. It can be observed that BMEP increases linearly with load for all the blends tested. As the load on the engine increases, the rate of fuel consumption increases resulting in greater thermal energy release and hence effective pressure on the piston increases to develop the required brake power.

It is also seen that BMEP is higher for blends than that for pure Diesel oil. However, the trend of variation of BMEP is same for all blends. The higher BMEP for blends may probably be due to higher rate of fuel consumption and greater overall heat release with complete burning of fuel due to the oxygenated nature of biodiesel.

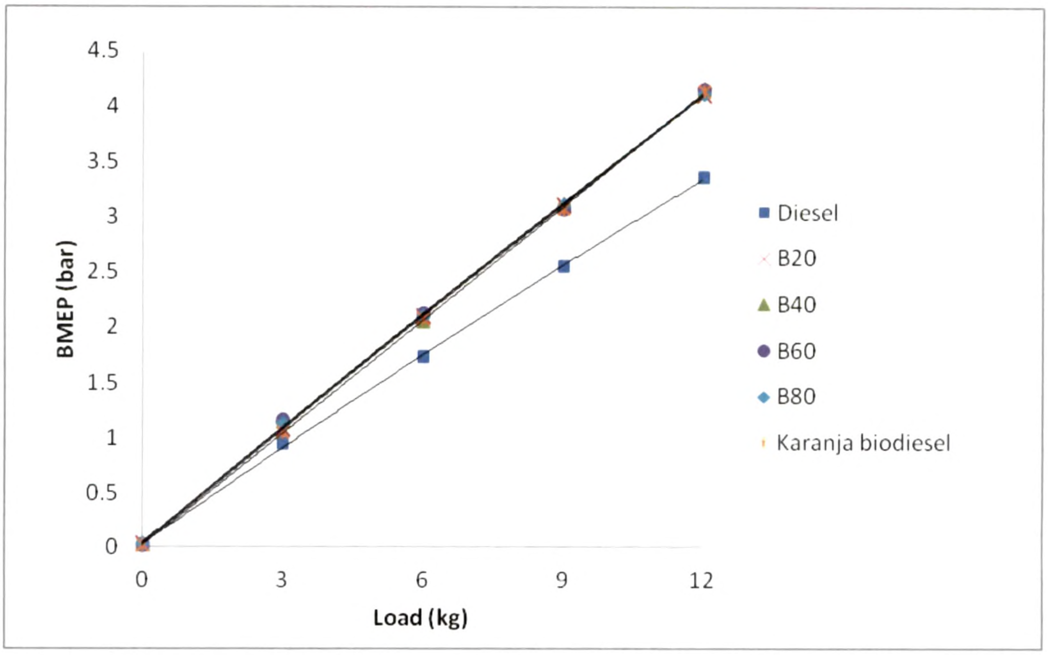

Figure 4.27 Comparison of Variation of BMEP with Load at a CR of 18 and IP of 200bar

The BMEP at full load for Diesel oil, B20, B40, B60, B80 and B100 are 3.36, 4.11, 4.16, 4.15, 4.12 and 4.14 bar respectively. With every increment of 3kg in load, there is an increase of about 1 bar of BMEP for the blends tested.

Figure 4.28 presents comparison of variation of volumetric efficiency with load for Karanja biodiesel and its blends with Diesel oil at CR of 18 and IP of 200bar. It can be seen that load has no significant effect on volumetric efficiency of the engine. At all tested loads, the engine runs with a higher and almost constant volumetric efficiency.

The performance with Karanja biodiesel is better than Diesel oil as fuel in terms of volumetric efficiency. The better performance may be due to greater mass of fuel actually inducted in case of Karanja biodiesel as compared to Diesel oil as fuels.

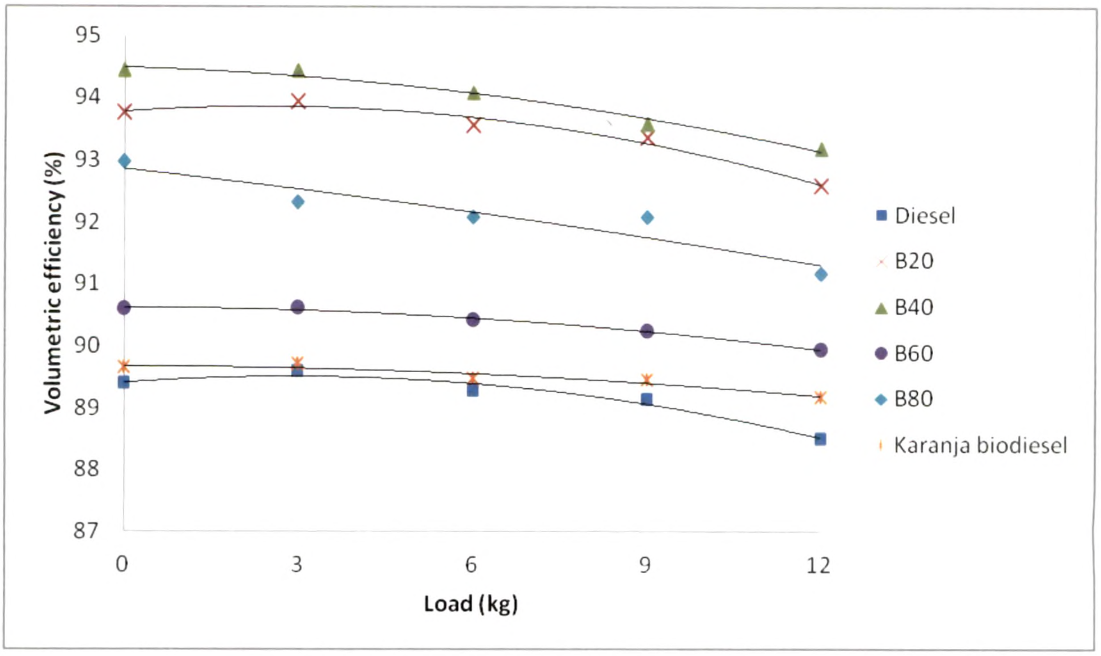

Figure 4.28 Comparison of Variation of Volumetric Efficiency with Load at a CR of 18 and IP of 200bar

Figure 4.29 presents the comparison of variation of HBP with load for Karanja biodiesel and its blends with Diesel oil at CR of 18 and IP of 200bar. It can be observed that HBP increases with increase in load for all the tested fuels. The trend observed is because at higher load fuel consumption increases which results in higher HBP. It can also be observed that HBP reduces with increase in blend proportion at a constant load which may be due to lower calorific value of Karanja biodiesel compared to Diesel oil.

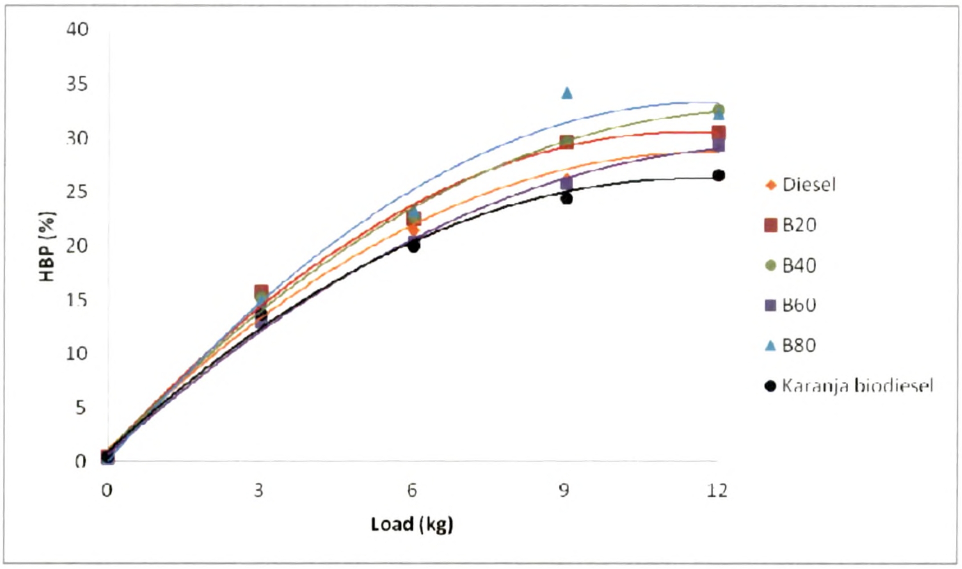

Figure 4.29 Comparison of Variation of HBP with Load at a CR of 18 and IP of 200bar

The values of HBP for Diesel oil are 0.33%, 15.04%, 21.46%, 26.17% and 29.29% and for Karanja biodiesel are 0.41%, 13.63%, 20.03%, 24.39% and 26.64% for the tested loads of 0kg, 3kg, 6kg, 9kg and 12kg. It can be noted that HBP for Karanja biodiesel is close to that of Diesel oil (just about 2% less for Karanja).

Figure 4.30 shows the comparison of variation of HGas with load for Karanja biodiesel and its blends with Diesel oil at CR of 18 and IP of 200bar. It is observed that change in load does not have much effect on the HGas of the engine. It can also be observed that HGas is less for blends compared to Diesel oil. The trend can be attributed to the lower calorific value of Karanja biodiesel. The trend can also probably be due to the result of complete oxidation of the fuel constituents due to inherent oxygen present in Karanja biodiesel.

It is always desirable to have less heat carried away by exhaust from the engine. The values of HGas for highest load tested are 24.08%, 29.03%, 31.18%, 24.92%, 30.35% and 21.71% for Diesel oil, B20, B40, B60, B80 and Karanja biodiesel respectively. HGas for Karanja biodiesel as compared to Diesel oil is 9.8% lower at a load of 12kg.

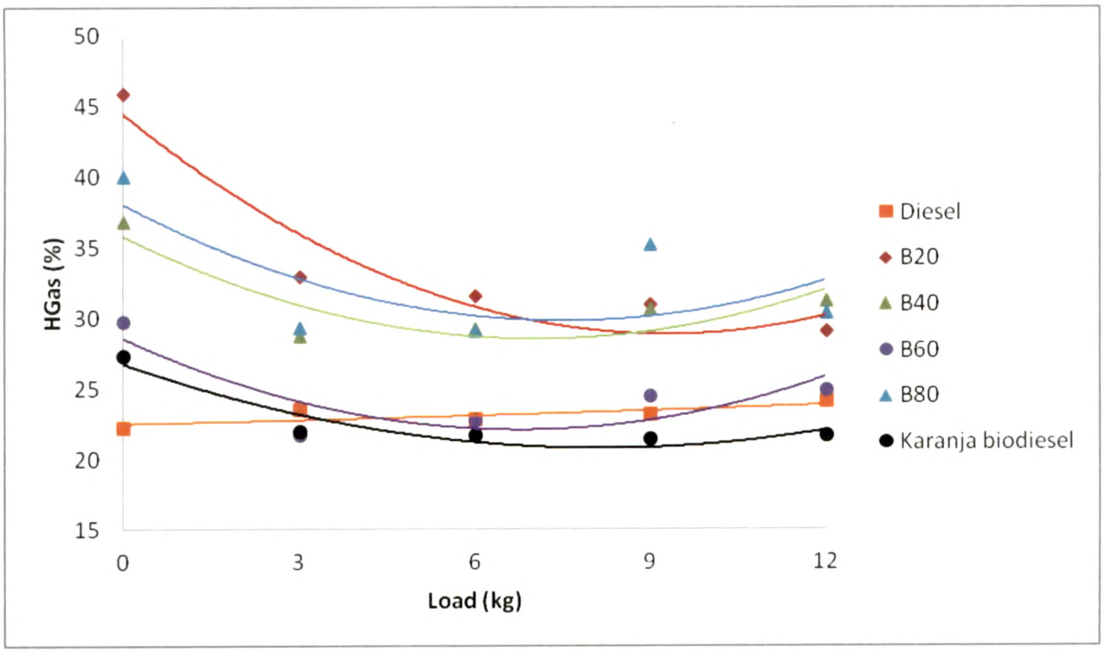

Figure 4.30 Comparison of Variation of HGas with Load at a CR of 18 and IP of 200bar

Figure 4.31 represents the comparison of variation of EGT with load for Karanja biodiesel and its blends with Diesel oil at CR of 18 and IP of 200bar. It can be observed that with the EGT increases with the increase in load. The trend may be due to higher temperature inside the engine cylinder as more fuel is burnt to meet the higher load demand.

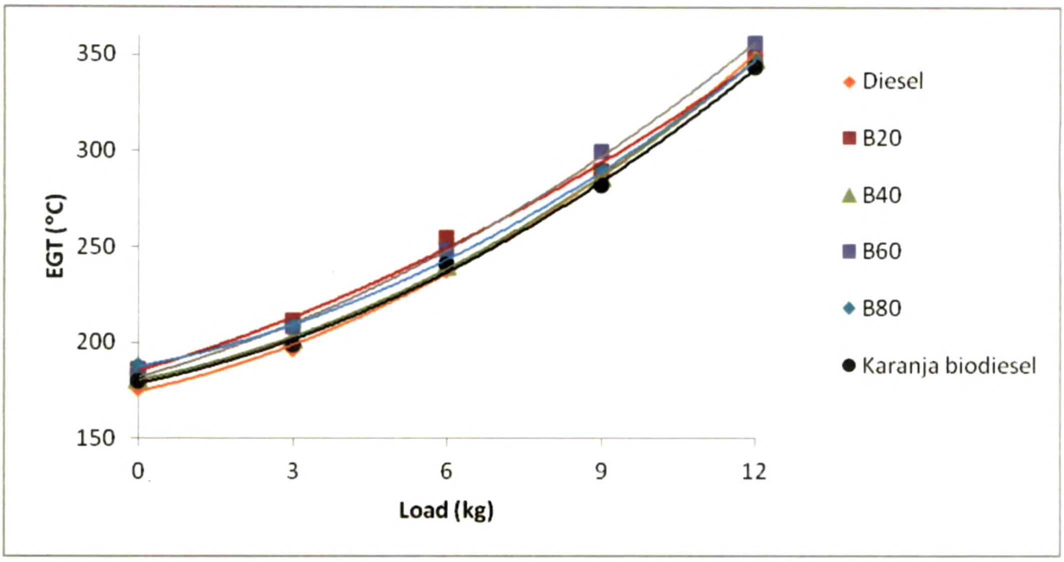

Figure 4.31 Comparison of Variation of EGT with Load at a CR of 18 and IP of 200bar

It is observed that EGT decreases with increase in blend proportion however the decrease is not significant. The trend may be attributed to the lower calorific value and complete combustion of blends due to their inherent oxygen content. The values of EGT at full load for Diesel oil, B20, B40, B60, B80 and Karanja biodiesel are 350.75 ^{0}C, 348.56 ^{0}C, 347.96 ^{0}C, 356.04 ^{0}C, 346.99 ^{0}C and 343.77 ^{0}C respectively.

Figure 4.32 shows the comparison of variation of EGT with Load at a CR of 18 and IP of 200bar of the present study with that of earlier investigations of Sureshkumar et al. [52], Raheman & Phadatare [17], Jindal et al. [66], Raheman & Ghadge [40].

Similar increasing trends of EGT with load as found in the present study are observed by Sureshkumar et al. [52], Raheman & Phadatare [17] and Raheman & Ghadge [40]. Sureshkumar et al. [52] and Raheman & Phadatare [17] used Karanja biodiesel and Raheman & Ghadge [40] used Mahua biodiesel for the study. Sureshkumar et al. [52] has reported 22% less EGT at a constant load of 9kg while 9% less EGT has been reported by Raheman & Phadatare at a constant load of 12kg using Karanja biodiesel as compared to the present study. It is seen that the EGT at 12kg load is more by 11% for Jatropha and less by 2% for Mahua as compared to that of Karanja biodiesel used in the present study.

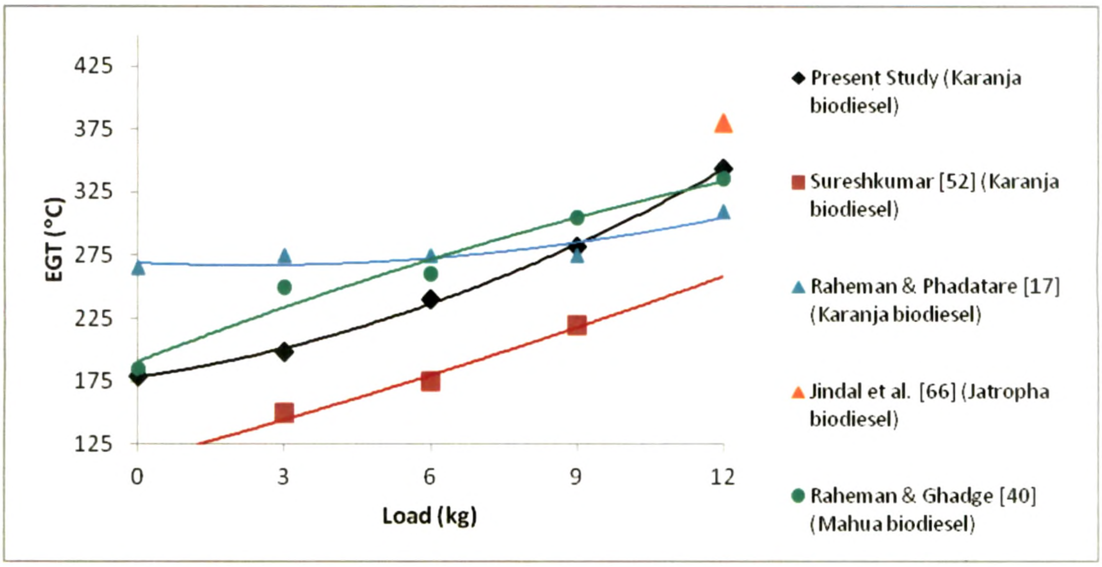

Figure 4.32 Comparison of Variation of EGT with Load at a CR of 18 and IP of 200bar with Earlier Studies

4.2.2.3 Injection Pressure

The variations of thermal performance parameters at different IPs from 150bar and 250bar in steps of 50bar are presented in Figures 4.33 to 4.41. The IP is varied maintaining at a constant CR and load at 18 and 12kg respectively.

The comparison of variation of BTHE with IP for Karanja biodiesel and its blends with Diesel oil at CR of 18 and load of 12kg is presented in Figure 4.33. It is observed that BTHE increases with the increase in IP for all the fuels tested. The trend observed is mainly due to higher degree of atomisation at higher IPs due to which more surface area of fuel droplets is available to be surrounded by oxygen ensuring complete combustion though the amount of fuel being injected is the same across different injection pressures.It is also observed that BTHE increases linearly for Karanja biodiesel, B40, B20 and Diesel oil fuel whereas the variation is non linear for B60 and B80. This can be attributed to experimental perturbations. BTHE is found to increase from 31.34%to 32.7% for Diesel oil and from 27.46% to 28.33% for Karanja biodiesel when the IP increased from 150bar to 250bar. BTHE variation for B60 and B80 has been shown with bestfit trend line.

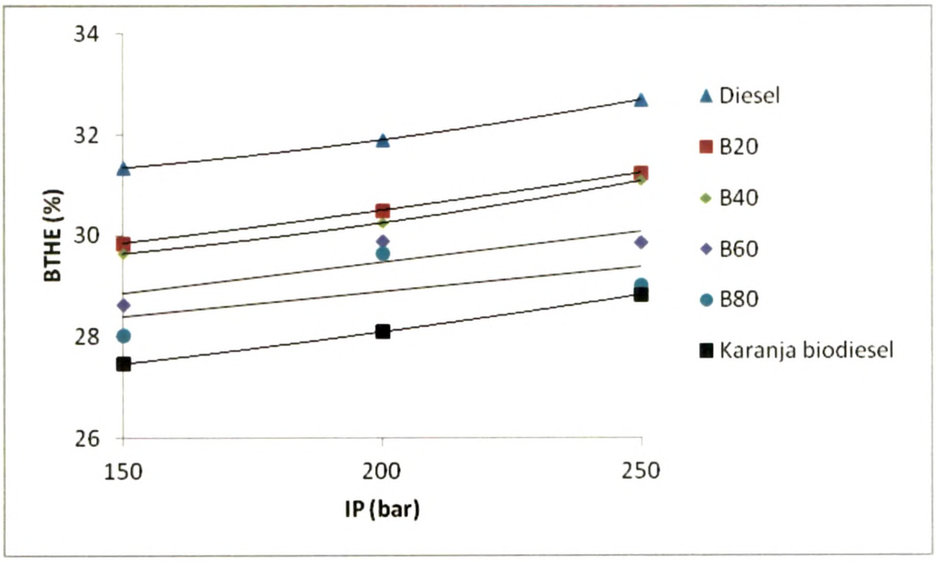

Figure 4.33 Comparison of Variation of BTHE with IP at CR of 18 and Load of 12kg

Figure 4.34 presents comparison of variation of BSFC with IP for Karanja biodiesel and its blends with Diesel oil at CR of 18 and load of 12kg. It can be observed that BSFC reduces with the increase in IP for all the fuels tested. The trend may be due to higher degree of atomisation at higher IP which exposes larger surface area of fuel droplet to the high temperature air inside the cylinder leading to complete combustion of fuel. Hence the power demand is met with less amount of fuel.

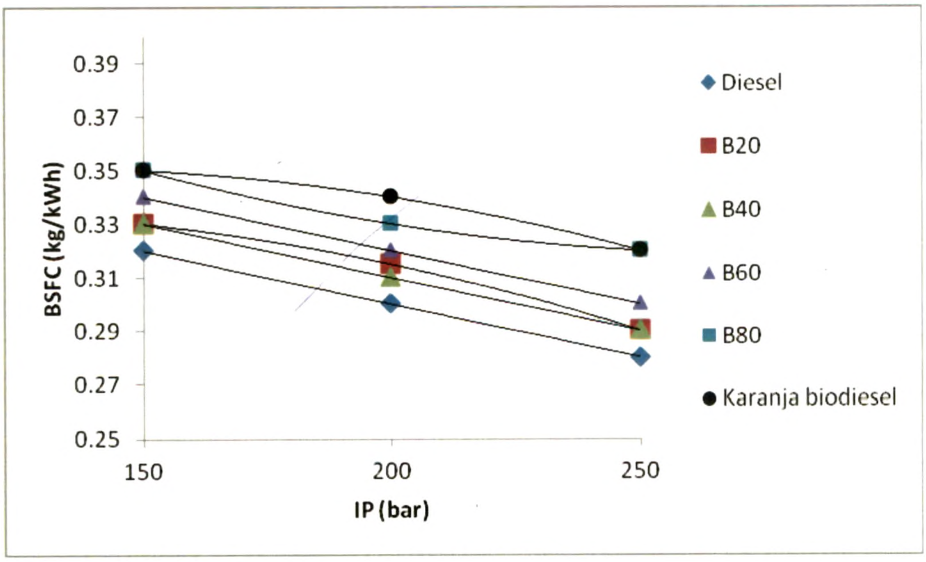

Figure 4.34 Comparison of Variation of BSFC with IP at CR of 18 and Load of 12kg

BSFC is higher for higher blend proportion at a constant IP. The trend is mainly due to greater requirement of fuel flow into the engine because of relatively higher viscosity and lower calorific value of Karanja biodiesel. BSFC for Karanja biodiesel is higher by 0.04 Kg/kW-hr as compared to that of Diesel oil at IP of 250 bar.

Figure 4.35 shows the comparison of variation of BTHE and BSFC with IP at a CR of 18 and load of 12kg of the present study with that of earlier investigations of Jindal et al. [66] using Jatropha biodiesel.

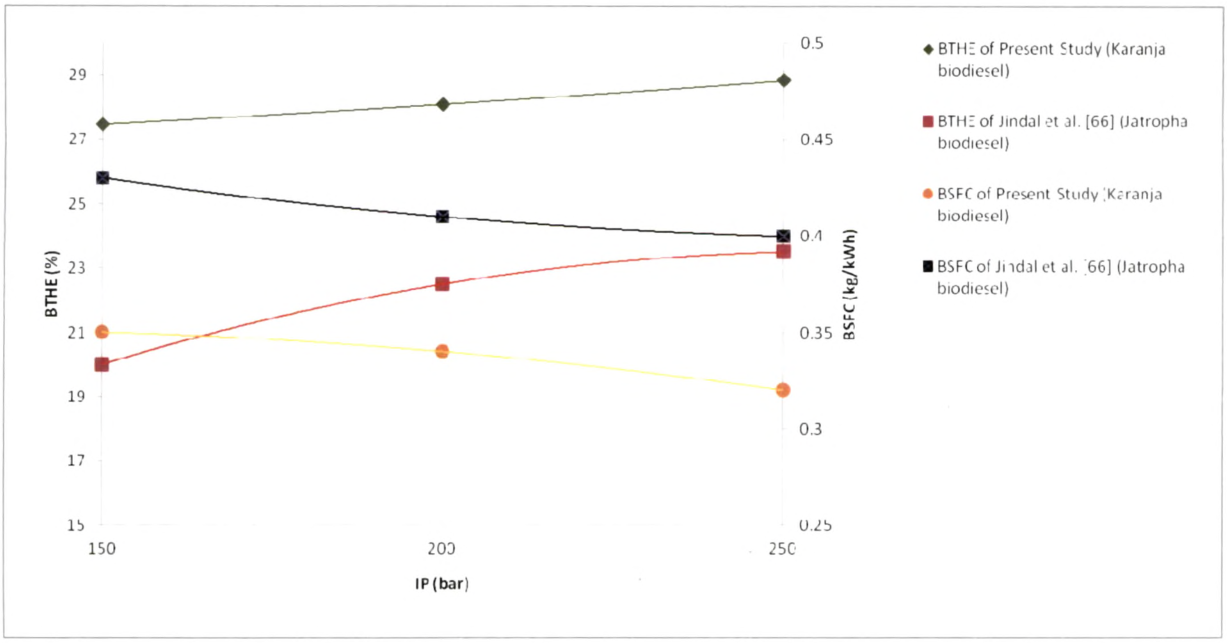

Figure 4.35 Comparison of Variation of BTHE and BSFC with IP at a CR of 18 and IP of 200bar with Earlier Studies

Similar increasing trend of BTHE with load as found in the present study is observed by Jindal et al. [66]. It is seen that the value of BTHE at an IP of 250bar is less by 18% for Jatropha as compared to that of Karanja biodiesel used in the present study. Also, similar decreasing trend of BSFC with load as found in the present study is observed by Jindal et al. [66]. It is seen that the value of BSFC at an IP of 250bar is more by 25% for Jatropha as compared to that of Karanja biodiesel used in the present study.

Figure 4.36 shows the comparison of variation of BMEP with IP for Karanja biodiesel and its blends with Diesel oil at CR of 18 and load of 12kg. It can be observed that the effect of IP on BMEP is not significant. However, a marginal increase in BMEP with increase in IP is observed for all the fuels tested. The trend may probably be due to finer degree of atomisation of fuel at higher IP, leading to proper mixing of fuel with the hot compressed air causing efficient combustion. The trend can also be attributed to more surface area of fuel droplets exposed to hot air in the engine cylinder leading to complete combustion. It can be observed that no specific trend is followed for the variation of BMEP with blend proportion. It can be inferred that BMEP is more a function of the injection pressure but not the blend.

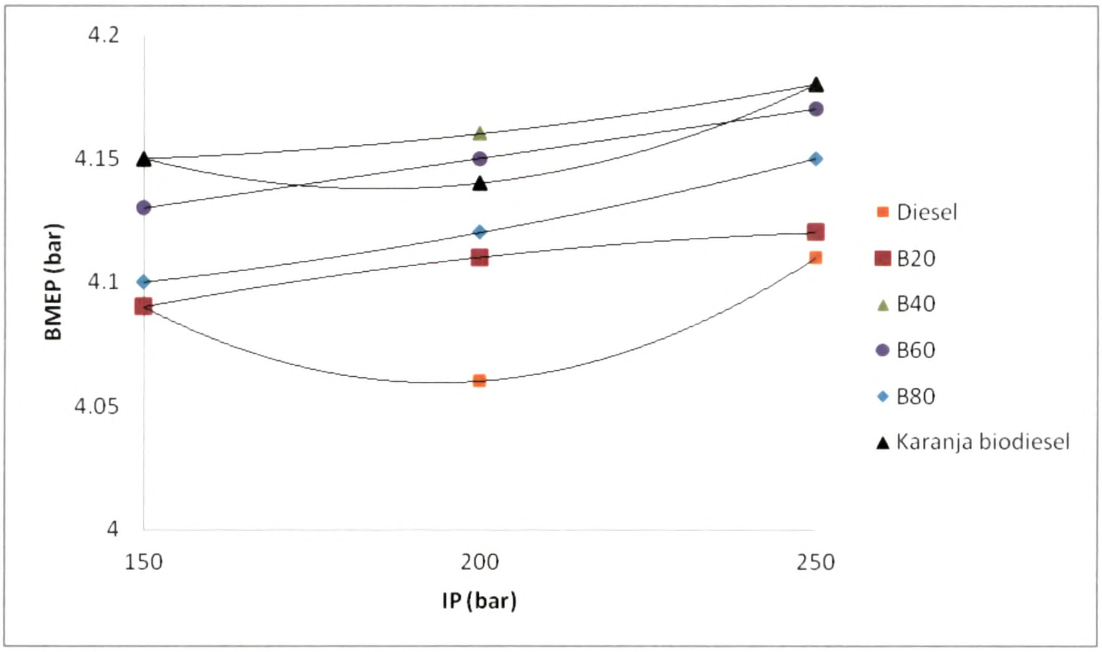

Figure 4.36 Comparison of Variation of BMEP with IP at CR of 18 and Load of 12kg

Figure 4.37 shows the comparison of variation of volumetric efficiency with IP for Karanja biodiesel and its blends with Diesel oil at CR of 18 and load of 12kg. It is observed that volumetric efficiency remains constant with IP for Diesel oil, B60 and Karanja biodiesel.

Although the blends B20, B40 and B80 show some variation in volumetric efficiency, the trend cannot be attributed to nature of fuel or change in IP. It can only be due to experimental perturbations. It is observed that volumetric efficiency for blends is more compared to that of Diesel oil. The trend may be due to more dilution of charge with residual gases with Diesel oil compared to Karanja biodiesel.

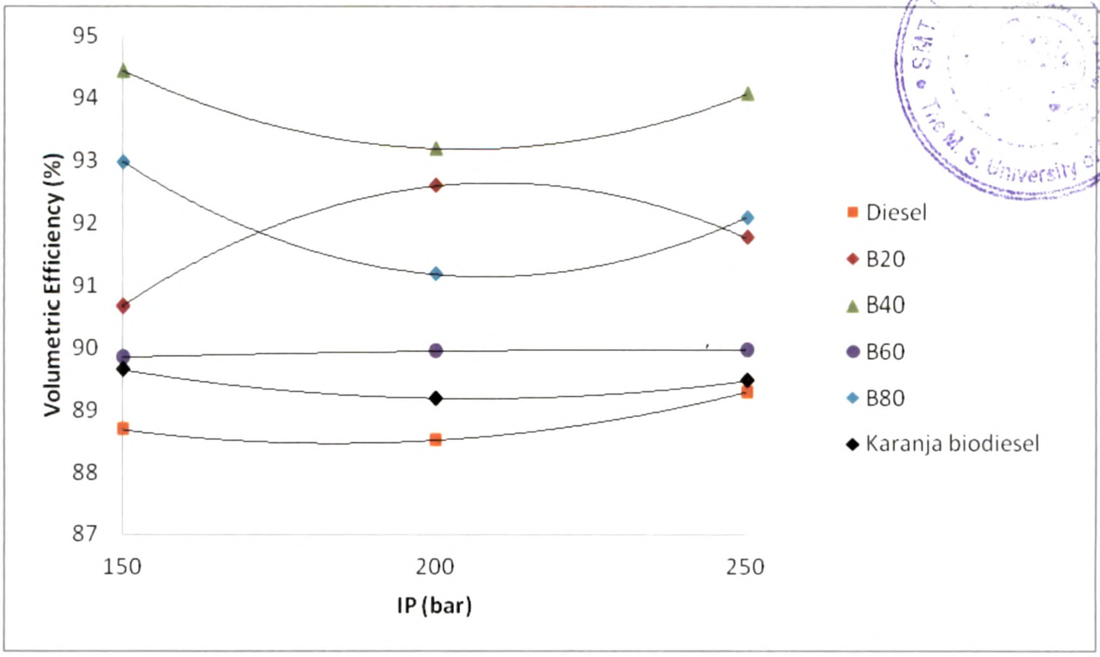

Figure 4.37 Comparison of Variation of Volumetric Efficiency with IP at CR of 18 and Load of 12kg

Figure 4.38 presents the comparison of variation of HBP with IP for Karanja biodiesel and its blends with Diesel oil at CR of 18 and load of 12kg. It is seen that the HBP increases with increase in IP for all the fuels tested. The trend is due to a reason that

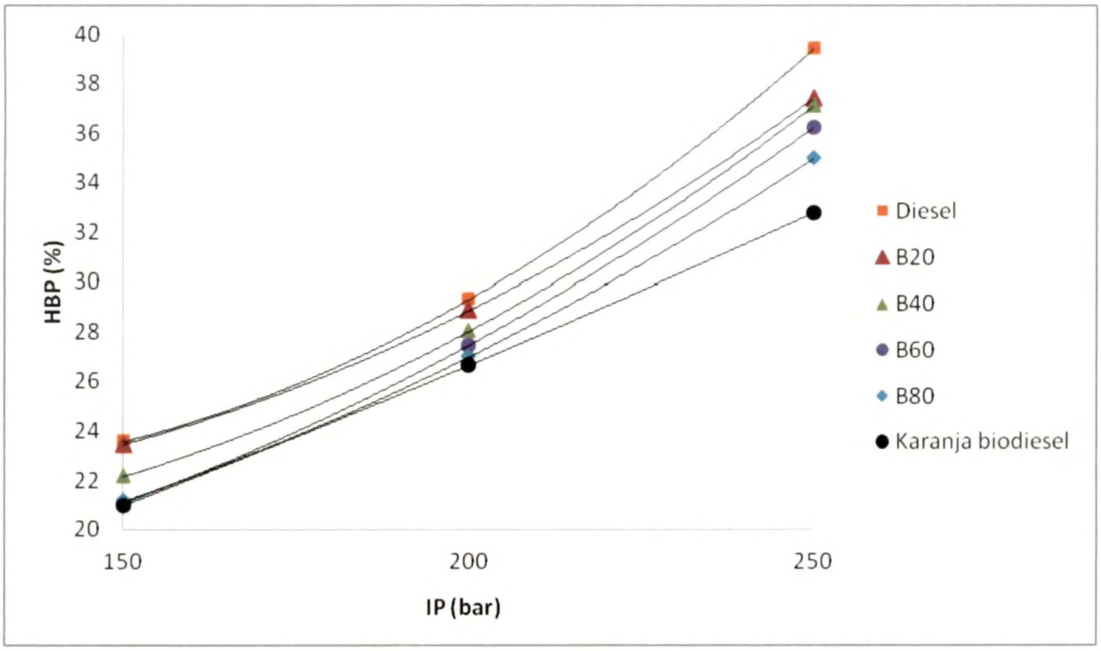

Figure 4.38 Comparison of Variation of HBP with IP at CR of 18 and Load of 12kg

at higher IP, the fuel is atomized to a higher degree which exposes larger surface area of fuel droplet to the high temperature air inside the cylinder which ensures complete combustion of fuel hence more heat is released.

It is also observed that HBP decreases with blend proportion at both lower and higher IPs. It may be due to lower calorific value of Karanja biodiesel. The HBP for Diesel oil for the respective IPs tested are 23.56%, 29.29% and 39.41% and for Karanja biodiesel are 20.98%, 26.64% and 32.78% respectively. It can be noted that HBP for Karanja biodiesel is close to that of Diesel oil at all IPs tested.

Figure 4.39 presents the comparison of variation of HGas with IP for Karanja biodiesel and its blends with Diesel oil at CR of 18 and load of 12kg. It is observed that HGas increases with increase in IP for blends B40, B60, B80 and Karanja biodiesel. The increase is linear for B60, B80 and Karanja biodiesel while it is initially decreasing and subsequently increasing for B40. The increasing trend may due to complete combustion of fuel at higher IP which in turn is due to finer atomisation. It is also observed that HGas for Diesel oil and B20 decrease with increase in IP. The trend may be due to experimental perturbations.

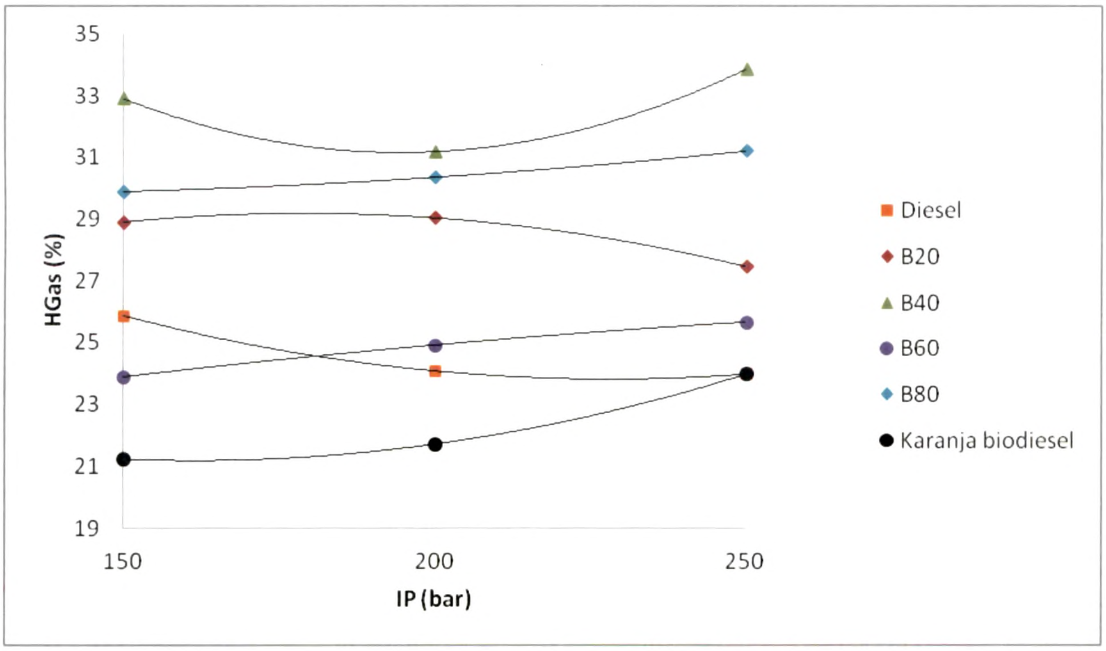

Figure 4.39 Comparison of Variation of HGas with IP at CR of 18 and Load of 12kg

The HGas at tested IPs for Diesel oil are 25.87%, 24.08% and 23.98% and Karanja biodiesel are 21.23%, 21.71% and 23.98% respectively. HGas is observed to be less for Karanja biodiesel compared to Diesel oil. The reason may be complete combustion of Karanja biodiesel as it is an oxygenated fuel.At IP of 200 bar the values of HGas are identical for Karanja biodiesel & Diesel oil.

The comparison of variation of EGT with IP for Karanja biodiesel and its blends with Diesel oil at CR 18 and Load of 12kg is presented in Figure 4.40. It is observed that EGT increases linearly with the increase in IP for all the fuels tested. The trend is due to complete combustion of fuel at higher IP due to which more heat is generated in the exhaust. The complete combustion is obviously due to better atomisation at higher IP. It is also observed that EGT is less for blends compared to Diesel oil. The trend may be due to lower calorific value of Karanja biodiesel.

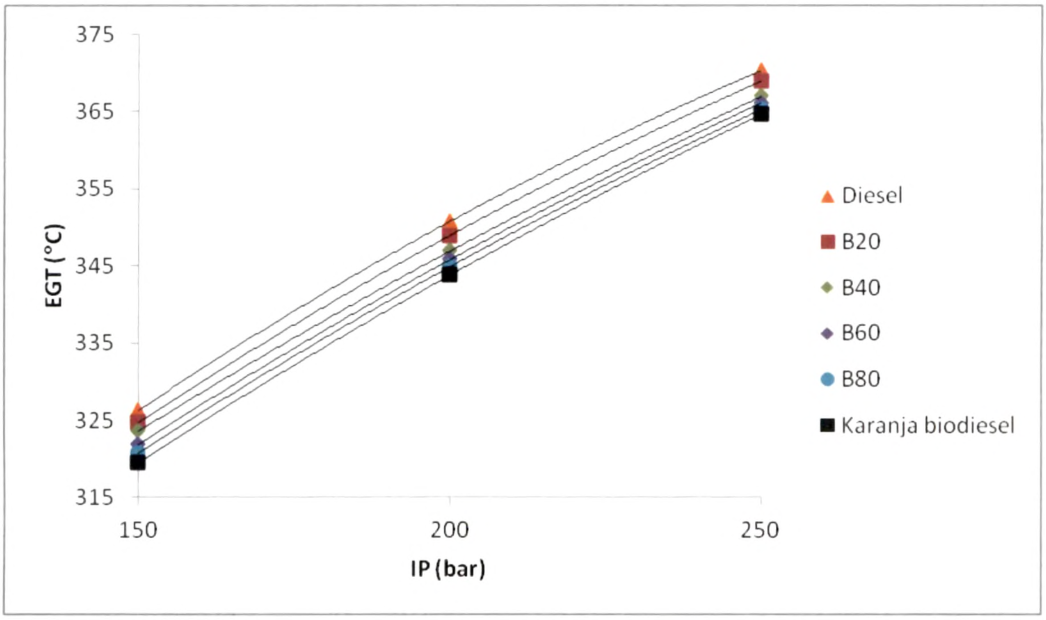

Figure 4.40 Comparison of Variation of EGT with IP at CR of 18 and Load of 12kg

The increase in EGT around 15% (50^0C) as the IP is increases from 150 to 250 bar. At IP of 250 bar, the values of EGT for Karanja biodiesel, B80, B60, B40, B20 and Diesel oil are found to be 364.59 ^{0}C, 365.23 ^{0}C, 366.09 ^{0}C, 366.9 ^{0}C, 368.9 ^{0}C and 370.26 ^{0}C respectively. It can be noted that EGT for Karanja biodiesel is about 2% less than that for Diesel oil.

A comparison of variation of EGT with IP of present study with Jindal et al. [66] is shown in Figure 4.41. They studied the variation of EGT with IP using Jatropha biodiesel. The EGT for Jatropha biodiesel is observed to be higher than Karanja biodiesel at all IPs. It is seen that the EGT at an IP of 250bar is 13% more for Jatropha biodiesel as compared to that of Karanja biodiesel used in the present study.

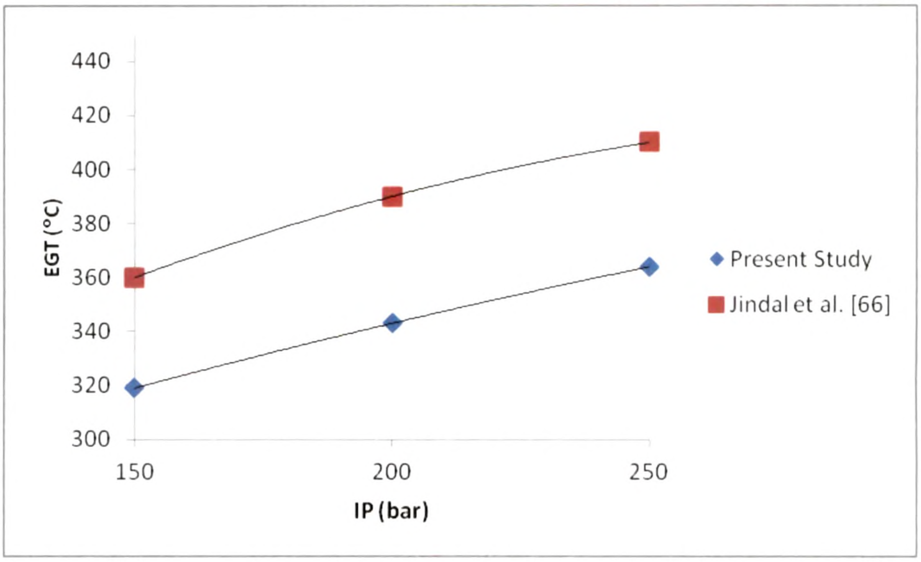

Figure 4.41 Comparison of Variation of EGT with IP at a CR of 18 and Load of 12kg of Present Study with Jindal et al. [66]

4.2.3 Emission Characteristics

The combustion product emissions from diesel engines are hydrocarbon emissions and form a significant part of the engine exhaust. Hydrocarbons in the exhaust may also condense to form white smoke during engine starting and warm up. Specific hydrocarbon compounds in exhaust gases are a source of diesel odour. Diesel engines are also a source of different particulate emissions. Between 0.2 to 0.5 % of the fuel mass is emitted as small particles which consist primarily of soot with some additional hydrocarbon material. Diesel engines are not a very significant source of carbon monoxide emission comparatively. The other exhaust emissions include NO_x i.e nitrogen oxides and aldehydes which are a significant source of air pollution. Half of NO_x, CO and HC pollutants in air are primarily because of IC engines. NO_x may react with solar radiation to form ozone. Hydrocarbons cause cellular mutations and are responsible for ground level ozone formation. SO_x formation is significant in diesel engines. However with the use of biofuels as fuels, the harmful constituents of HC, CO, SO_x can significantly be brought down.

The emission constituents considered for evaluation are Carbon dioxide (CO_2), Carbon monoxide (CO), Oxides of Nitrogen (NO_x), Unburned Hydrocarbon (HC), Oxygen (O_2), Smoke intensity (HSU) and Oxides of Sulphur (SO_x). The variations of the emission constituents with CR, Load and IP are interpreted in three different sections 4.2.3.1, 4.2.3.2 and 4.2.3.3 respectively. For each constituent, the variations for Diesel oil, Karanja biodiesel and blends of Karanja biodiesel with diesel as fuels are superposed and analysed.

4.2.3.1 Compression Ratio

The variations of exhaust emission constituents at different values of CRs at 14, 15, 16, 17, 17.5 and 18 with a constant rated load of 12kg and IP of 200bar is presented in Figures 4.42 to 4.50.

Figure 4.42 presents the comparison of variation of CO with CR for Karanja biodiesel and its blends with Diesel oil at load of 12kg and IP of 200 bar. It can be observed that CO emission decreases with increase in CR.

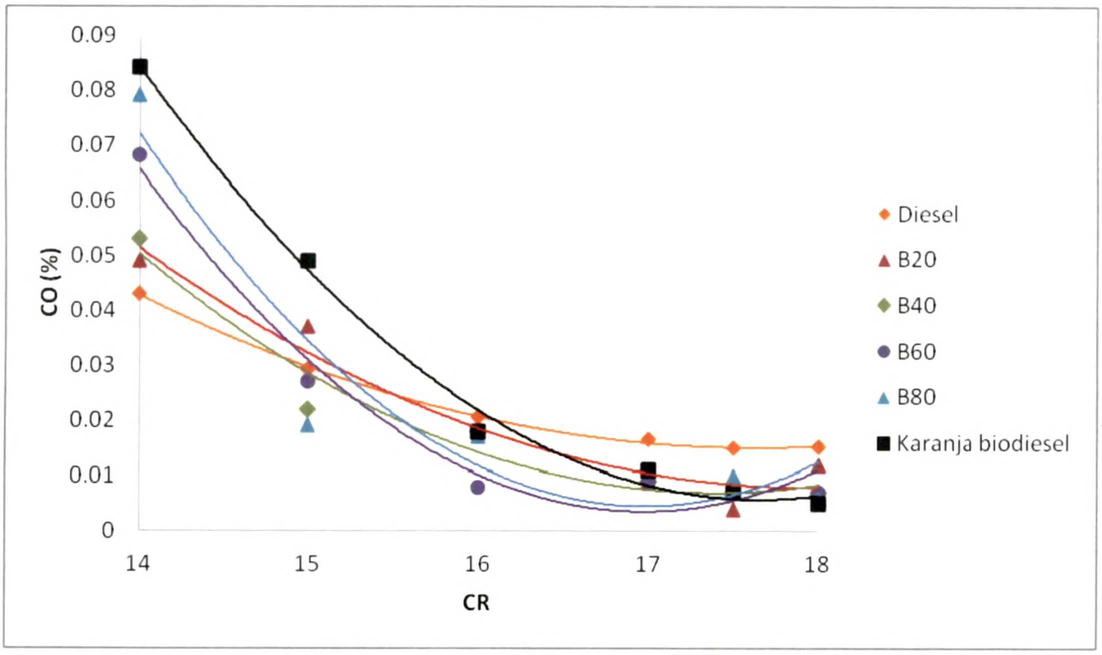

Figure 4.42 Comparison of Variation of CO with CR at Load of 12kg and IP of 200bar

The trend may be due to better combustion of fuel at higher CR which in turn is due to high air temperature inside the cylinder. It can also be observed that at low CRs, CO emissions are higher and at higher CRs, it is lesser for blends compared to Diesel oil. The lower CO emissions for blends may be due to the oxygenated nature of Karanja biodiesel due to which more of carbon gets oxygenated forming CO. The higher CO emissions for the blends at low CR may be due to higher viscosity of biodiesel which leads to poor atomization and incomplete combustion.

The values of CO emissions for Diesel oil at tested CRs are 0.043%, 0.0293%, 0.0205%, 0.0166%, 0.015% and 0.0152% and for Karanja biodiesel 0.084%, 0.049%, 0.018%, 0.011%, 0.007% and 0.005% respectively. It can be noted that CO emissions are 66% less for pure Karanja biodiesel as compared to Diesel oil at CR of 18.

The comparison of variation of HC with CR for Karanja biodiesel and its blends with Diesel oil at a load of 12kg and IP of 200 bar is shown in Figure 4.43. The unburnt hydrocarbons (HC) are generated in the exhaust as the result of incomplete combustion of fuel. Hydrocarbons cause eye irritation and choking sensations. They are major contributors to the characteristic diesel exhaust smell and also have a negative environmental effect, being an important component of smog. Hydrocarbon from diesel engines come primarily from (i) the fuel trapped in the injector at the injection that later diffuses out, (ii) the fuel mixed into the air surrounding the burning spray so lean that it cannot burn, (iii) the fuel trapped along the walls by crevices, deposits, or oil due to impingement by the spray.

It can be observed from the figure that HC emissions decrease with increase in CR for all the fuels tested. The trend observed may be due to complete combustion of fuel which is due to high heat of compressed air at higher CR.

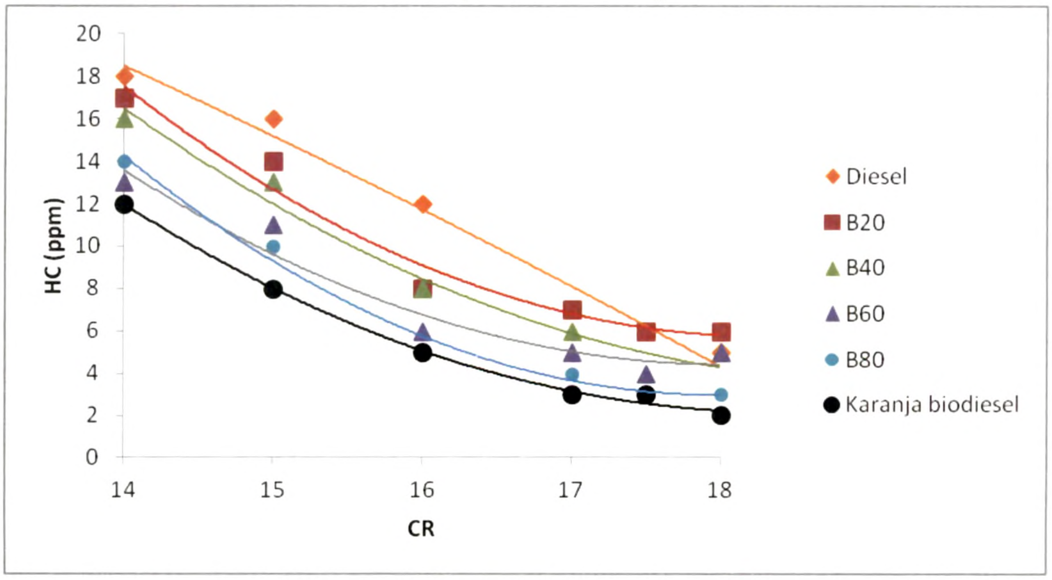

Figure 4.43 Comparison of Variation of HC with CR at Load of 12kg and IP of 200bar

It is also observed that HC decreases with the increase in blend proportion. The trend may be due to better combustion of Karanja biodiesel due to its oxygenated nature. The mean percentage decrease in HC emission with Karanja biodiesel as compared to Diesel oil is of the order of 60% except at 14 CR where it is around 33%.

Figure 4.44 shows the comparison of variation of HC emissions with CR at a load of 12kg and IP of 200bar of the present study with that of earlier investigations of Banapurmath et al. [44] and Jindal et al. [66]. The biodiesel used by the investigators are Karanja and Jatropha respectively.

Banapurmath et al. [44] studied HC emissions at a constant CR of 17.5 using Karanja biodiesel. The investigators reported 59ppm higher HC emissions as compared to that of the present study. The trends of HC emissions with CR observed by Jindal et al. [66] using Jatropha biodiesel are not as found in the present study. The HC emissions are almost constant at all the CRs for Jatropha biodiesel. It is seen that the HC emissions at a CR of 18 is more by 13ppm for Jatropha as compared to that of Karanja biodiesel used in the present study.

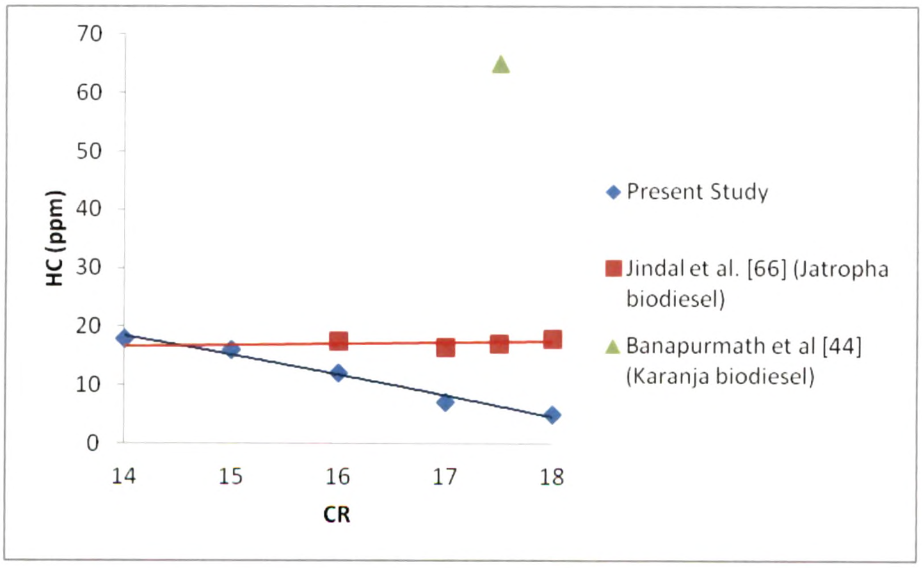

Figure 4.44 Comparison of Variation of HC with CR at a Load of 12kg and IP of 200bar Present Study with Earlier Studies

Figure 4.45 shows comparison of variation of NO_x with CR for Karanja biodiesel and its blends with Diesel oil at load of 12kg and IP of 200 bar. Nitrogen oxides are formed throughout the combustion chamber during the combustion process due to the reaction of atomic oxygen and nitrogen. Reactions forming NO_x are very temperature dependent and NO_x emissions from the engine are low at lesser loads. NO_x emissions consist of nitrogen dioxide (NO_2) and nitric oxide (NO).

It can be observed from the figure that NO_x emissions increases for blends while it decreases for Diesel oil with increase in CR. The trend observed for blends is because at lower CR, less oxygen is available from blends to form NO_x due to less heat of compressed air, but at higher CR greater availability of oxygen and higher heat of compressed air initiates early combustion ensuring complete oxidation of fuel.

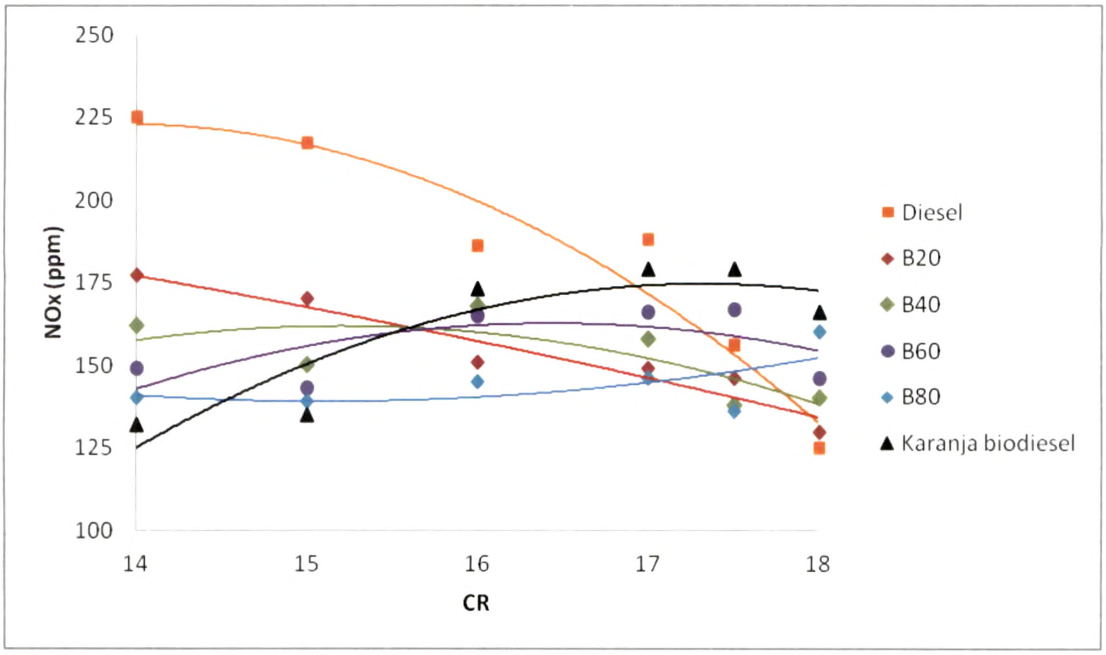

Figure 4.45 Comparison of Variation of NO_X with CR at Load of 12kg and IP of 200bar

The values of NO_x emissions in ppm for Diesel oil at CRs of 14, 15, 16, 17, 17.5 and 18 are 225, 217, 186, 188, 156, and 125 and for pure Karanja biodiesel are 132, 135, 173, 179, 179, and 166 respectively. At a CR of 14 the NO_X emissions for Diesel oil are higher by 70.4% and at CR 18 they are lower by 24.6% as compared to Karanja biodiesel. At higher CRs of 17 to 18 NO_x emission is found to be higher as compared to that of Diesel oil

Figure 4.46 presents the comparison of variation of CO_2 with CR for Karanja biodiesel and its blends with Diesel oil at load of 12kg and IP of 200bar. The amount of

CO_2 in the exhaust is an indication of degree of complete oxidation of the carbon constituent of the fuel and hence indicates the extent of conversion of chemical energy into thermal energy. It is observed from the figure that CO_2 emission initially decrease, reach the lowest and subsequently increase with the increase in CR for all the fuels tested. It is also observed that CO_2 emission is higher for Karanja biodiesel compared to Diesel oil at all CRs. The trend may be due to complete oxidation of carbon present in the biodiesel due to its inherent oxygen content.

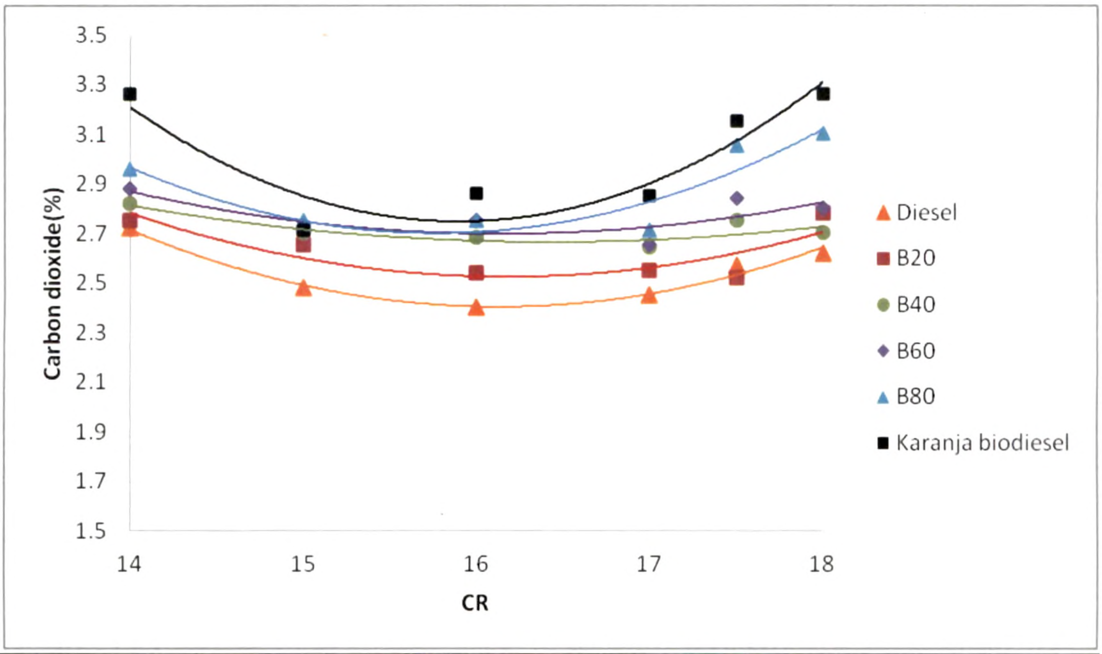

Figure 4.46 Comparison of Variation of CO_2 with CR at Load of 12kg and IP of 200bar

As the CR increases from 14 to 18 the values of CO_2 emission for Diesel oil are 2.72%, 2.48%, 2.4%, 2.45%, 2.57% and 2.62% and for Karanja biodiesel are 3.26%, 2.71%, 2.86%, 2.85%, 3.15% and 3.26%. It can be noted that the percentage decrease in CO_2 emissions between Karanja Biodiesel and Diesel oil over the range of CRs is 22%.

The comparison of variation of O_2 emission with CR for Karanja biodiesel and its blends with Diesel oil at load of 12kg and IP of 200bar is presented in Figure 4.47. It can be observed that O_2 content in the exhaust increases with increase in CR. At low CRs, O_2 emission is less with Diesel oil as compared to Karanja biodiesel and its blends. However, at higher CRs of 16, 17 and 18, O_2 emission is found to be almost the same for all the tested fuels existing in the range of 17 to 18 indicating only a marginal increase at at higher CRs which in turn indicates that the O_2 emission is not affected by CR except for Diesel oil at CR of 14 where it is around 1% less. This is inconfirmity with the variation of A/F with CR. The trend observed may be due to high temperature inside the cylinder at higher CR which results in better combustion of fuel releasing more oxygen.

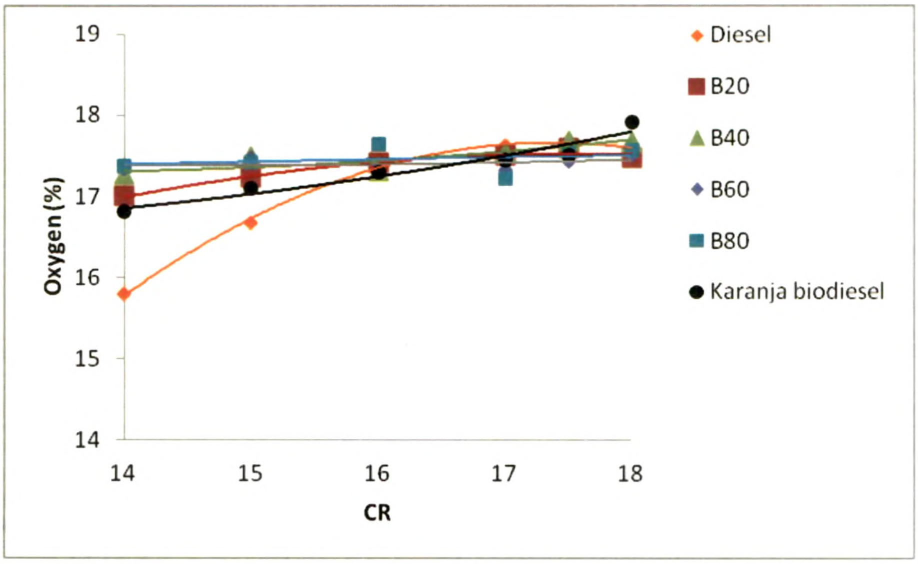

Figure 4.47 Comparison of Variation of O_2 with CR at Load of 12kg and IP of 200bar

It is also seen that O_2 is more for Karanja biodiesel than Diesel oil at all CRs. The trend may be due to inherent presence of oxygen in the biodiesel. The O_2 in the exhaust increases by 12%, 2.76%, 2.37%, 0.92%, 1.1% and 6.54% for Diesel oil, B20, B40, B60, B80 and Karanja biodiesel respectively when the CR is increased from 14 to 18. The O_2 emission is 2.8% more for Karanja biodiesel than Diesel oil.

Figure 4.48 gives the comparison of variation of SO_x with CR for Karanja biodiesel and its blends with Diesel oil at load of 12kg and IP of 200bar. Sulphur dioxide is a colourless toxic gas with a characteristic of irritating odour. Oxidation of sulphur dioxide produces sulphur trioxide which is the precursor of sulphuric acid which, in turn, is responsible for the sulphate particulate matter emissions. Sulphur oxides have a profound impact on environment being the major cause of acid rains. Sulphur dioxide is generated from the sulphur present in Diesel oil fuel. The concentration of SO_2 in the exhaust gas depends on the sulphur content of the fuel.

It can be observed from the figure that SO_x decreases with the increase in CR for all the fuels tested. It can also be seen that SO_x emissions are highest for Karanja biodiesel at low CRs and it reduces with increase in CR and becomes minimum at highest CR. At lower CR, there is a chance of incomplete combustion. Hence formation of carbon dioxide is less due to which the oxygen present in fuel as well as that in air reacts with sulphur present in air in case of Karanja biodiesel and sulphur present in fuel in case of blends forming oxides of sulphur. With the increase in CR the oxides of sulphur reduce by 67, 51, 59, 55, 47 and 127 ppm for Diesel oil, B20, B40, B60, B80 and Karanja biodiesel respectively. This is consistent with lower air fuel ratio at higher CR for the fuels tested though oxygen present in the exhaust is same at higher CRs (Refer Appendinx III, P291-a for the results of variation of A/F ratio with CR, load and IP).

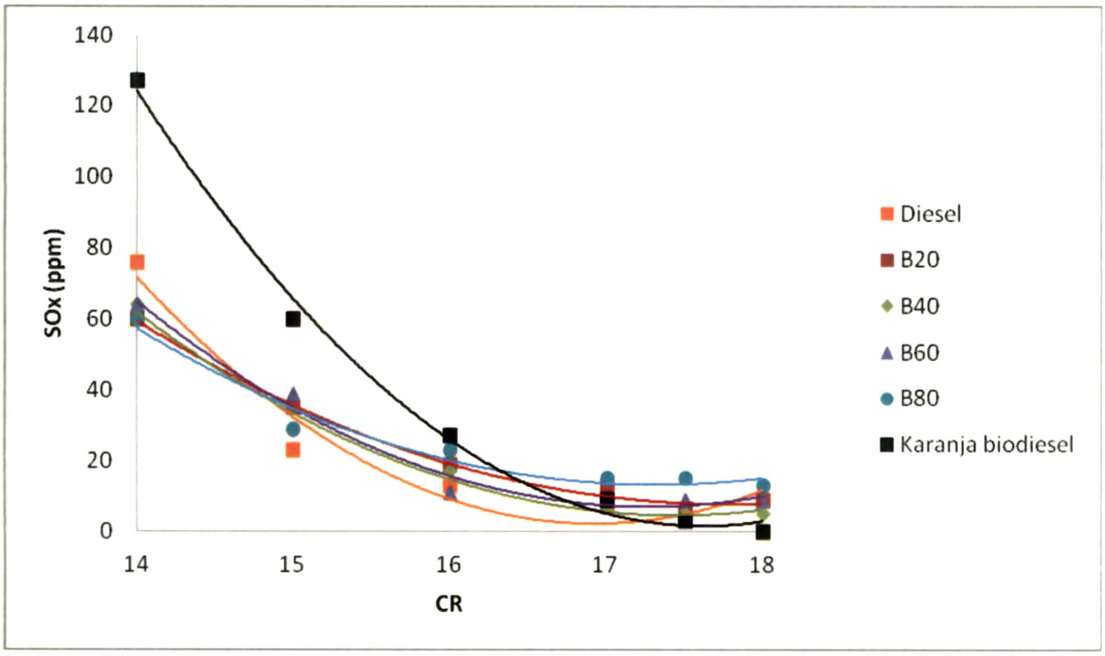

Figure 4.48 Comparison of Variation of SO_X with CR at Load of 12kg and IP of 200bar

The Figure 4.49 illustrates the variation of smoke intensity with CR for all the fuels tested. Smoke intensity is also known as soot or particulate emissions in the form of solid carbon, unburnt hydrocarbons in the exhaust gases. These emissions are a major problem with diesel engine's heterogeneous combustion. Even partial oxidation products are considered under this category. Smoke intensity is measured in Hartridge Smoke Unit (HSU) and expressed in '%'. Higher HSU indicates that either more fuel is burnt or the fuel burning process is hindered by some unfavourable conditions. It is observed from the figure that smoke is less at higher CR for all the fuels. This may be due to a reason that at higher CR the heat of the compressed air is high enough to cause complete combustion of fuel. At lower CR, smoke is high as incomplete combustion of fuel takes place.

Generally smoke intensity is high for Karanja biodiesel & its blends because they have more viscosity than pure Diesel oil and this has a negative effect on the combustion

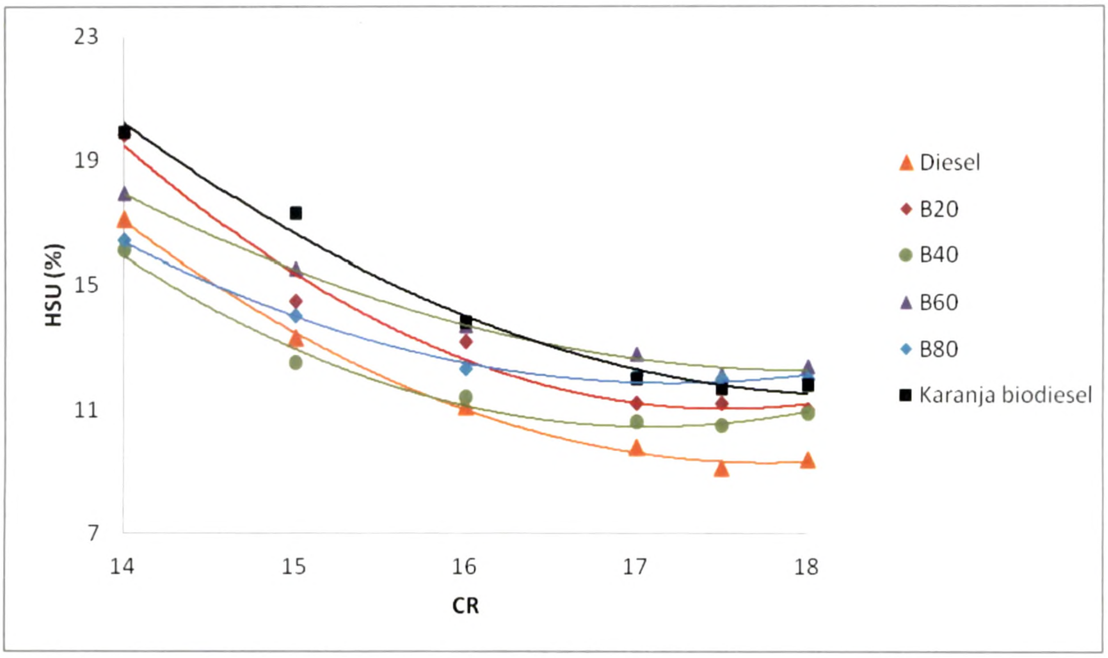

Figure 4.49 Comparison of Variation of HSU with CR for at Load of 12kg and IP of 200bar

process. The HSU decreases by 45% for Diesel oil and 40% for pure Karanja biodiesel as the CR increases from 14 to 18. At a CR of 18, the HSU for pure Karanja biodiesel is 2.4% higher than that for Diesel oil.

The engine may be operated with any higher CR ranging from 16 to 18 so far as the emission constituents such as CO, HC, CO_2, O_2 and SO_x are concerned. The reason is the mentioned emission constituents are least and remain constant in the CR range of 16 to 18. However the NO_x emissions are found to be more at higher CRs with Karanja biodiesel as compared to Diesel oil. Therefore, the selection of CR can be made based on the relative combined effect on thermal performance and emissions. It is preferable to operate the engine at CR 18, as the CR is also selected earlier for thermal performance evaluation.

Figure 4.50 shows the comparison of variation of NO_x emissions and smoke (HSU) of exhaust gas with CR at a load of 12kg and CR of 18 of the present study with that of earlier investigations of Sureshkumar et al. [52], Jindal et al. [66] and Raheman & Phadatare [17]. The biodiesel used by the investigators are Karanja and Jatropha.

Sureshkumar et al. [52] and Raheman & Phadatare [17] studied NO_x at a constant CR of 16.5 and 16 respectively using Karanja biodiesel. Sureshkumar et al. [52] reported 8% higher NO_x while 95% less NO_x is reported by Raheman & Phadatare [17] as compared to that of the present study. Similar increasing trends of NO_x with CR as found in the present study are observed by Jindal et al. [66] using Jatropha biodiesel. It is seen that the NO_x emissions at a CR of 18 is more by 32% for Jatropha as compared to that of Karanja biodiesel used in the present study.

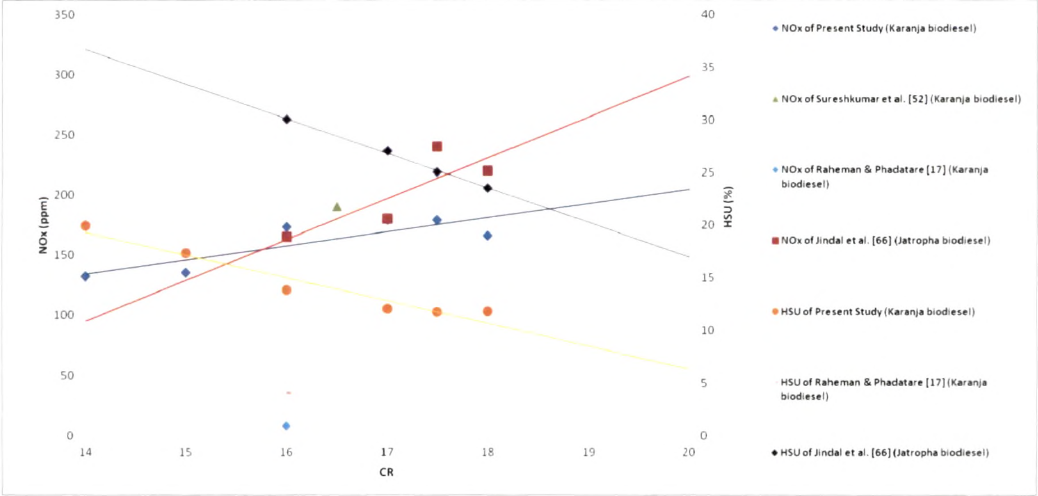

Figure 4.50 Comparison of Variation of NO_x and HSU with CR at a Load of 12kg and IP of 200bar with Earlier Studies

Raheman & Phadatare [17] reported a 71% reduction in HSU using Karanja biodiesel as compared to that of the present study. Similar decreasing trends of HSU with CR as found in the present study are observed by Jindal et al. [66] using Jatropha biodiesel. It is seen that HSU at a CR of 18 is almost double for Jatropha as compared to that of Karanja biodiesel used in the present study.

4.2.3.2 Load

The variations of exhaust emission constituents at different loads from 0kg to 12kg in steps of 3kg at a constant CR of 18 and IP of 200bar are presented in Figures 4.51 to 4.58.

Figure 4.51 gives the comparison of variation of CO emission with Load for Karanja biodiesel and its blends with Diesel oil at load of 12kg and IP of 200bar. It is observed that CO emissions increase with the increase in load. The trend can be attributed to more fuel being consumed at higher loads which means rich running of the engine and there being insufficient oxygen to convert all the carbon in the fuel to carbon dioxide. It is a well known fact that the formation of CO as an emission constituent in the exhaust gases is mainly due to incomplete oxidation of carbon constituent in the fuel.

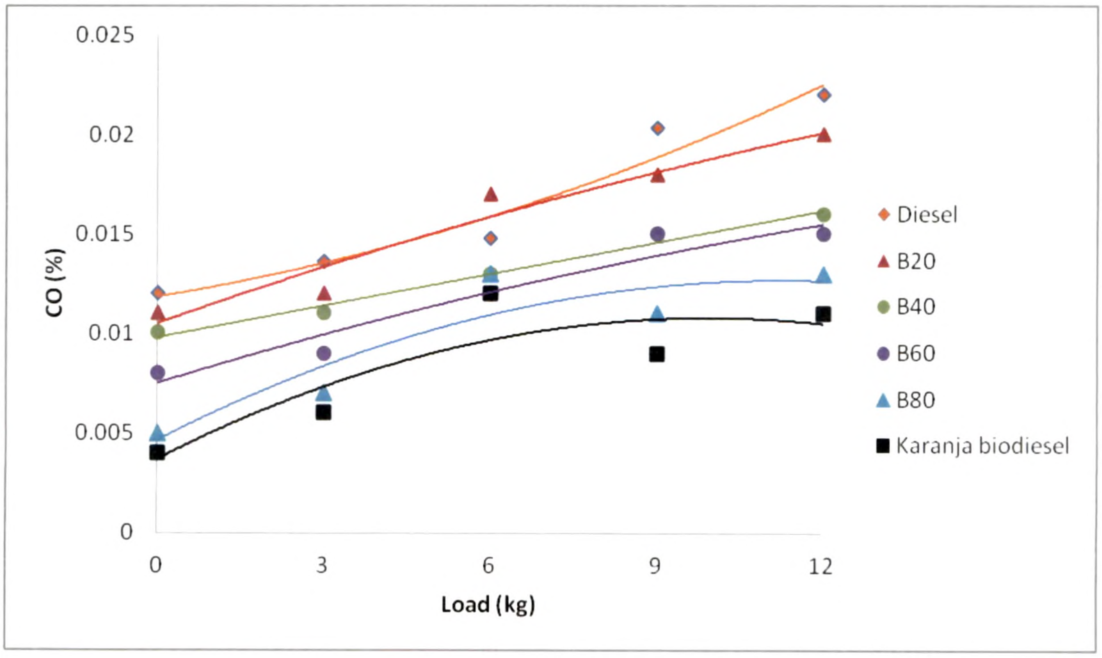

Figure 4.51 Comparison of Variation of CO with Load at CR of 18 and IP of 200bar

As Karanja biodiesel contains more oxygen, the increase in blend proportion reduces CO emissions because oxygen promotes complete combustion. It is found that the CO emissions increase up to about 175% from no load to full load condition for all the fuels tested. At full load of 12kg, it is seen that there is a 66% reduction in CO emissions when Karanja biodiesel is used as compared to Diesel oil.

Figure 4.52 gives the comparison of variation of HC with load for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and IP of 200bar. It can be observed that HC emissions increase with increase in load for all the fuels tested. The increase is steeper at higher loads than at lower loads. The steeper increase at higher loads may be due to the rich fuel air mixture as compared to stoichiometric which leads to improper burning thereby resulting in increase of HC content in the exhaust.

It can be observed that HC emissions decrease with increase in blend proportion at a constant load. The trend can be attributed to the higher oxygen content of Karanja biodiesel due to which complete combustion takes place inside the cylinder. HC emissions increase by 30% to 100% for all blends when load is increased from 0kg to 12 kg. With the increase in blend ratio, up to 66% of reduction is observed in HC emissions for all the loads under consideration. The unburned HC emissions for Diesel oil vary between 6 to 8ppm and for Karanja biodiesel they vary between 2ppm to 4ppm.

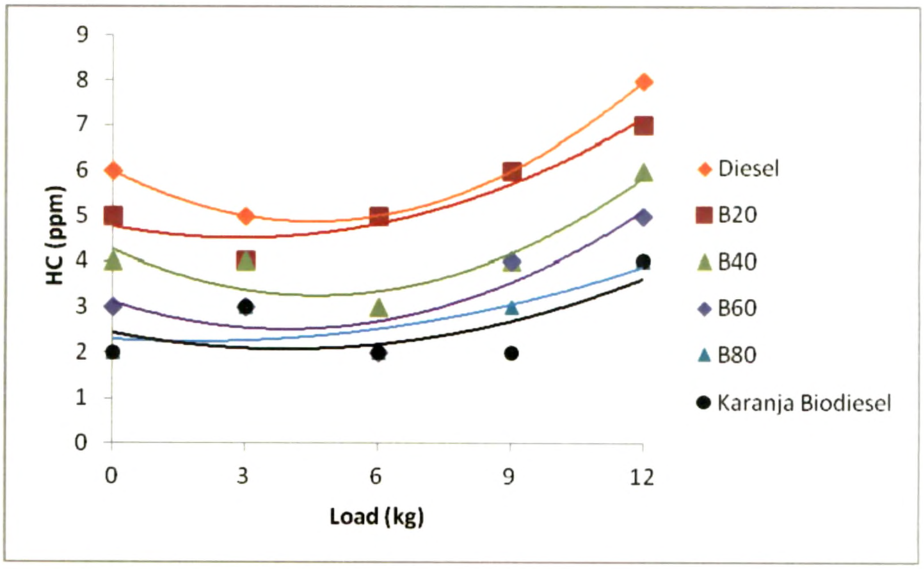

Figure 4.52 Comparison of Variation of HC with Load at CR of 18 and IP of 200bar

Figure 4.53 gives the comparison of variation of NO_x with load for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and IP of 200bar. It can be observed that NO_x emissions increase with increase in load. The trend can be attributed to more temperature with diesel as fuel and higher temperature and inherint higher oxygen content with biodiesel and its blends as fuels.

It can be observed that the NO_x emissions are higher for biodiesel blends. The reason for higher NO_x is higher oxygen content of Karanja biodiesel than Diesel oil. During combustion process of blends, more oxygen is available from fuel and nitrogen from air readily gets combined with oxygen at higher cylinder temperatures and forms compounds like nitrogen dioxide (NO_2) and nitric oxide (NO) which constitute NO_x.

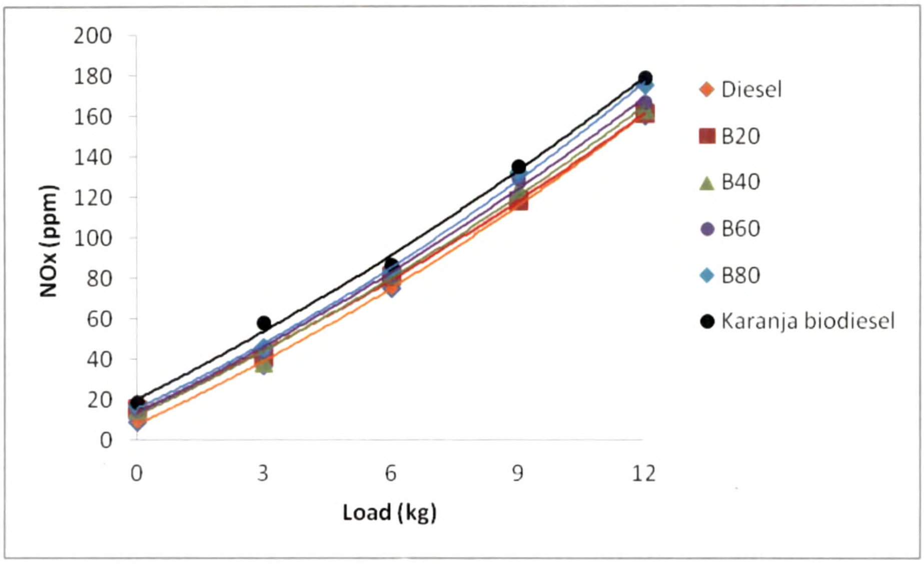

Figure 4.53 Comparison of Variation of NOx with Load at CR of 18 and IP of 200bar

The NO_x emissions for Karanja biodiesel are 11.8% higher than that for Diesel oil at a full load of 12kg. The values of NO_x emissions at the respective tested loads for Diesel oil are 9ppm, 37ppm, 75ppm, 118ppm and 160ppm and for Karanja biodiesel are 19ppm, 58ppm, 87ppm, 135ppm and 179ppm. It is noted that even though NO_x emissions are high for Karanja biodiesel, they are not appreciably high as compared to Diesel oil.

Figure 4.54 presents the comparison of variation of CO_2 with load for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and IP of 200bar. It can be observed that CO_2 increases with the increase in load for all fuels tested. The trend observed may be because of more fuel being burnt at higher loads due to which more carbon is available to form CO_2.

It can also be observed that CO_2 emissions are marginally more for Karanja biodiesel than Diesel oil and it reduces with reduction in blend proportion. The reduction in CO_2 emission is because of high oxygen content in the biodiesel due to which more of the carbon gets oxygenated during combustion inside the cylinder which results in higher CO_2 emission. The percentage increase in CO_2 emissions is about 5% for Karanja biodiesel as compared to Diesel oil at full load of 12kg.

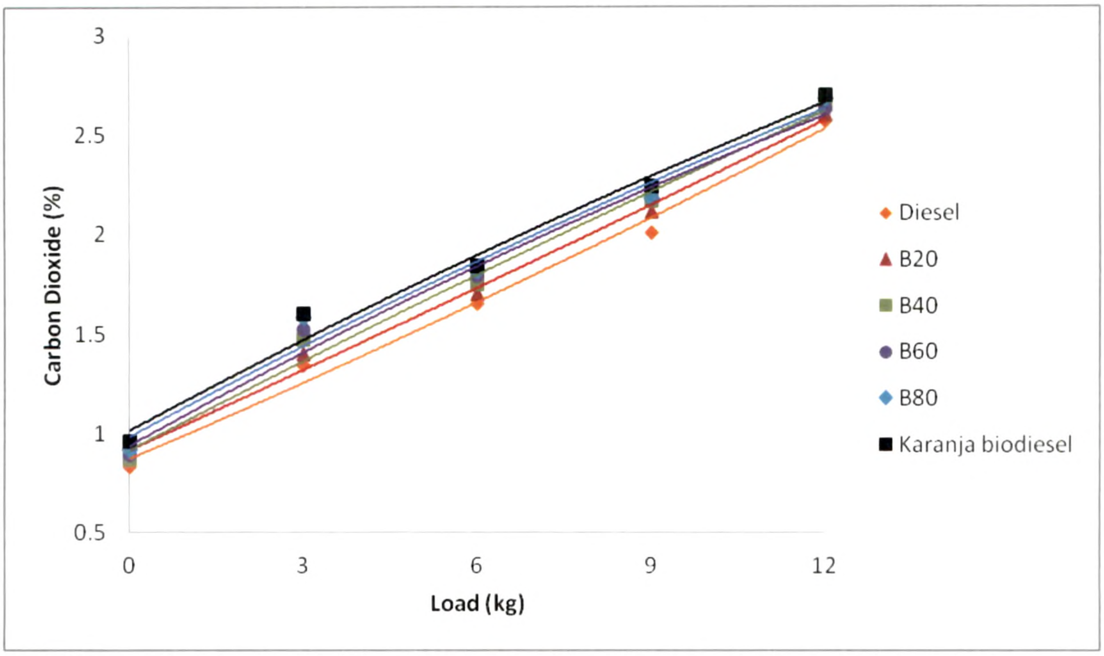

Figure 4.54 Comparison of Variation of CO_2 with Load at CR of 18 and IP of 200bar

Excess air used for combustion results in more of oxygen content in the exhaust. It is also an indicator of the extent of combustion of the fuel and oxygenated nature of the fuel used in the engine. Figure 4.55 presents the comparison of variation of O_2 with load for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and IP of 200bar.

The observed decrease in O_2 content in exhaust decreases with increase in load may be due to richer mixture being burnt in the engine cylinder. This trend also seen in Figures 4.51, 4.53 and 4.54 shows that larger portion of oxygen available in the cylinder additionally due to high temperature reacts with nitrogen and carbon to form CO, NO_x and CO_2 at higher loads. Hence less O_2 is released to the atmosphere. It can also be observed that the O_2 emissions increase with increase in blend proportion. Further, the increase in O_2 emission with increase in blend proportion may be due to the inherent oxygen present in Karanja biodiesel. It can be noted that the percentage of oxygen in the exhaust is maximum for pure Karanja biodiesel and it decreases for other blends in the order B80, B60, B40, B20 and Diesel oil. As the load increases from 0kg and 12kg, the for Karanja biodiesel is higher by about 0.6% compared to that of Diesel oil. Decrease in oxygen percent in exauahst and converging to a almost a constant value shows a similar trend for the variation of A/F ratio with load.

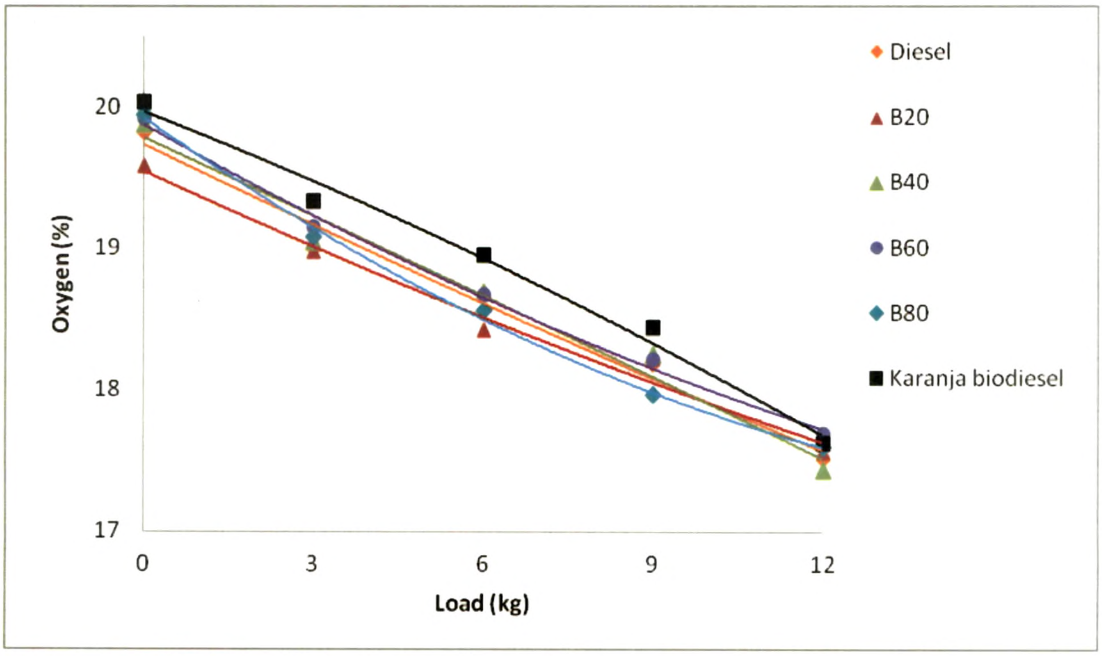

Figure 4.55 Comparison of Variation of O_2 with Load at CR of 18 and IP of 200bar

The comparison of variation of SO_x with load for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and IP of 200bar is given in Figure 4.56. It can be observed that with the increase in load SO_x in the exhaust decreases. The trend may be due to rich fuel air mixture being burnt in the cylinder due to which less oxygen is available to form SO_x.

It is also observed that SO_x emissions decrease with increase in blend proportion. The trend observed is due to the reason that Karanja biodiesel is practically a sulphur free fuel. When engine is fuelled with Karanja biodiesel, traces of sulphur oxide emissions observed at low loads are only due to sulphur present in atmospheric air in vehicular emissions.

With the increase in load from 0kg to 12kg, SO_x emissions reduce by 78%, 84%, 86%, 92%, 100% and 100% for Diesel oil, B20, B40, B60, B80 and Karanja biodiesel respectively.

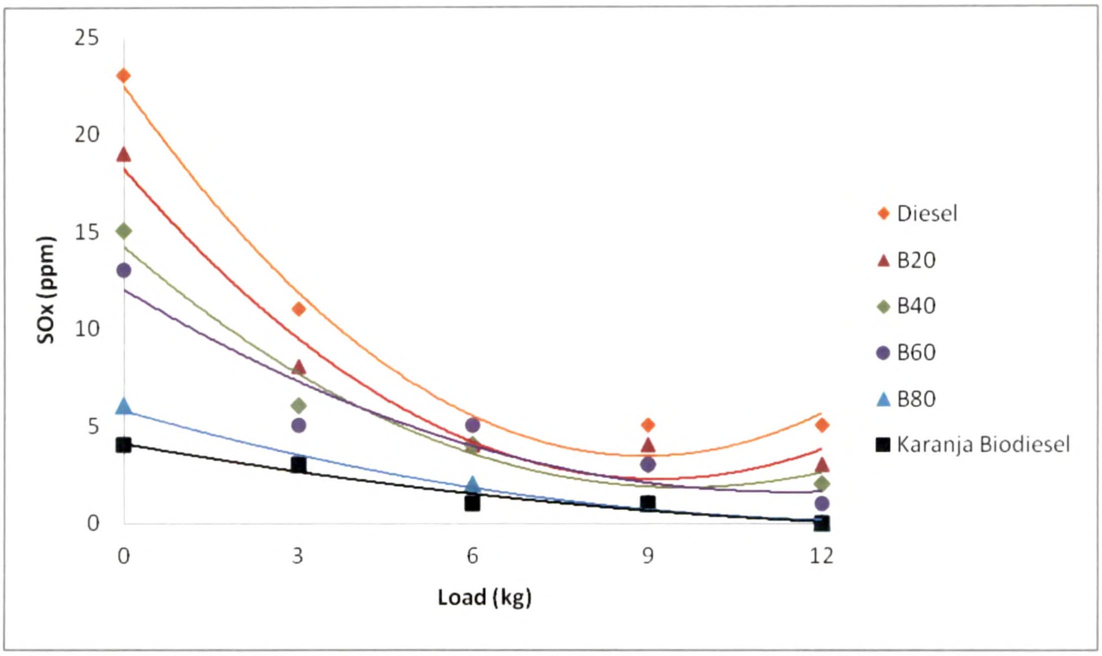

Figure 4.56 Comparison of Variation of SO_x with Load at CR of 18 and IP of 200bar

Figure 4.57 shows the comparison of variation of HSU with load for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and IP of 200bar. The observed increase in smoke intensity (HSU) with increase in load may be due to richer mixture being burnt in the cylinder at higher loads. It is also observed that HSU increases with the increase in blend proportion. The increase in HSU may probably be due to the higher viscosity and lower volatility of Karanja biodiesel due to which it becomes difficult for the fuel to undergo proper atomization and hence incomplete combustion of fuel takes place.

As the load increases from 0kg to 12kg, the HSU for Diesel oil and Karanja biodiesel increase by about 19% and 53% respectively. At a load of 12kg, HSU for Karanja biodiesel is more by about 33% compared to Diesel oil.

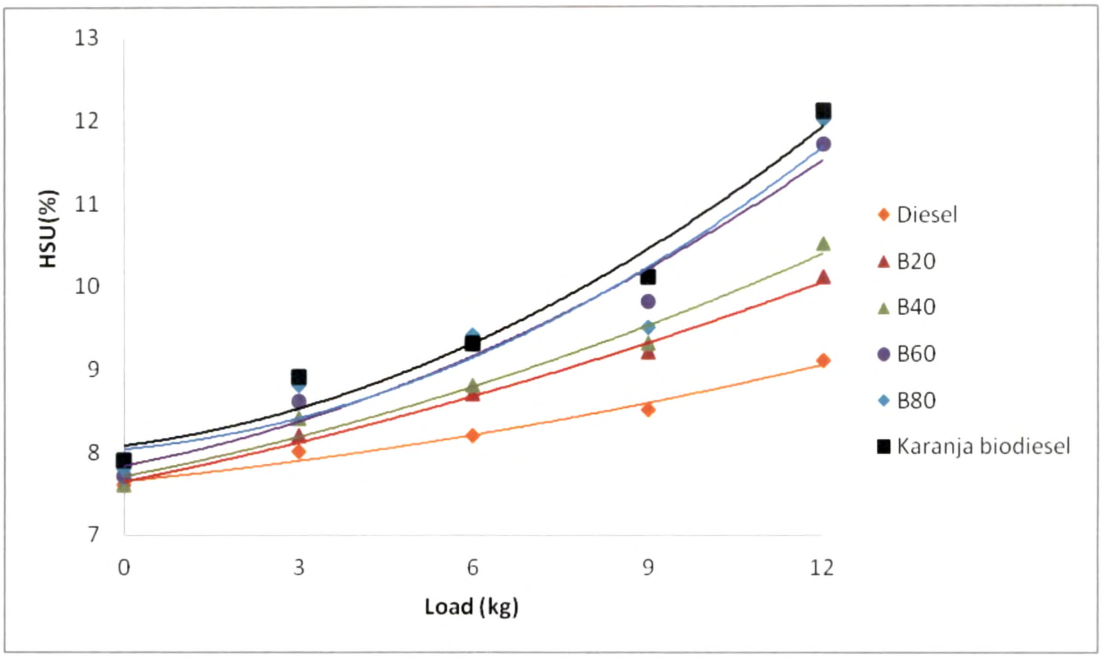

Figure 4.57 Comparison of Variation of HSU with Load at CR of 18 and IP of 200bar

Figure 4.58 shows the comparison of variation of NO_x emissions and smoke (HSU) of exhaust gas with load at a CR of 18 and IP of 200bar of the present study with that of earlier investigations of Sureshkumar et al. [52] and Jindal et al. [66]. The biodiesel used by the investigators are Karanja and Jatropha respectively.

Similar increasing trends of NO_x with load as found in the present study are observed by Sureshkumar et al. [52] using Karanja biodiesel. It is seen that NO_x at a load of 12kg is more by 40% for Sureshkumar et al. [52] as compared to that found in the present study. Jindal et al. [66] studied NO_x emission at full load of 12kg using Jatropha biodiesel. They reported 2.2% less NO_x for Jatropha biodiesel as compared to that of the present study. It is also seen that the HSU at a load of 12kg is almost double for Jatropha as compared to that of Karanja biodiesel used in the present study.

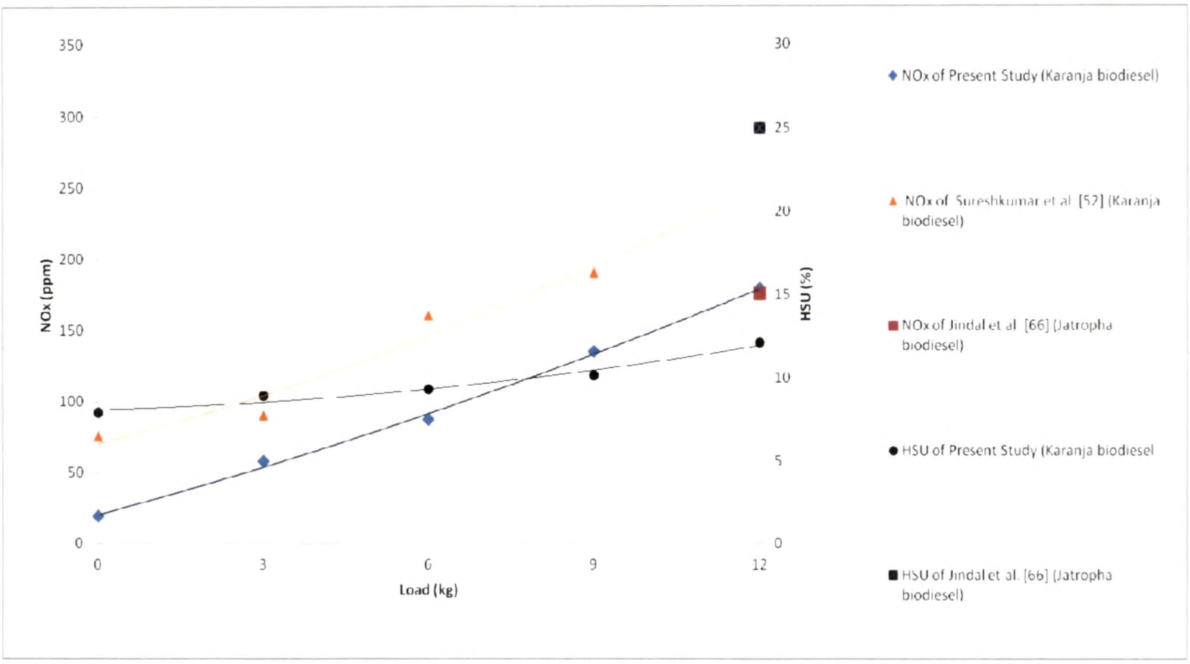

Figure 4.58 Comparison of Variation of NO_x and HSU with Load at a CR of 18 and IP of 200bar with Earlier Studies

4.2.3.3 Injection Pressure

The variations of exhaust emission constituents at different values of IPs from 150bar to 250bar in steps of 50bar at a constant rated load of 12kg and CR of 18 is presented in Figures 4.59 to 4.69.

Figure 4.59 shows the comparison of variation of CO with IP for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and load of 12kg. It is observed that CO emission reduces with increase in IP. The trend observed is due to the reason that as IP increases, the fuel is atomized into very fine droplets and hence more surface area is available for combustion which results in formation of a good quality fuel mixture due to which combustion is complete.

It is also observed that CO emission reduces with increase in blend proportion. The trend observed is because as the concentration of Karanja biodiesel in the blend increases the percentage of oxygen in the blend also increases. Due to higher oxygen content, when the fuel is burnt in the engine cylinder, more of carbon gets oxygenated forming CO_2 resulting in lesser CO emissions.

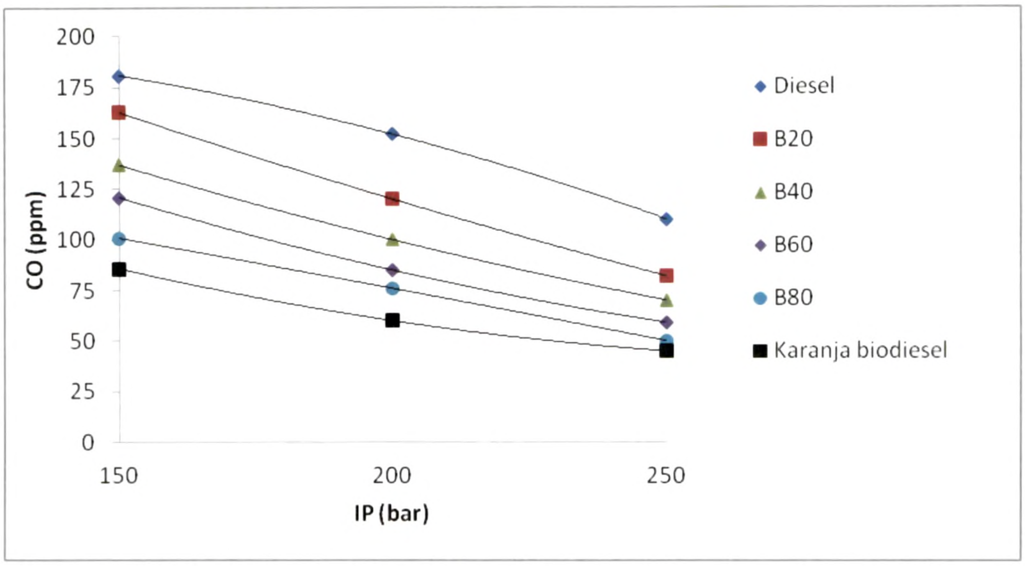

Figure 4.59 Comparison of Variation of CO with IP at CR of 18 and Load of 12kg

The CO emissions reduce up to 39.2%, 49%, 48%, 51.23%, 50% and 47% for Diesel oil, Karanja biodiesel, B80, B60, B40 and B20 respectively when the IP is increased from 150bar to 250bar. It can be noted that at an IP of 250bar, CO emissions for Karanja biodiesel are lesser by about 60% as compared to Diesel oil.

Figure 4.60 shows the comparison of variation of CO emission with IP at a CR of 18 and load of 12kg of the present study with that of Jindal et al. [66] using Jatropha biodiesel. Similar decreasing trends as found in the present study are observed by them.

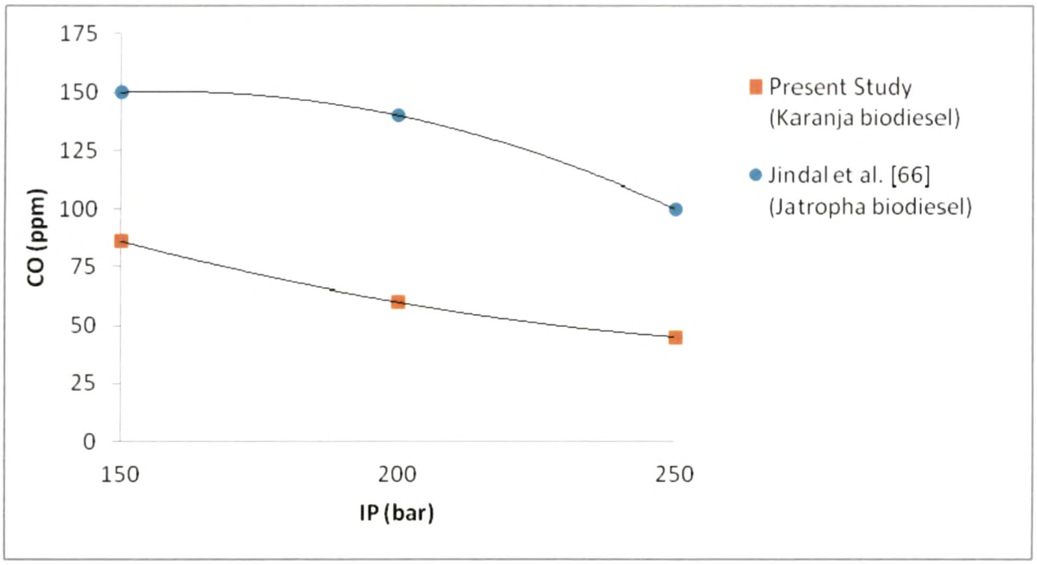

Figure 4.60 Comparison of Variation of CO with IP at a CR of 18 and Load of 12kg with Jindal et al. [66]

The difference between two fuels might be due to better combustion characterstic of Karanja biodiesel at higher CR and IP as compared Jatropha biodiesel of Jindal et.al[66].

It is seen that CO emission at an IP of 250bar is almost double for Jatropha biodiesel as compared to that of Karanja biodiesel used in the present study.

The comparison of variation of HC with IP for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and load of 12kg is shown in Figure 4.61. It can be observed that HC reduces significantly with increase in IP.

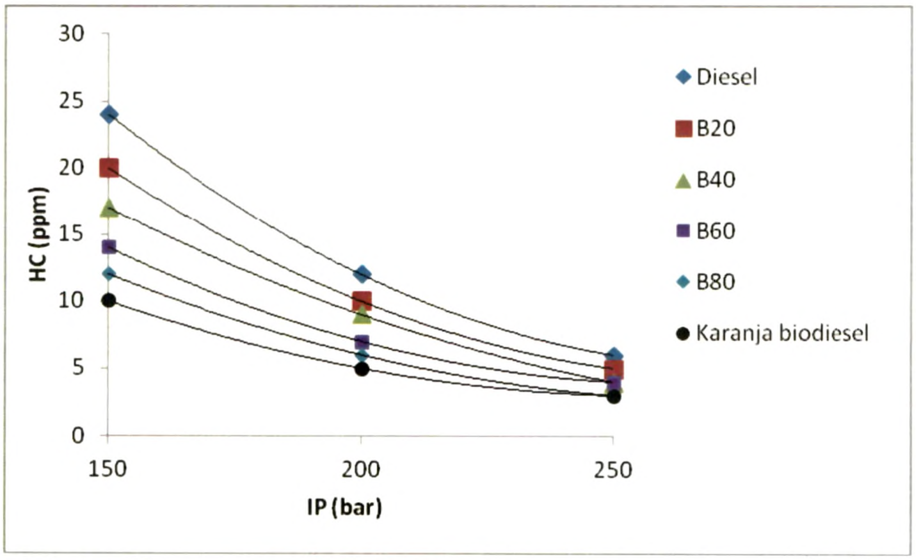

Figure 4.61 Comparison of Variation of HC with IP at CR of 18 and Load of 12kg

The trend observed is because of better combustion of fuel taking place at higher IP. The observed decrease in HC emission with increase in blend proportion may be due to complete combustion of blends as a result of their higher oxygen content. The HC emissions decrease by 75% and 70% for Diesel oil and Karanja biodiesel respectively when the IP increases from 150 bar to 250 bar.

Figure 4.62 shows the comparison of variation of HC emissions with IP at a load of 12kg and CR of 18 of the present study with that of Jindal et al. [66]. Similar decreasing trends of HC with IP as found in the present study using Karanja biodiesel are observed by Jindal et al. [66] using Jatropha biodiesel. It is seen that the HC emissions at an IP of 250bar is higher by 13ppm for Jatropha as compared to that of Karanja biodiesel used in the present study, indicating better combustion of Karanja biodiesel.

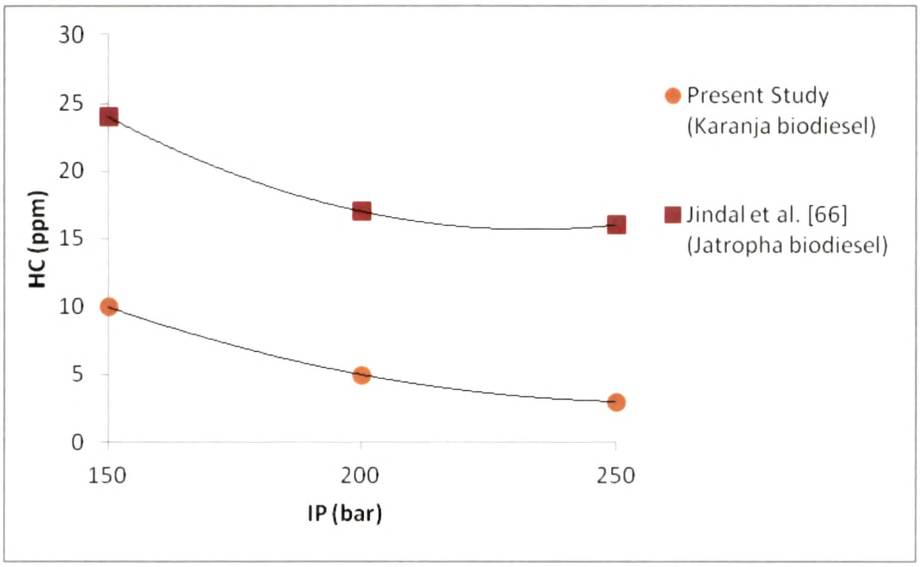

Figure 4.62 Comparison of Variation of HC with IP at CR of 18 and Load of 12kg of Present Study with Jindal et al. [66]

The comparison of variation of NO_x with IP for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and load of 12kg is shown in Figure 4.63. It can be observed that NO_x emissions increase linearly with increase in IP. The trend is due to more fuel being burnt at higher IP. The observed increase in NO_x emissions with blend proportion is mainly due to higher oxygen content in Karanja biodiesel and higher temperature existing in the engine cylinder.

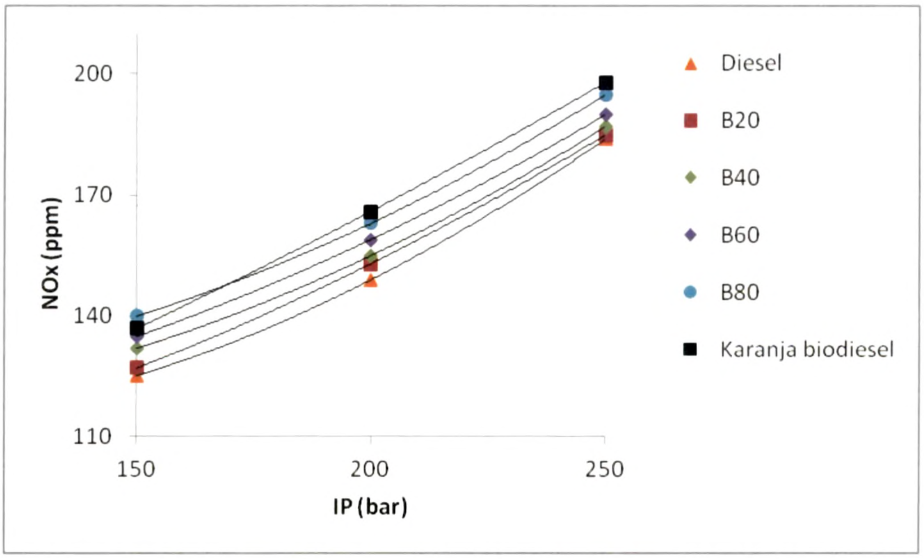

Figure 4.63 Comparison of Variation of NO_x with IP at CR of 18 and Load of 12kg

The NO_x emission for Karanja biodiesel is 7.6% higher than that for Diesel oil at an IP of 250 bar. As the IP increases from 150 to 250 bar, the NO_x emissions increase by about 47% and 44% for Diesel oil and for Karanja biodiesel respectively.

Figure 4.64 gives the comparison of variation of CO_2 with IP for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and load of 12kg. It can be seen that CO_2 content in the exhaust gas increases with the increase in IP. The trend observed is obvious as fuel is burnt to a greater degree at higher IPs due to which more carbon is available to form CO_2.This result is constitent with smaller value of HC for the fuel in present study. (Figures 4.61 and 4.62).

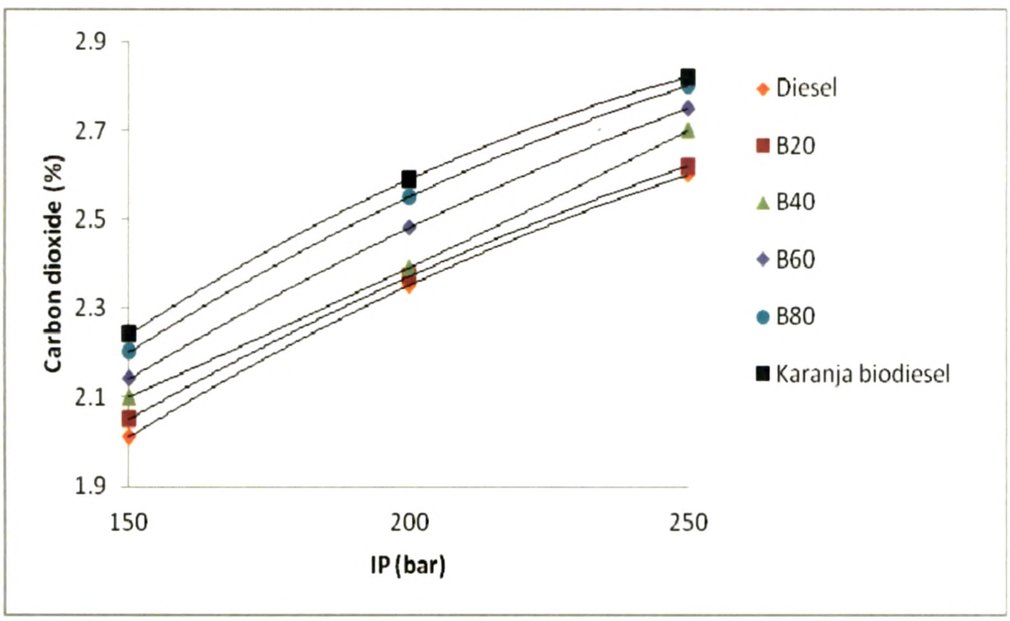

Figure 4.64 Comparison of Variation of CO_2 with IP at CR of 18 and Load of 12kg

It is also observed that CO_2 emissions increase with blend proportion. The trend observed is because of high oxygen content in the Karanja biodiesel due to which more of the carbon gets oxygenated during combustion inside the cylinder which results in higher CO_2 emission. The CO_2 emissions increase by 29% and 25% for Diesel oil and Karanja biodiesel as the IP increases from 150 to 250bar. At an IP 250 bar, CO_2 emission for Karanja biodiesel is found to increase by about 8% as compared to Diesel oil.

Figure 4.65 shows the comparison of variation of CO_2 emissions with IP at a load of 12kg and CR of 18 of the present study with the earlier investigation of Jindal et al. [66]. It is seen that at standard setting of the engine viz. 18CR, 12kg load and 200 bar IP, the

CO_2 emission is more by 82% for Jatropha as compared to that of Karanja biodiesel used in the present study. This is consistent with smaller value of HC for Karanja biodiesel at higher values of IP as compared to Jatropha biodiesel. (Figure 4.62).

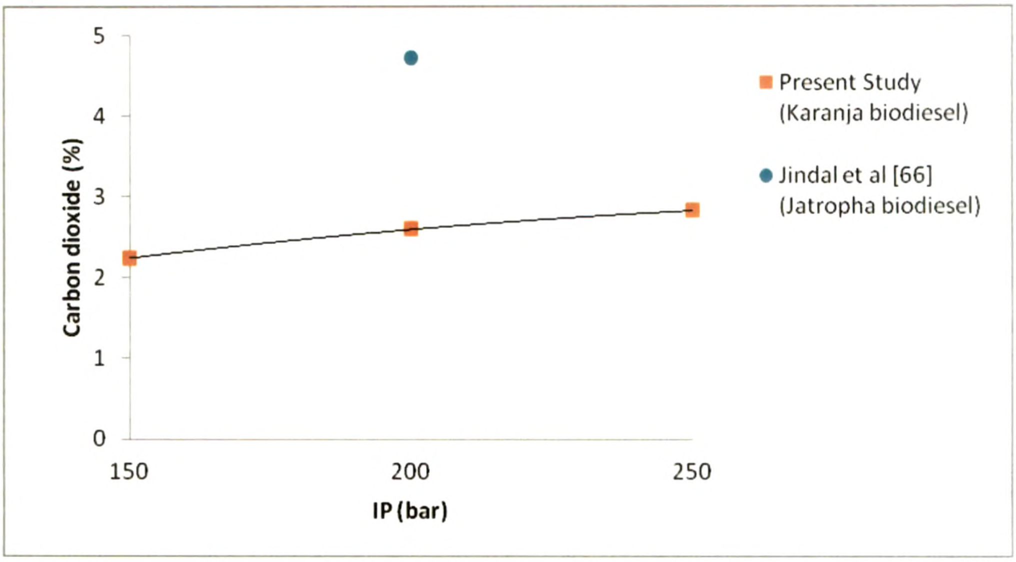

Figure 4.65 Comparison of Variation of CO_2 with IP at a CR of 18 and Load of 12kg of Present Study with Jindal et al. [66]

Figure 4.66 gives the comparison of variation of O_2 with IP for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and load of 12kg. The trend may be due to the reason that fuel is atomized to a higher degree at higher IP, hence combustion of fuel is better which results in more oxygen content in the exhaust. This is also supported by variation of A/F ratio with increase in IP. The percent Oxygen in the exhaust is about 0.25% higher for biodiesel as compared to diesel oil.indicating closer behavior of biodiesel with diesel at higher IPs.

It is also observed that O_2 emissions in the exhaust increase with increase in blend proportion. The observed increase is because of higher oxygen content of Karanja biodiesel. The O_2 emission in the exhaust increases by 12% and 10% for Diesel oil and Karanja biodiesel respectively when the IP is increased from 150 to 250. At an IP of 250bar, O_2 emission for Karanja biodiesel is higher by about 2% as compared to Diesel oil.

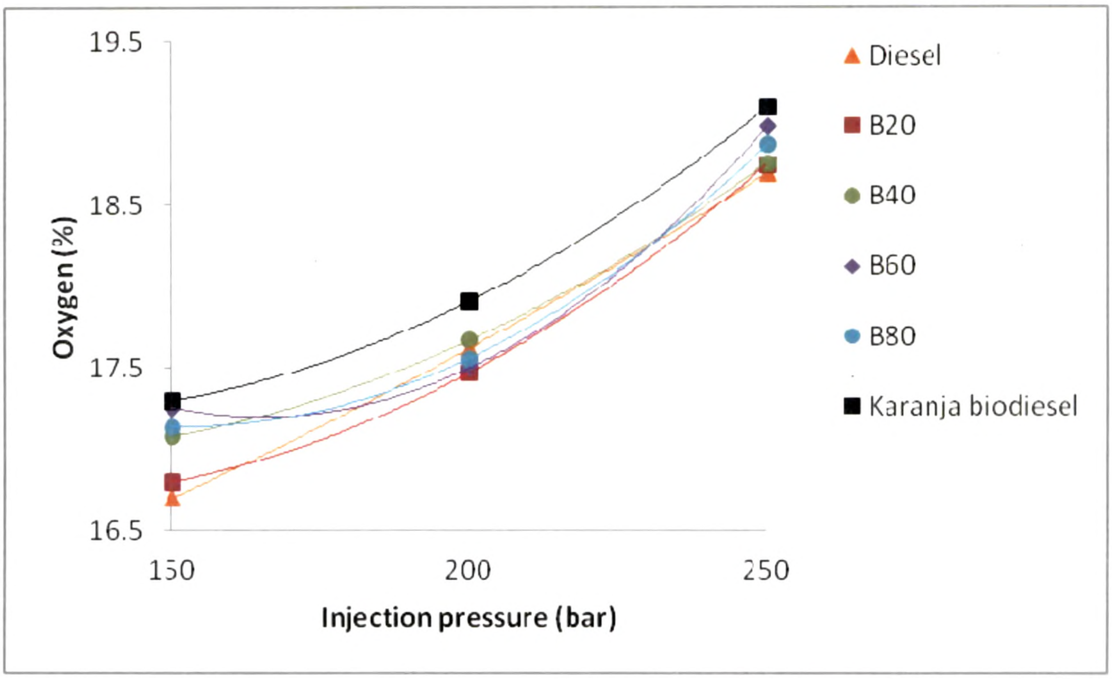

Figure 4.66 Comparison of Variation of O_2 with IP for Tested Fuels at CR of 18 and Load of 12kg

The comparison of variation of SO_x with IP for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and load of 12kg is presented in Figure 4.67. It is observed that SO_x reduce with increase in IP for all the fuels tested. The trend observed is due complete combustion of fuel which is aided by finer atomization. It is also observed that SO_x emissions decrease with increase in blend proportion. The trend may be due to sulphur free nature of Karanja biodiesel. However, at an IP of 250 bar there is a small increase in SO_x. The reason may be attributed to lean mixture burning associated with higher temperature of combustion. Oxygen present in the exhaust may dissociate at high temperatures and combine with sulphur present in air to produce SO_x.

As the IP increases from 150 to 250 bar the SO_x reduce by 77% and 50% for Diesel oil and Karanja biodiesel respectively. At an IP of 250bar SO_x for Karanja biodiesel is 50% less compared to Diesel oil.

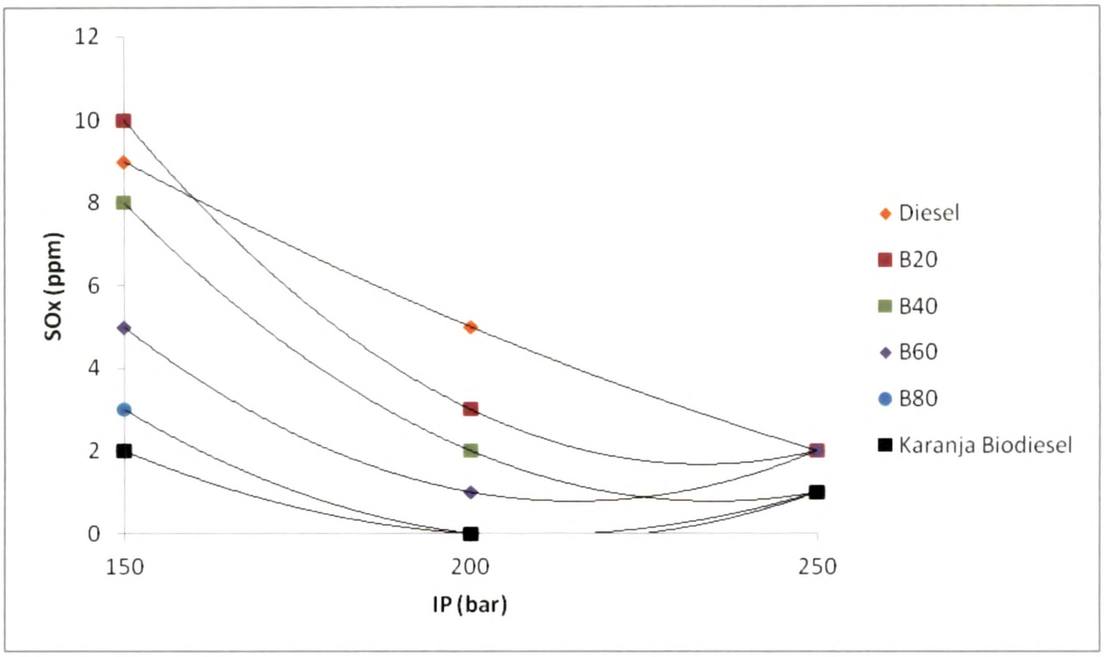

Figure 4.67 Comparison of Variation of SO_x with IP at CR of 18 and Load of 12kg

The comparison of variation of HSU with IP for Karanja biodiesel and its blends with Diesel oil at a CR of 18 and load of 12kg is presented in Figure 4.68. It is observed that HSU decreases with increase in IP for all tested fuels. The trend is due to the fact that at higher IP the degree of the atomization of fuel is high enough to cause complete combustion of fuel.

It is also seen that HSU increases with increase in blend proportion at any constant IP. HSU is higher for Karanja biodiesel by 23% as compared to that of Diesel oil at an IP of 250bar. As the IP increases from 150 to 250 bar the HSU reduces by 58% and 53% for Diesel oil and Karanja biodiesel.

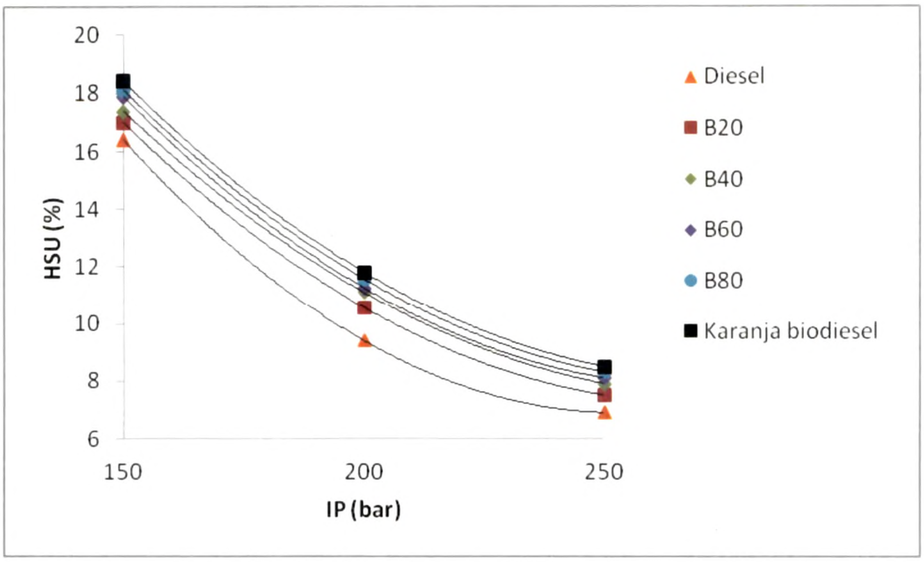

Figure 4.68 Comparison of Variation of HSU with IP at CR of 18 and Load of 12kg

Figure 4.69 shows the comparison of variation of NO_x emissions and HSU of exhaust gas with IP at a load of 12kg and CR of 18 of the present study with that of earlier investigations of Jindal et al. [66].

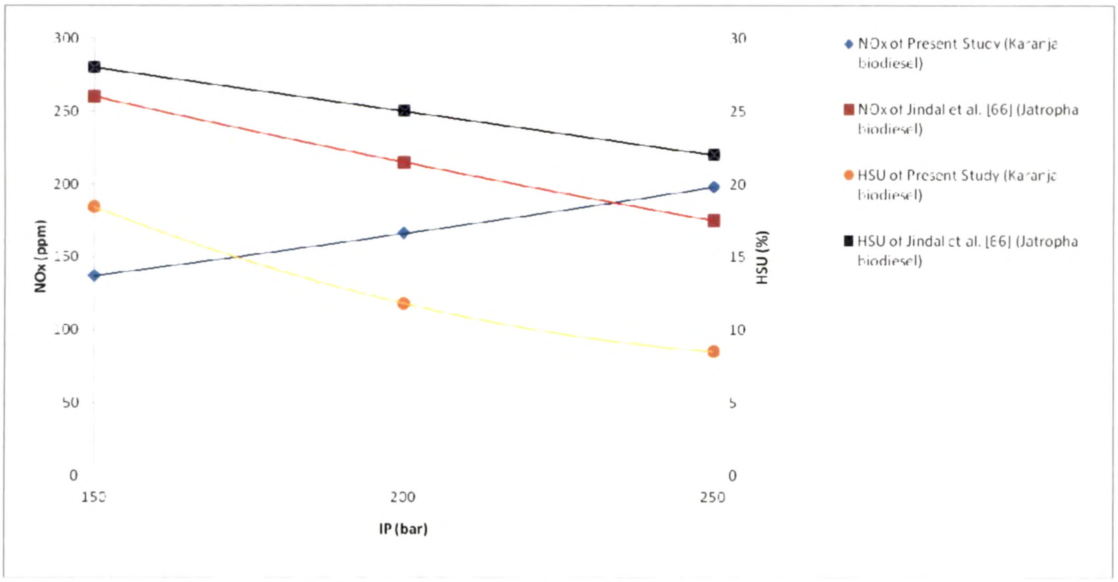

Figure 4.69 Comparison of Variation of NO_x and HSU with IP at a CR of 18 and Load of 12kg with Jindal et al. [66]

Similar decreasing trends of HSU with IP as found in the present study are observed by Jindal et al. [66] using Jatropha biodiesel. It is seen that HSU at an IP of 200bar is almost double for Jatropha as compared to that found in the present study. Jindal et al. [66] also studied the variation of NO_x emission with IP at full load of 12kg using Jatropha biodiesel. The investigators reported an opposite trend as compared to that of the present as compared to that of Kāranja biodiesel used in the present study. Generally NO_x emissions increase at the expense of HSU with increase in IP. The trend concurs with available literature (Fergusson & Kirkpatrick [98]), but Jindal et al. [66] has observed that both NO_x and HC show a decreasing trend with increase in IP.This is consistent with the value of HC and NO_x at higher IPs. (Figure 4.61, 4.62 and 4.63).

4.2.4 Combustion Analysis

The combustion processes are engine dependent, involving the oxidation of chemical constituents of a fuel resulting in release of thermal energy. A compression ignition engine has separate fuel and air streams that combust as they are mixed together. The chemical reaction which produces a diffusion flame takes place at the interface between the fuel and the air. The heat release begins at a relatively high value and then decreases as the available oxygen is depleted. Combustion chemistry is very complex and depends on the type of fuel used in the combustion process. Oxidation of the hydrocarbon fuel is modelled by earlier investigators using reaction pathways (Ferguson & Kirkpatrick [98]).

The Diesel oil combustion process has been classified into four distinct phases: ignition delay, premixed combustion, mixing controlled combustion and late combustion. Ignition delay is the period during which some fuel has been admitted but not yet ignited. In premixed combustion phase which takes place over a few degrees of crank angle, there is a rapid rise in pressure due to combustion of fuel. In mixing controlled combustion the fuel droplets injected burn almost instantaneously. During late combustion phase some fuel droplets which are not yet burnt, due to their poor distribution, get combusted and heat release continues at a lower rate well into the expansion stroke.

This section deals with the combustion analysis of a VCR diesel engine fuelled with Karanja biodiesel and Diesel oil separately. The combustion parameters considered for analysis in subsequent sections are cylinder pressure, net heat release, rate of pressure rise, mass fraction burnt, mean gas temperature, cylinder pressure-volume (PV) plot, cumulative heat release rate and injection pressure. The study is conducted at full load of 12kg and preset IP of 200bar.

4.2.4.1 Cylinder pressure

Cylinder pressure (CP) with crank angle (CA) over an engine operating cycle gives the quantitative information on the progress of combustion. The variation of CP during a complete cycle with CA for three settings of CRs of 14, 16 and 18 for both Karanja biodiesel and Diesel oil as fuels are shown in Figures 4.70 to 4.75.

The variation of CP with CA at a CR of 14 for Karanja biodiesel and Diesel oil are shown in Figures 4.70 and 4.71 respectively. It is observed that start of combustion (SOC) takes place at 10^0 of CA later for Karanja biodiesel as compared to Diesel oil. The trend observed is because the heat of compressed air is not high enough to initiate combustion at earlier CA in comparison with Diesel oil, which may probably be due to reduced atomization due to higher viscosity and hence less intense premixed combustion phase with Karanja biodiesel as compared to Diesel oil.

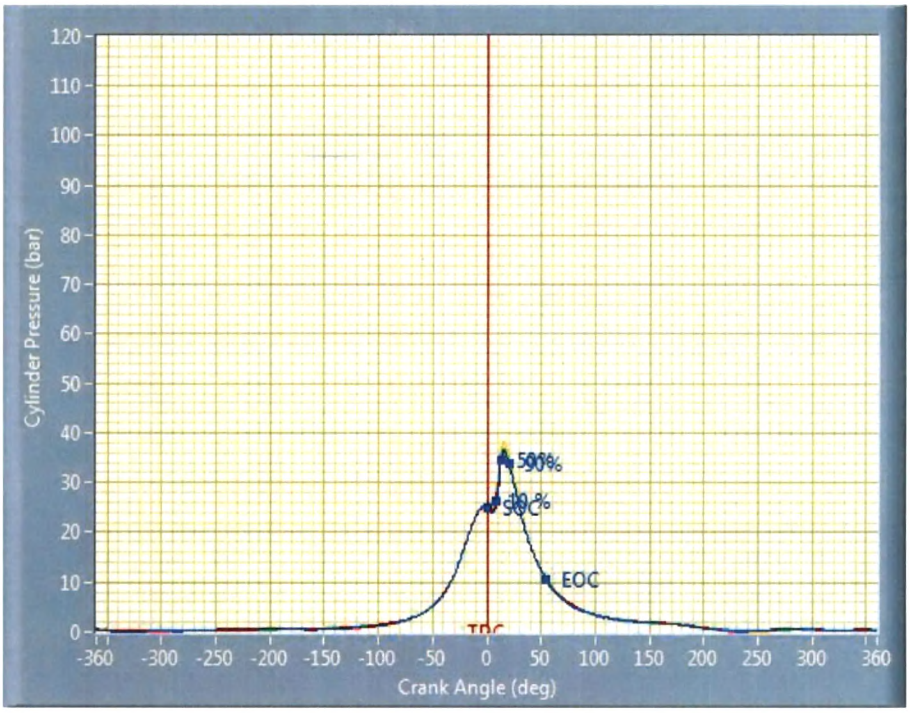

Figure 4.70 Variation of CP With CA at CR of 14 for Karanja Biodiesel

It may also be due to the reason that diffusion burning (during mixing controlled combustion) is more intense with Karanja biodiesel. The peak CP is about 38 bar for Karanja biodiesel as against 40 bar for Diesel oil i.e. CP achieved is lower by 2 bar for Karanja biodiesel. The duration of combustion (CA covered from SOC to end of combustion (EOC)) is 55^0 CA for Karanja biodiesel and 75^0 CA for Diesel oil. It is also observed that EOC is advanced by 10^0 in case of Karanja biodiesel as compared to Diesel oil.

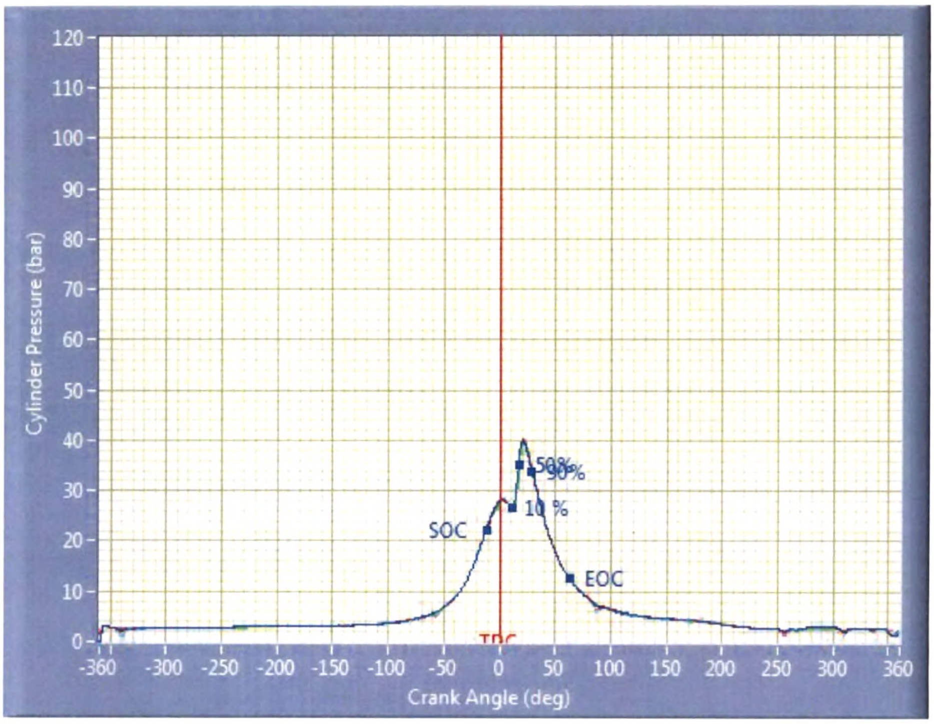

Figure 4.71 Variation of CP With CA at CR of 14 for Diesel Oil

The variation of CP with CA at a CR of 16 for Karanja biodiesel and Diesel oil are shown in Figures 4.72 and 4.73 respectively. It is observed that SOC takes place at TDC for both Karanja biodiesel and Diesel oil. The peak CP is about 42 bar for Karanja biodiesel as against 46 bar for Diesel oil i.e. CP achieved is lower by 4 bar for Karanja biodiesel.

The duration of combustion is 47^0 CA for Karanja biodiesel and 55^0 CA for Diesel oil. It can be noted that the deviation in performance between both the fuels reduces with the increase in CR from 14 to 16. However, engine with Diesel oil as fuel may be marginally performing better due to higher CP achieved.

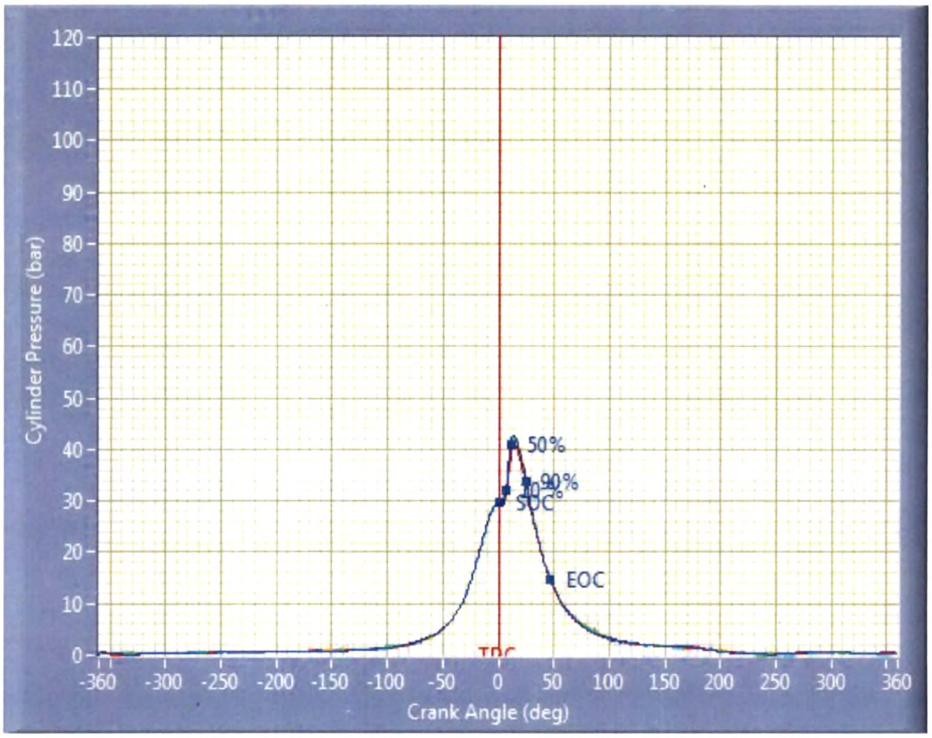

Figure 4.72 Variation of CP With CA at CR of 16 for Karanja Biodiesel

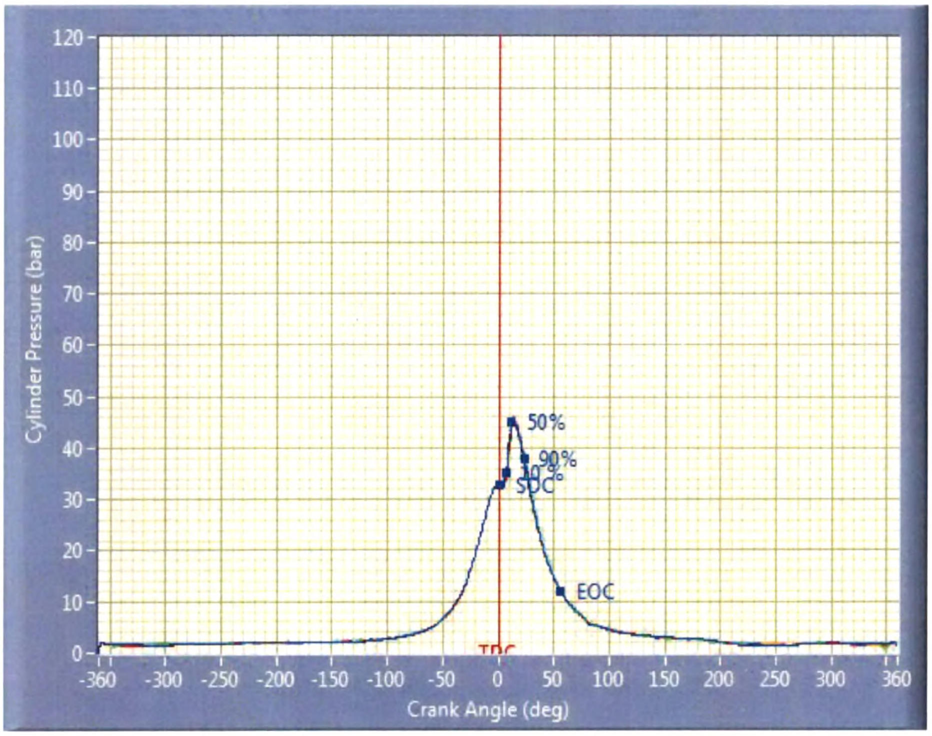

Figure 4.73 Variation of CP With CA at CR of 16 For Diesel Oil

The variation of CP with CA at a CR of 18 for Karanja biodiesel and Diesel oil are shown in Figures 4.74 and 4.75 respectively. It can be observed that the trend of variation of CP with CA is almost same for Karanja biodiesel and Diesel oil. SOC takes place at 25^0 CA before TDC and 20^0 CA before TDC for Karanja biodiesel and Diesel oil respectively indicating about 5^0 advance for Karanja biodiesel. SOC at 25^0 CA before TDC may be attributed to perturbation in the engine. The peak CP attained is same (50 bar) for both the fuels and the duration of combustion is spread over 80^0 of CA for both Karanja biodiesel and Diesel oil. It can be inferred that the engine operated using Karanja biodiesel gives similar performance as that of Diesel oil as fuel at CR of 18.

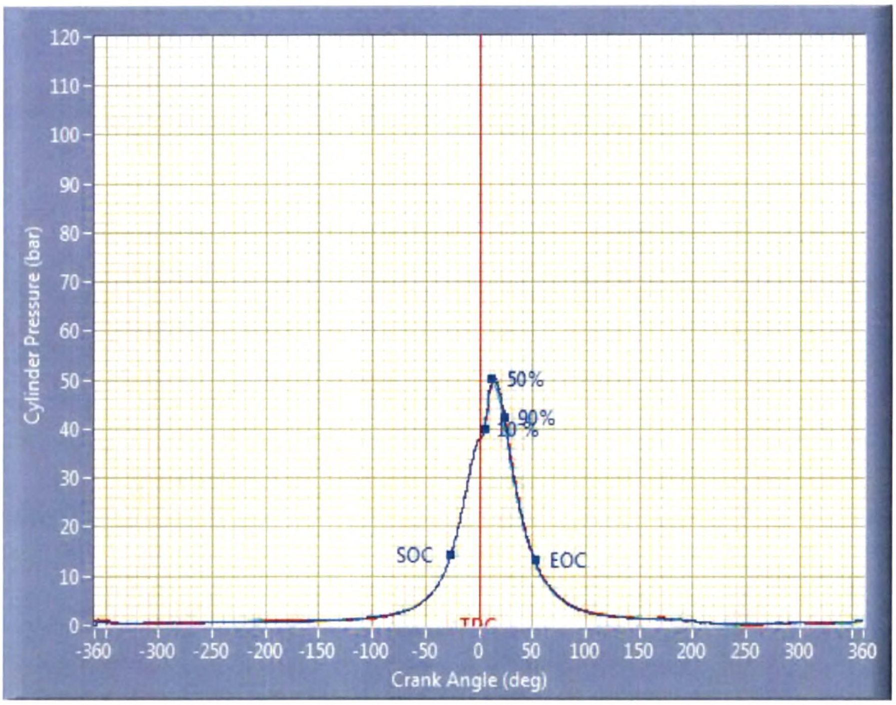

Figure 4.74 Variation of CP With CA at CR of 18 for Karanja Biodiesel

The data of CA positions at different CRs for SOC, Peak CP and EOC is given in Table 4.4. It can be noted that peak pressure development for Karanja biodiesel takes place at earlier CA at 14 CR as compared to Diesel oil. However, the peak pressures at all CRs using both the fuels always takes place after TDC which ensures safe and efficient operation as peak pressure at or before TDC causes knocking which affects engine durability (Ganesan [97]). The peak CP attained for Karanja biodiesel is about 2 to 4 bar less at CR of 14 and 16, whereas at CR of 18 the peak CP is same for both the fuels. As CR increases there is a reduced delay observed for Karanja biodiesel as compared to Diesel by about 5^0 of CA and the peak CP is same for both the fuels.

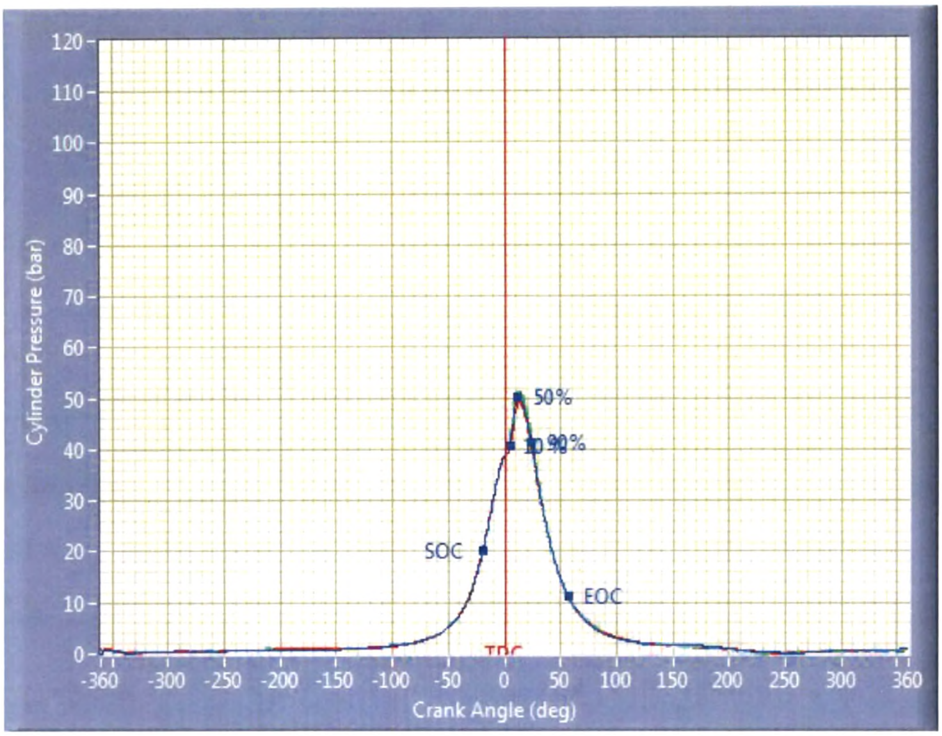

Figure 4.75 Variation of CP With CA at CR of 18 for Diesel Oil

Table 4.4 Crank Angle Data for different CRs for SOC, Peak CP and EOC (Reproduced from Figures 4.70–4.75)

	Karanja biodiesel				Diesel oil			
	SOC	Position of Peak CP (^{0}CA)	EOC	Peak CP (bar)	SOC	Peak CP (^{0}CA)	EOC	Peak CP (bar)
14CR	TDC	15^0 ATDC	55^0 ATDC	38	10^0 BTDC	20^0 ATDC	65^0 ATDC	40
16CR	TDC	10^0 ATDC	47^0 ATDC	42	TDC	10^0 ATDC	55^0 ATDC	46
18CR	25^0 BTDC	15^0 ATDC	55^0 ATDC	50	20^0 BTDC	15^0 ATDC	60^0 ATDC	50

Figure 4.76 shows the comparison of variation of peak CP with CR at full load of 12kg and IP of 200bar of the present study with that of earlier investigations of Sahoo & Das [86], Devan & Mahalaxmi [64], Gattamaneni et al. [85], Buyukkaya [87], Murugan [99]. Sahoo & Das [86] used Karanja, Jatropha and Polanga biodiesels, Devan & Mahalaxmi [64] and Gattamaneni et al. [85] used Poon and Rice bran biodiesels respectively. Murugan [99] and Buyukkaya [87] used Distilled tyre pyrolisis oil and Rapeseed oil respectively.

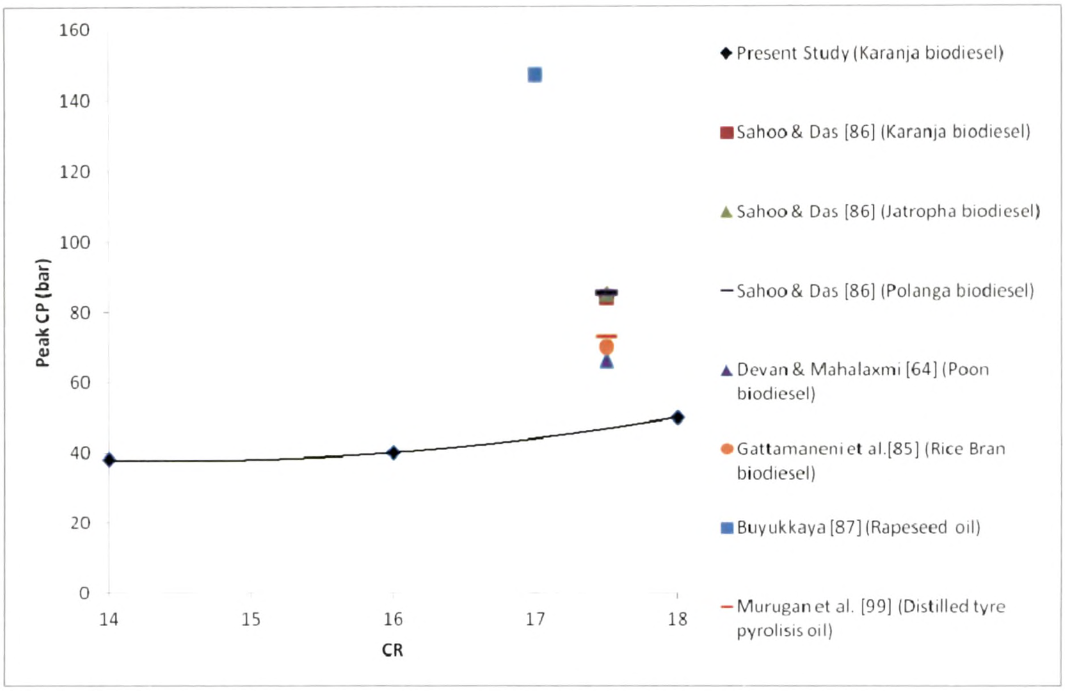

Figure 4.76 Comparison of Variation of Peak CP with CR at a Load of 12kg and an IP of 200bar of the Present Study with that of Earlier Investigations

It is observed that peak CP increases with increase in CR for Karanja biodiesel used in the present study. It can be noted that there is no study reported for variation of Peak CP with CR on a diesel engine. Therefore comparison of trend of the present study with earlier investigations is not possible. However, various studies of peak CP at constant preset CR using different biodiesels are reported.

It is observed that peak CP achieved in investigation by Sahoo & Das [86] using Karanja biodiesel at a constant CR of 17.5 is 75% higher as compared that of present study. They also conducted studies using Jatropha and Polanga biodiesels. The peak CP is higher by about 75% for Jatropha and Polanga biodiesel as compared that of Karanja biodiesel used in the present study. Various investigators also reported higher peak CP at constant CR of 17.5 using Poon biodiesel, Ricebran biodiesel and Distilled tyre pyrolisis oil. It is observed that peak CP is higher by 37.5%, 46% and 52% for Poon biodiesel, Ricebran biodiesel and Distilled tyre pyrolisis oil respectively as compared to Karanja biodiesel used in the present study. At a constant CR of 17, peak CP for Rapeseed oil is more by almost 200% as compared to that of Karanja biodiesel used in the present study. The results of a study on a CI engine indicate that the maximum peak pressure achieved is about 48bar at 18^0 CA after TDC (Ferguson & Kirkpatrick [98]). The values of this study closely match with the present study.

4.2.4.2 Net Heat Release Rate

The variation of net heat release rate during a complete cycle with CA for three settings of CRs of 14, 16 and 18 for both Karanja biodiesel and Diesel oil as fuels are shown in Figures 4.77 to 4.82. The net heat release rate *(dQ_n /dt)* is the difference between the heat released by combustion of fuel *(dQ_{ch} /dt)* and the heat transfer rate to the walls of the engine cylinder *(dQ_{ht}/dt)*. The net heat release rate also equals to the sum of work done on the piston *[$p(dV/dt)$]* and change of sensible internal energy of the cylinder contents *(dU_s /dt)*.

The heat transfer rate to the walls is the loss of heat. So, if loss is more the net heat release rate would be less and it can be clearly observed from the equation below that net heat release rate increases with the decrease in the heat transfer rate to the walls keeping heat released by combustion of fuel the same.

$$(dQ_n)/dt = (dQ_{ch})/dt - (dQ_{ht})/dt = p\, dV/dt + (dU_s)/dt$$ (Heywood [96])

The dual function which is known as Wiebe function can also be used to fit the diesel combustion heat release data.

$$dQ/d\theta = a(Q_p/\theta_p)\,(m_p)\,(\theta/\theta_p)^{m_p-1}\, exp\,[-a(\theta/\theta_p)^{m_p}] + a(Q_d/\theta_d)(m_d)(\theta/\theta_d)^{m_d-1} exp[-a(\theta/\theta_d)^{m_d}]$$ (Ferguson & Kirkpatrick [98])

The subscripts p and d refer to premixed combustion and mixing controlled combustion portions, respectively, a is the non dimensional constant, θ_p and θ_d are the burning duration for each phase , Q_p and Q_d are the integrated energy for each phase and m_p and m_d are non dimensional shape factors for each phase (Heywood [96], Ferguson & Kirkpatrick [98]).

The variation of net heat release rate with CA over one cycle at a CR of 14 for Karanja biodiesel and Diesel oil are shown in Figures 4.77 and 4.78 respectively. It is observed that the peak net heat release rate occurs at 9^0 CA after TDC for Karanja biodiesel and 16^0 CA after TDC for Diesel oil.

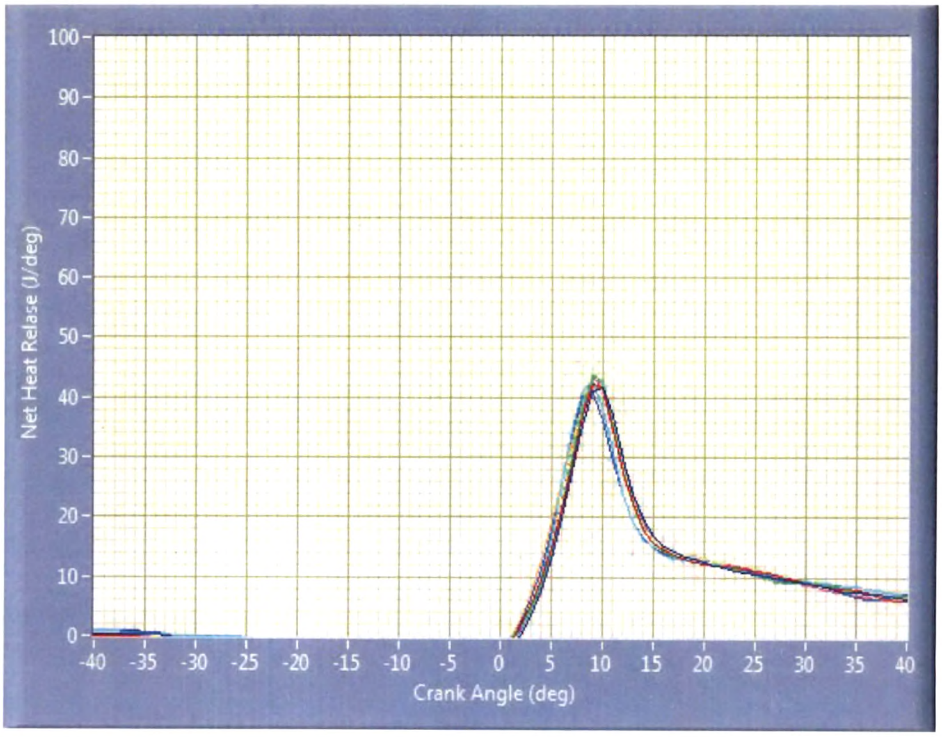

Figure 4.77 Variation of Net Heat Release Rate With CA at CR of 14 for Karanja Biodiesel

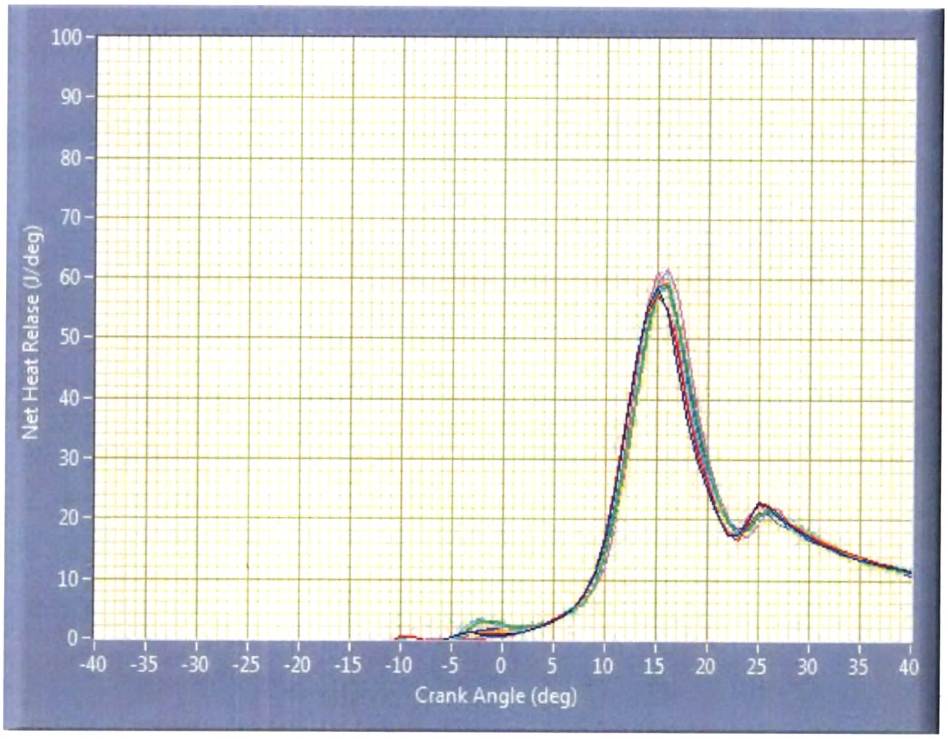

Figure 4.78 Variation of Net Heat Release Rate With CA at CR of 14 for Diesel Oil

The peak value of heat release rate for Karanja biodiesel is 44 J/deg as against 60 J/deg for Diesel oil. The lower net heat release rate for Karanja biodiesel can be attributed to its lower calorific value. It is a well known fact that the double peak shape of the heat release rate curve observed for Diesel oil is the characteristic of diesel combustion (Figure 4.78). The first peak that occurs during the premixed combustion phase results from rapid combustion of the portion of the injected fuel that has vaporized and mixed with air during the ignition delay period. The second peak occurs during the mixing controlled combustion phase. It can be noted that curves of different colours are observed in all the figures of combustion analysis henceforth. It should be noted that these curves are the perturbations of repeated cycles of engine operation.

The variation of net heat release rate with CA for one cycle of engine operation at a CR of 16 for Karanja biodiesel and Diesel oil are shown in Figures 4.79 and 4.80 respectively. It is observed that the peak net heat release rate for Karanja biodiesel is about 39 J/deg corresponding to 8^0 CA after TDC as against 40 J/deg for Diesel oil corresponding to 8^0 CA after TDC. For Karanja biodiesel the peak net heat release rate decreases by about 5 J/deg as compression ratio increases from 14 to 16 and the decrease is about 20 J/deg for Diesel oil.

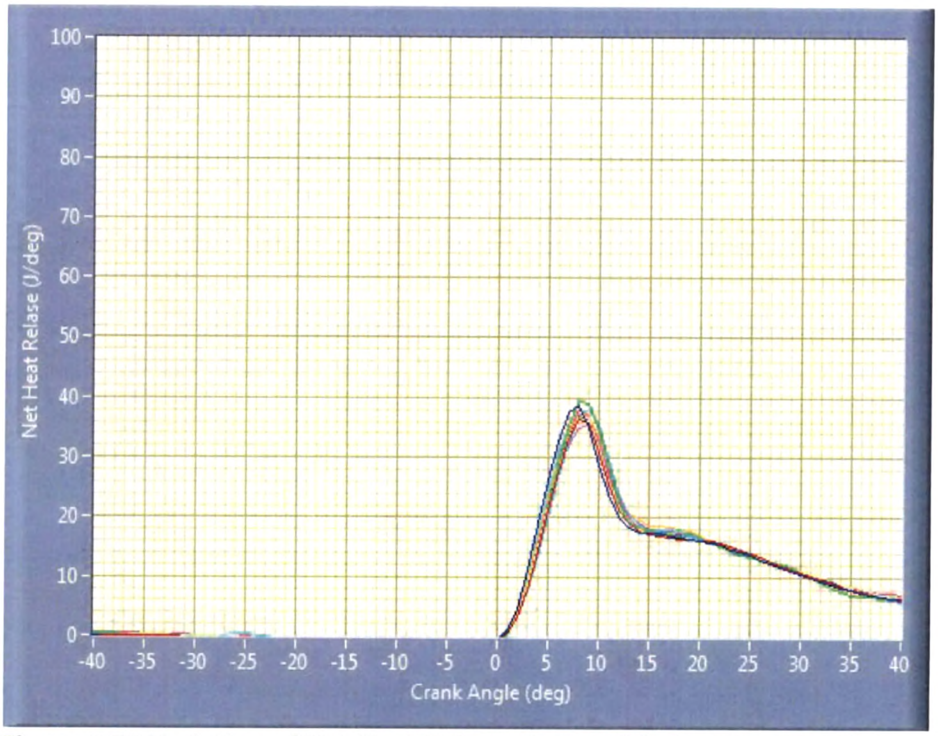

Figure 4.79 Variation of Net Heat Release Rate With CA at CR of 16 for Karanja Biodiesel

Reduced premixed combustion at higher CR for both the fuels can also be attributed to as the reason. The second peak of the net heat release rate curve is observed at the same CA of 18^0 for Karanja biodiesel and Diesel oil corroborates the identical thermal performance of both the fuels at higher CR of 16.

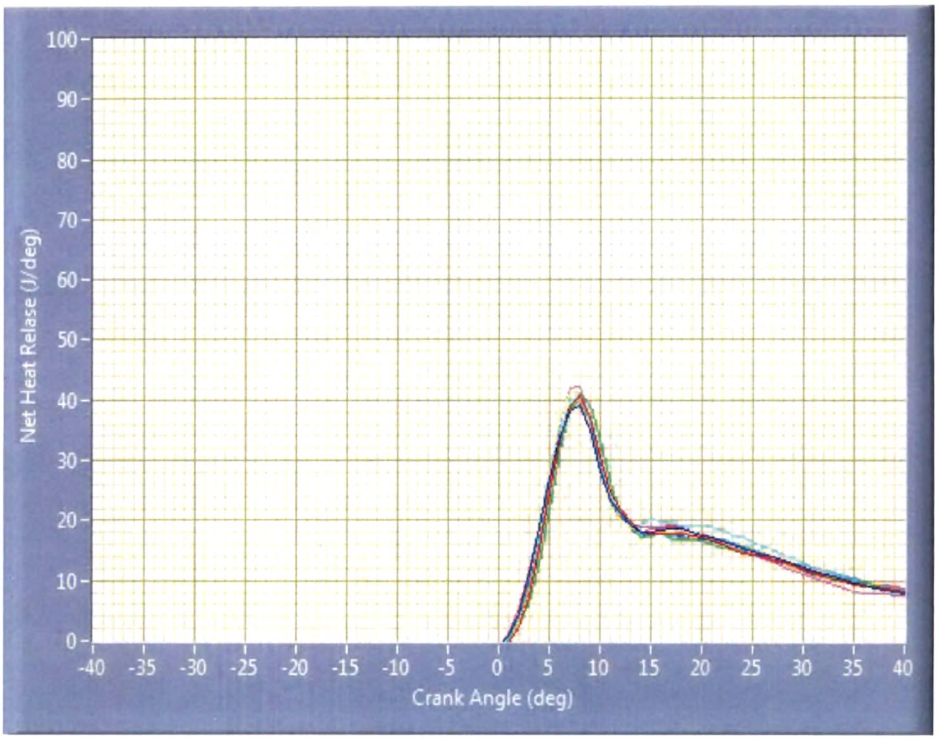

Figure 4.80 Variation of Net Heat Release Rate With CA at CR of 16 for Diesel Oil

The variation of net heat release rate with CA at a CR of 18 over one cycle of engine for Karanja biodiesel and Diesel oil are shown in Figures 4.81 and 4.82 respectively. It can be observed that the peak net heat release rate is same for both the fuels. Also, the second peak observed in case of Karanja biodiesel which is a characteristic of Diesel combustion in a diesel engine is found to occur at CR 18 which corroborates the closeness of thermal performance of Karanja biodiesel as compared to Diesel. The second peak occurs at 18^0 CA for both Karanja biodiesel and Diesel oil. Therefore, it can be inferred that at higher CRs the nature of variation of net heat release rate profile of Karanja biodiesel closely follows that of Diesel oil.

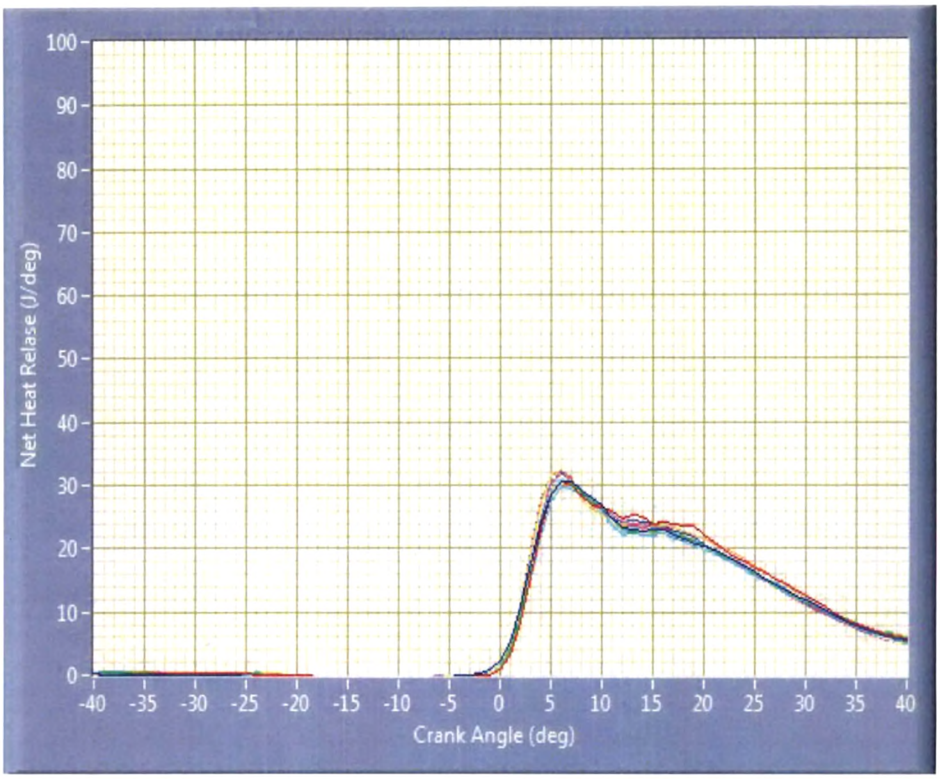

Figure 4.81 Variation of Net Heat Release Rate with CA at CR of 18 for Karanja Biodiesel

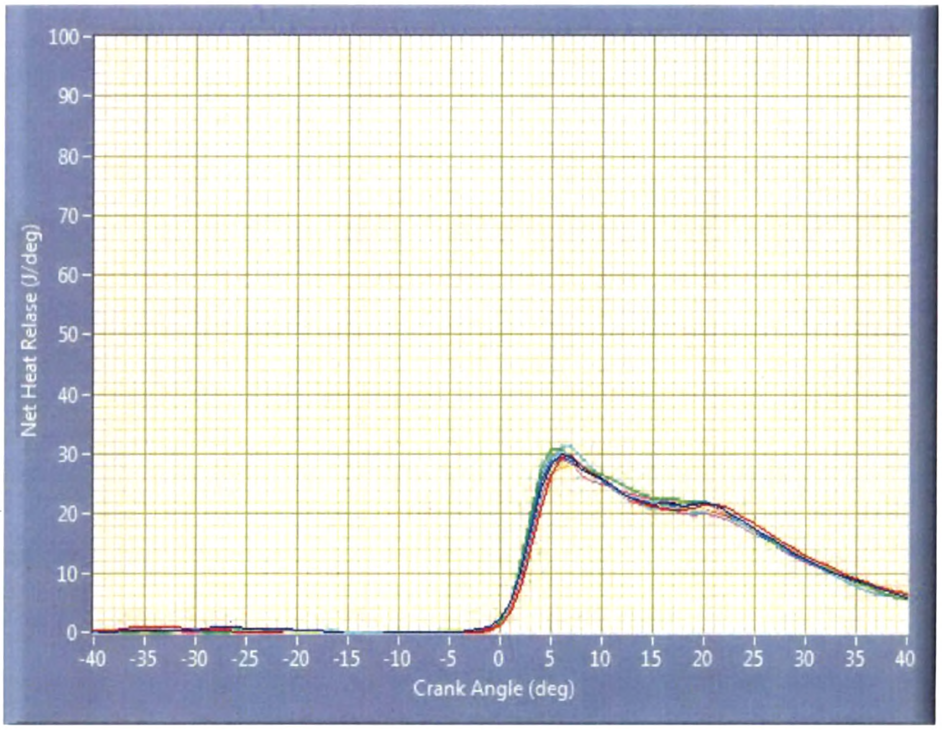

Figure 4.82 Variation of Net Heat Release Rate with CA at CR of 18 for Diesel Oil

Higher CR should be the mode of operation when operating with Karanja biodiesel. It can be noted that the peak net heat release rate for Karanja biodiesel is same as for Diesel oil which may probably be due to equal spread of the duration of combustion & the oxygenated nature of Karanja biodiesel resulting in complete combustion even though Diesel oil has a higher calorific value of about 6% as compared to Karanja biodiesel.

A comparison of peak net heat release rateof Karanja biodiesel with that of Diesel oil is given in Table 4.5. It can be observed that the first peak of heat release rate curve occurs early in case of Karanja biodiesel than Diesel oil. The trend is due to reduced ignition delay resulting in earlier combustion for Karanja biodiesel as its cetane number is more than of Diesel oil (47 for Diesel and 55 for Karanja biodiesel) (H. Aydin, C. Ilkilic [79]). The observed trend of shift of point of occurrence of first peak net heat release rate curve closer to TDC with increase in CR for both the fuels may be attributed to increased intensity of combustion due to higher temperature of compressed air as CR increases. At 14 CR no significant second peak observed for comparison for Karanja biodiesel. At CR of 16 the second peak heat release for Karanja biodiesel is 10% less as compared to Diesel oil. As CR increases from 16 to 18, the second peak net heat release rate increases for Karanja biodiesel and it is same as that of Diesel oil at 18CR.

Table 4.5 Comparison of Peak Net Heat Release Rate of Karanja Biodiesel with that of Diesel Oil (Reproduced From Figures 4.77-4.82)

CR	Fuel	Peak Net Heat Release ($J/^0CA$)		Position (^0CA)	
		First peak (Premixed Combustion)	Second peak (Mixing Controlled Combustion)	First Peak	Second Peak
14	Karanja biodiesel	44	--	9^0 after TDC	--
	Diesel oil	60	24	16^0 after TDC	25^0 after TDC
16	Karanja biodiesel	39	18	8^0 after TDC	17^0 after TDC
	Diesel oil	40	20	8^0 after TDC	17^0 after TDC
18	Karanja biodiesel	30	24	6^0 after TDC	18^0 after TDC
	Diesel oil	30	24	6^0 after TDC	20^0 after TDC

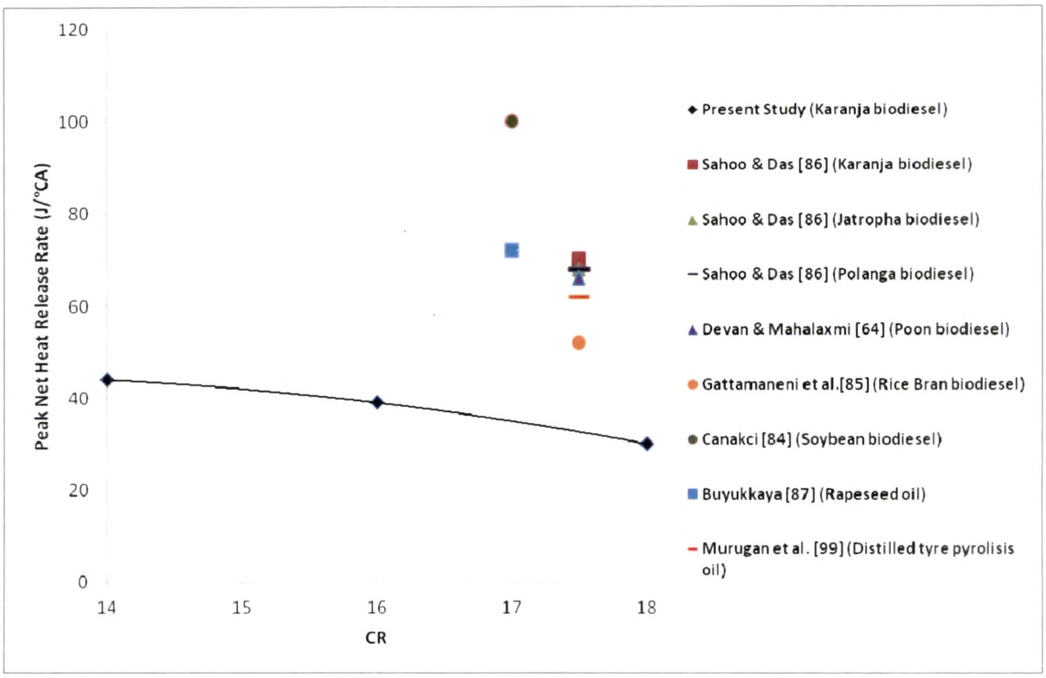

Figure 4.83 Comparison of Variation of Peak Net Heat Release Rate with CR at a Load of 12kg and an IP of 200bar of the Present Study with that of Earlier Investigations

Figure 4.83 shows the comparison of variation of net heat release rate with CR at full load of 12kg and IP of 200bar of the present study with that of earlier investigations of Sahoo & Das [86], Devan & Mahalaxmi [64], Gattamaneni et al. [85], Buyukkaya [87], Canakci [84], Murugan [99]. Sahoo & Das [86] used Karanja, Jatropha and Polanga biodiesels, Devan & Mahalaxmi [64], Gattamaneni et al. [85] and Canakci [84] used Poon, Rice bran and Soybean biodiesels respectively. Murugan [99] and Buyukkaya [87] used Distilled tyre pyrolisis oil and Rapeseed oil respectively.

It is observed that net heat release rate decreases with increase in CR for Karanja biodiesel used in the present study. It can be noted that there is no study reported for variation of net heat release rate with CR. Therefore comparison of trend of the present study with earlier investigations is not possible. However, various studies of net heat release rate at constant preset CR using different biodiesels are reported.

It is observed that net heat release rate achieved in investigation by Sahoo & Das [86] using Karanja biodiesel at a constant CR of 17.5 is 112% higher as compared that of present study. They also conducted studies using Jatropha and Polanga biodiesels. The net heat release rate is higher by about 106% for Jatropha and Polanga biodiesel as compared that of Karanja biodiesel used in the present study. Various investigators also reported higher net heat release rate at constant CR of 17.5 using Poon biodiesel, Ricebran biodiesel and Distilled tyre pyrolisis oil. It is observed that net heat release rate is higher by 100%, 57% and 87% for Poon biodiesel, Ricebran biodiesel and Distilled tyre pyrolisis oil respectively as compared to Karanja biodiesel used in the present study. At a constant CR of 17, net heat release rate for Rapeseed oil and Soybean biodiesel is 94% and 170% higher respectively as compared to that of Karanja biodiesel used in the present study. The observed deviation could not be attributed to any specific reason existing in the available literature. However, an earnest effort has been made in this direction and the results are presented for further exploration and analysis in this area.

4.2.4.3 Rate of Pressure Rise

Variations of rate of pressure rise (also known as pressure derivative, dP/dΘ) with CA as obtained by the plots directly indicated by the software for Karanja biodiesel and Diesel oil at CRs of 14, 16 and 18 are presented in the Figures 4.84-4.89. dP/dΘ curves indicate the slope of PΘ diagram. The maximum rate of pressure rise $(dP/d\Theta)_{max}$ and CA at which it occurs are clearly visible from these figures. The rate of change of pressure is substantially affected by the rate of burning. The occurrence of maximum rate of pressure rise should be close to TDC for proper burning and knock free combustion to take place (Heywood [96], V. Ganesan [97]). The shapes of the curves depend on whether the combustion process is fast and robust. Under robust conditions the distributions are closer to normal distributions i.e. attainment of peak pressure and rate of pressure rise taking place after TDC but not too far from the same. The point of attainment of peak pressure indicates that major part of the heat release has taken place. This phase is followed by a sharp fall in the rate of pressure rise (Heywood [96]) and a steady value of dp/dΘ.

The variation of rate of pressure rise with CA at a CR of 14 for Karanja biodiesel and Diesel oil are shown in Figures 4.84 and 4.85 respectively. It is observed that for Karanja biodiesel as fuel, the maximum rate of pressure rise occurs at 10^0 of CA after TDC and the value is 2.5 bar/^{0}CA whereas it is 2.6 bar/^{0}CA at 15^0 after TDC for Diesel oil.

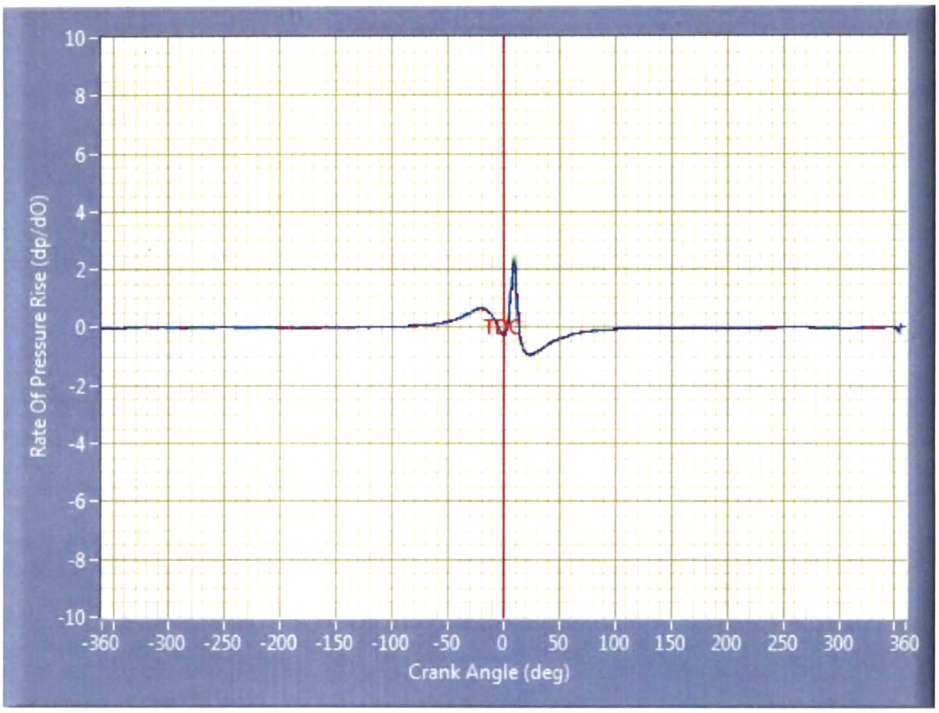

Figure 4.84 Variation of Rate of Pressure Rise with CA at CR of 14 for Karanja Biodiesel

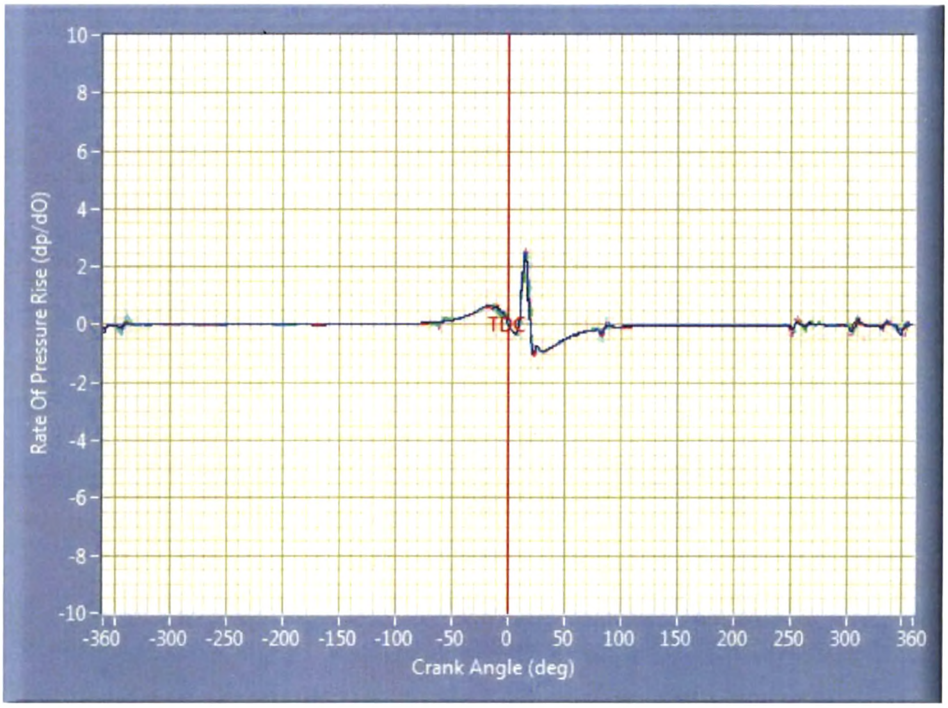

Figure 4.85 Variation of Rate of Pressure Rise With CA at CR of 14 for Diesel Oil

It can also be observed that the maximum rate of pressure rise takes place closer to TDC is case of Karanja biodiesel as fuel than Diesel oil. This observation can be supported by the fact that Karanja biodiesel has higher cetane number due to which combustion begins earlier and is fairly smooth. The spikes appearing with respect to Diesel oil combustion is due to experimental perturbations.

The variation of rate of pressure rise with CA at a CR of 16 for Karanja biodiesel and Diesel oil are shown in Figures 4.86 and 4.87 respectively. It is observed that the maximum rate of pressure rise is 2.5 bar/^{0}CA and it occurs at 8^0 after TDC for both Karanja biodiesel and Diesel oil. It can be noted here is that the maximum rate of pressure rise occurs 2^0 for Karanja biodiesel and 7^0 for Diesel oil closer to TDC as compared to that at 14 CR which results in knock free combustion.

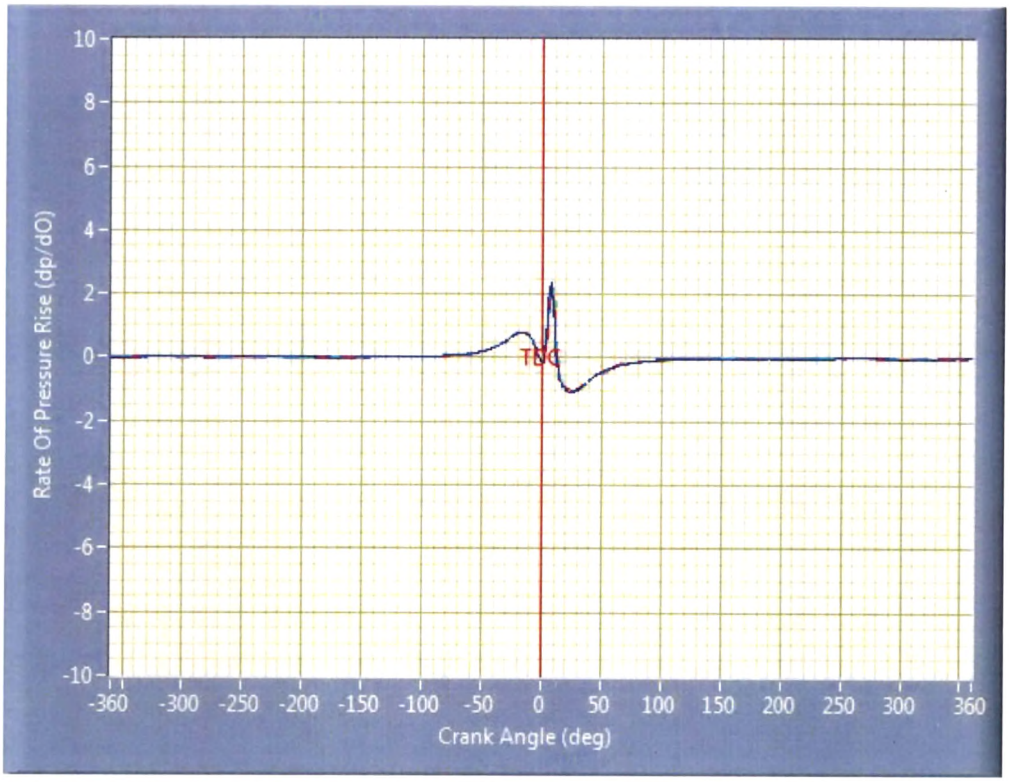

Figure 4.86 Variation of Rate of Pressure Rise With CA at CR of 16 for Karanja Biodiesel

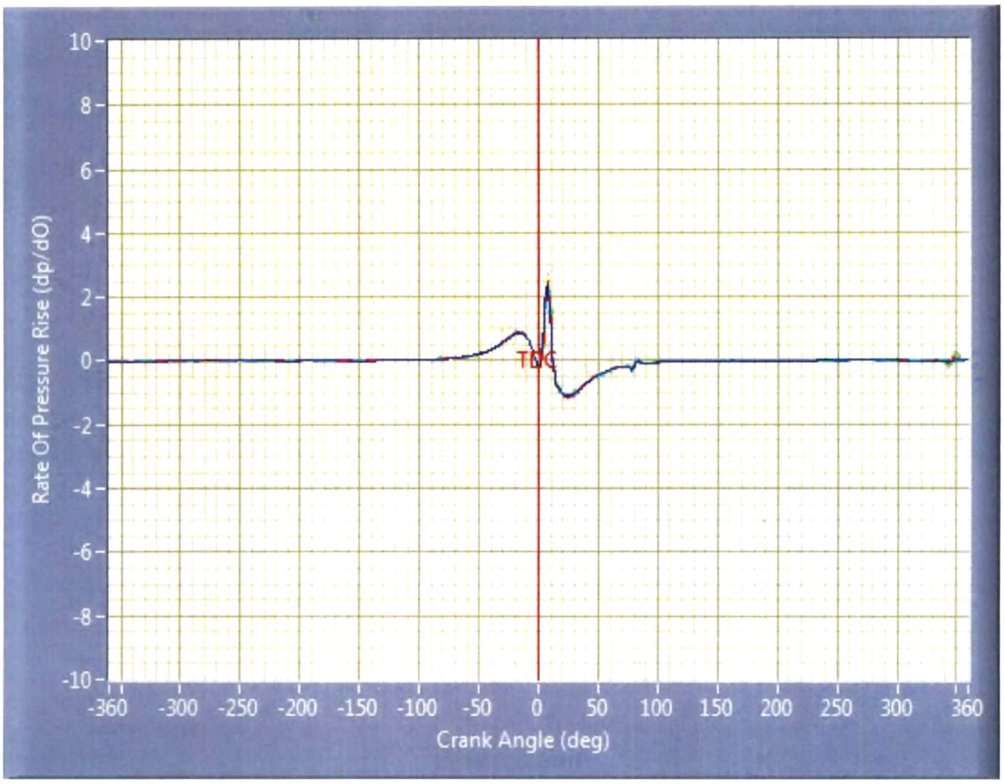

Figure 4.87 Variation of Rate of Pressure Rise with CA at CR of 16 for Diesel Oil

The variation of rate of pressure rise with CA at a CR of 18 for Karanja biodiesel and Diesel oil are shown in Figures 4.88 and 4.89 respectively. The trend of variation observed is similar to that observed at CR of 16 but maximum rate of pressure rise is 2 bar/deg of crank angle and takes place at 5^0 CA after TDC for both Karanja biodiesel and Diesel oil. All the discussions indicate that an engine can perform better with reduced chances of abnormal combustion at a CR of 18 as the maximum rate of pressure rise occurs closer to but after TDC. The performance with Karanja biodiesel is similar that of Diesel oil.

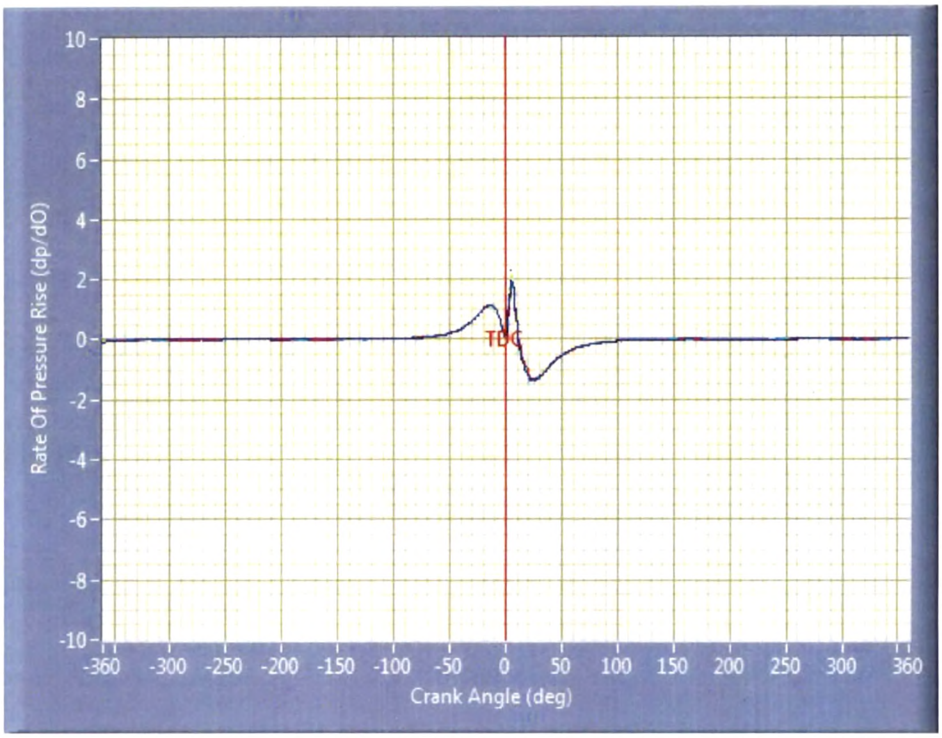

Figure 4.88 Variation of Rate of Pressure Rise With CA at CR of 18 for Karanja Biodiesel

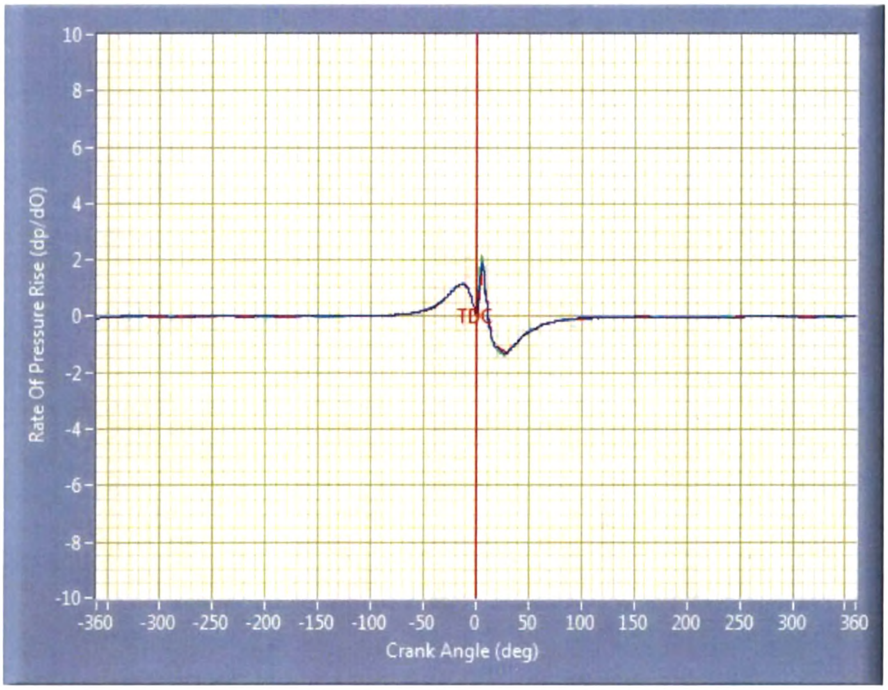

Figure 4.89 Variation of Rate of Pressure Rise with CA at CR of 18 for Diesel Oil

From Figures 4.84-4.89 it can be observed that each curve consists of two peaks and one trough for the fuels tested. They correspond to the phases of premixed combustion, mixed controlled combustion and late combustion respectively. Table 4.6 gives a comparison of rate of pressure rise of Karanja biodiesel with that of Diesel oil. It can be noted that the deviation of performance between Karanja biodiesel and Diesel oil reduces with increasing CR. It is observed that the first peak increases with increase in CR from 0.7 to 1.2 bar/^{0}CA for both the fuels due to higher rate of premixed combustion as CR increases.

Table 4.6 Comparison of Rate of Pressure Rise of Karanja Biodiesel With that of Diesel Oil (Reproduced From Figures 4.84-4.89)

CR	Fuel	Rate of Pressure Rise (bar/^{0}CA)		Position (^{0}CA)	
		First Peak	Second Peak	First Peak	Second Peak
14	Karanja biodiesel	0.7	2.5	20^0 before TDC	10^0 after TDC
	Diesel oil	0.7	2.6	20^0 before TDC	15^0 after TDC
16	Karanja biodiesel	0.8	2.5	17^0 before TDC	8^0 after TDC
	Diesel oil	1	2.5	18^0 before TDC	8^0 after TDC
18	Karanja biodiesel	1.2	2	15^0 before TDC	5^0 after TDC
	Diesel oil	1.2	2	13^0 before TDC	5^0 after TDC

Figure 4.90 shows the comparison of variation of maximum rate of pressure rise with CR at full load of 12kg and IP of 200bar of the present study with that of earlier investigations of Gattamaneni et al. [85] and Murugan [99]. The investigators used Rice bran biodiesel and Distilled tyre pyrolisis oil respectively.

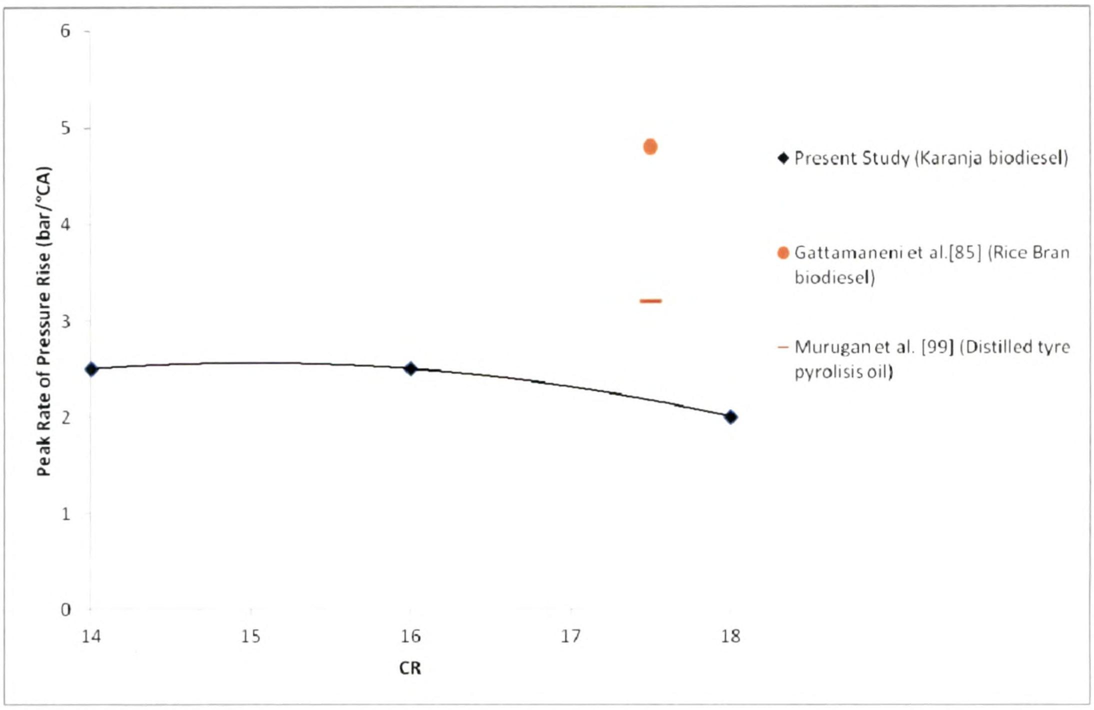

Figure 4.90 Comparison of Variation of Peak Rate of Pressure Rise with CR at a Load of 12kg and an IP of 200bar of the Present Study with that of Earlier Investigations

It is observed that maximum rate of pressure rise is uniform but marginally decreases with increase in CR for Karanja biodiesel used in the present study. The trend may be due to more uniform pressure rise as a result of even spread of combustion duration for different phases. It can be noted that there is no study reported for variation of maximum rate of pressure rise with CR. Therefore comparison of trend of the present study with earlier investigations is not possible. However, various studies of maximum rate of pressure rise at constant preset CR using different biodiesels are presented in Figure 4.90.

It is observed that at a constant CR of 17.5, maximum rate of pressure rise for Ricebran biodiesel and Distilled tyre pyrolisis oil is higher by almost 118% and 45% respectively as compared to that of Karanja biodiesel used in the present study. The reasons for the trend could not be ascertained from the earlier literature.

4.2.4.4 Mass Fraction Burnt

Variation of mass fraction burnt with CA for the engine operated with Karanja biodiesel and Diesel oil at CRs of 14, 16 and 18 are given in Figures 4.91 to 4.96. When combustion of the charge in a CI engine begins, a single flame front travels through the charge until it gets fully burnt. During the burning of the charge, the combustion zone can be divided into burnt and unburned zone. As the combustion progresses, the burnt zone part increases and unburned zone part reduces. Mass fraction burnt is the fraction of charge burnt for each cycle and it is expressed in percentage. In other words, the percent mass fraction burnt is an indication of the percentage of fuel burnt in the combustion chamber during the combustion process (Ferguson & Kirkpatrick [98]).

The variation of mass fraction burnt with CA at a CR of 14 for Karanja biodiesel and Diesel oil are shown in Figures 4.91 and 4.92 respectively. It is seen that 90 % of the fuel mass is burnt at 21^0 CA after TDC (over a total of 21^0CA) when Karanja biodiesel is the fuel, whereas, the same amount of fuel mass is burnt at 27^0 CA after TDC (over a total of 40^0 CA) using Diesel oil as fuel. A higher rate of fuel burning (same mass fraction is burnt in less CA) is observed for Karanja biodiesel as compared to Diesel oil (Table 4.7). The trend may be due to higher oxygen content and higher value of cetane number of Karanja biodiesel which initiates early combustion, complete burning of fuel over lesser ^{0}CA as compared to Diesel. 80% of mass is burned over 14^0 CA for Karanja biodiesel and over 17^0 CA for Diesel oil.

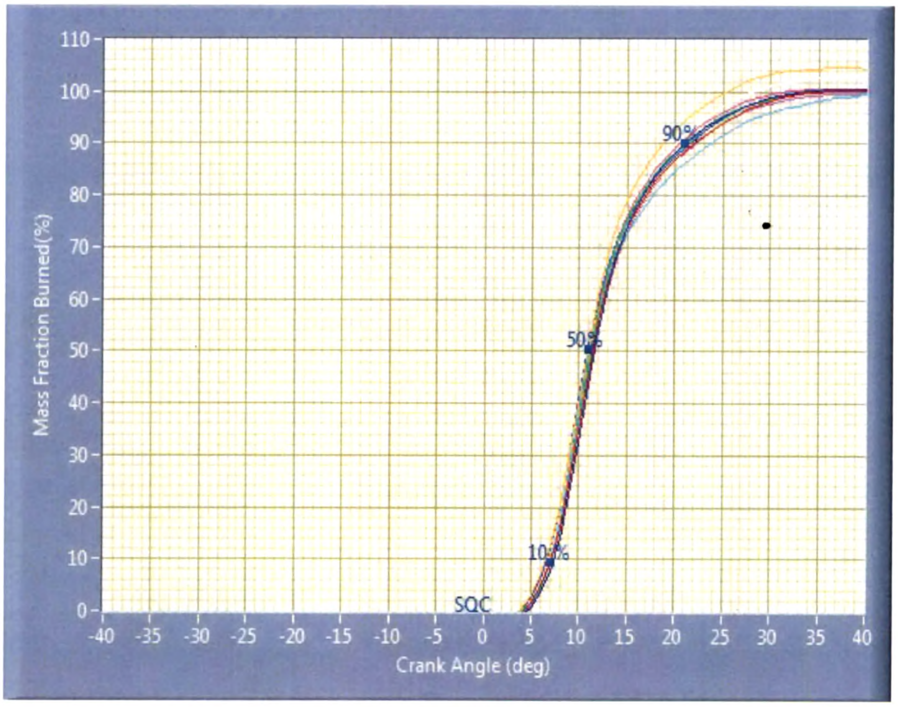

Figure 4.91 Variation of Mass Fraction Burnt With CA at CR of 14 for Karanja Biodiesel

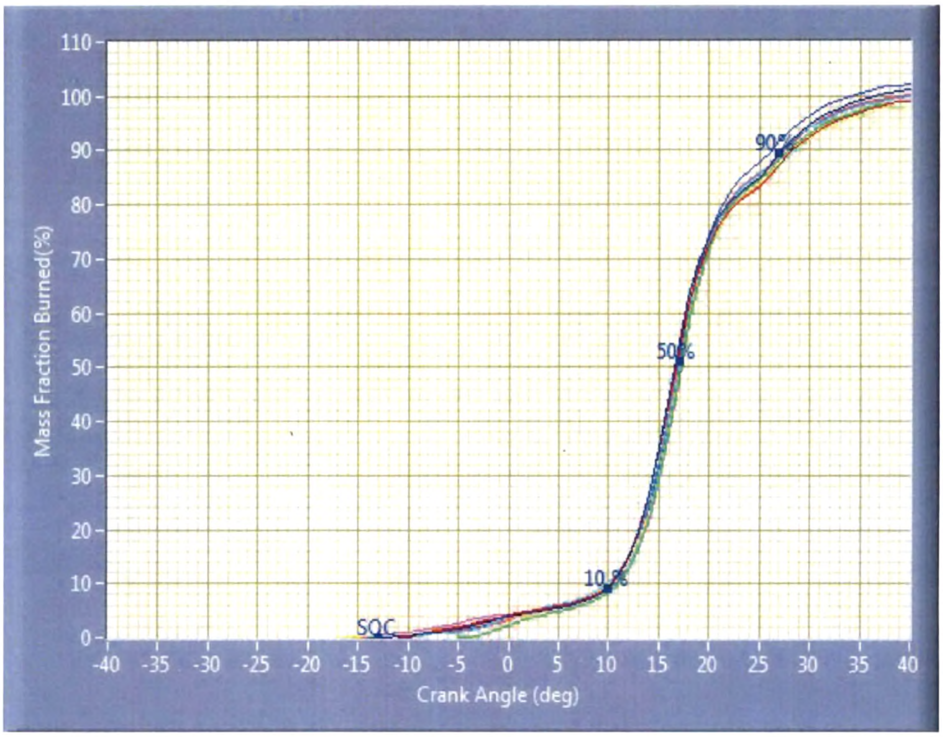

Figure 4.92 Variation of Mass Fraction Burnt With CA at CR of 14 for Diesel Oil

The variation of mass fraction burnt with CA at a CR of 16 for Karanja biodiesel and Diesel oil are shown in Figures 4.93 and 4.94 respectively. 90% fuel mass is burnt at 23^0 CA after TDC for Karanja biodiesel and 22^0 CA after TDC for Diesel oil as observed. It can be noted that as the CR is increased from 14 to 16 the deviation of performance between the two fuels used reduces. The same observation can also be made from Figures 4.70 to 4.75, 4.77 to 4.82 and 4.84 to 4.89. 80% mass fraction is burnt nearly over the same value of 17^0 CA for Karanja biodiesel and Diesel oil indicating that the performance is similar for both fuels.

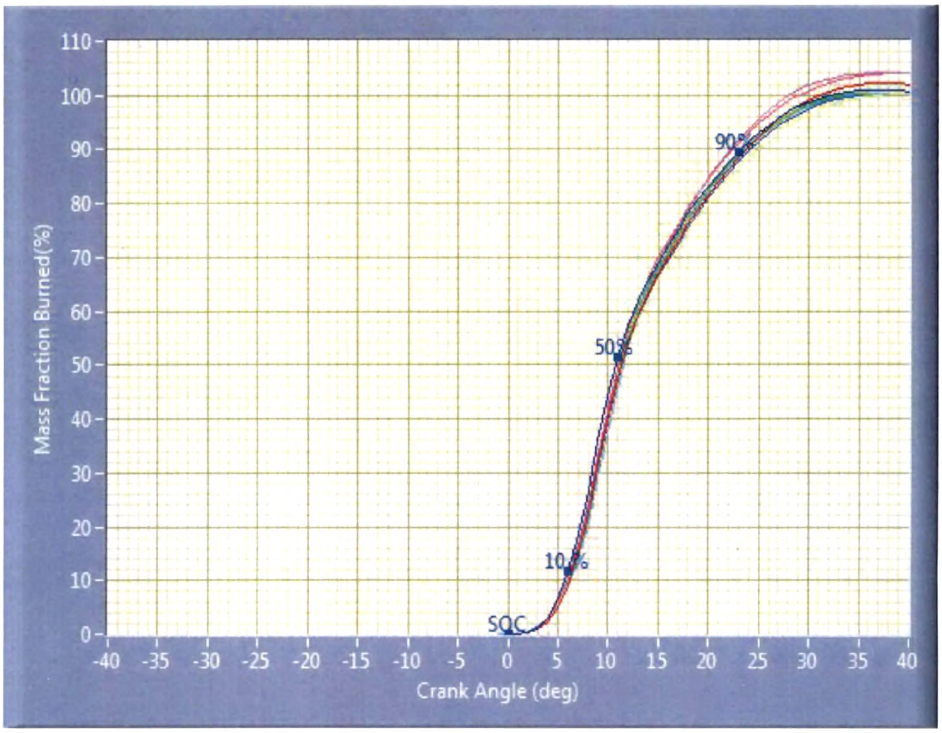

Figure 4.93 Variation of Mass Fraction Burnt With CA at CR of 16 for Karanja Biodiesel

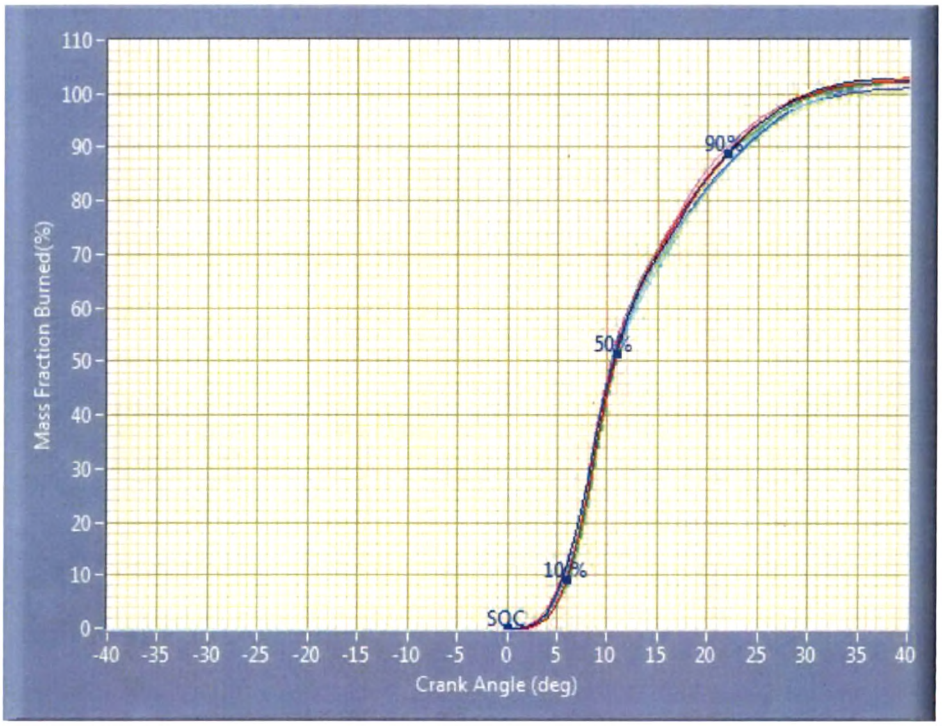

Figure 4.94 Variation of Mass Fraction burnt with CA at CR of 16 for Diesel Oil

The variation of mass fraction burnt with CA at a CR of 18 for Karanja biodiesel and Diesel oil are shown in Figures 4.95 and 4.96 respectively. It can be observed that there is no difference in mass fractions burnt with CA for both the fuels at higher CR of 18. Hence, it is better to substitute Diesel oil with Karanja biodiesel completely in a diesel engine at higher CRs.

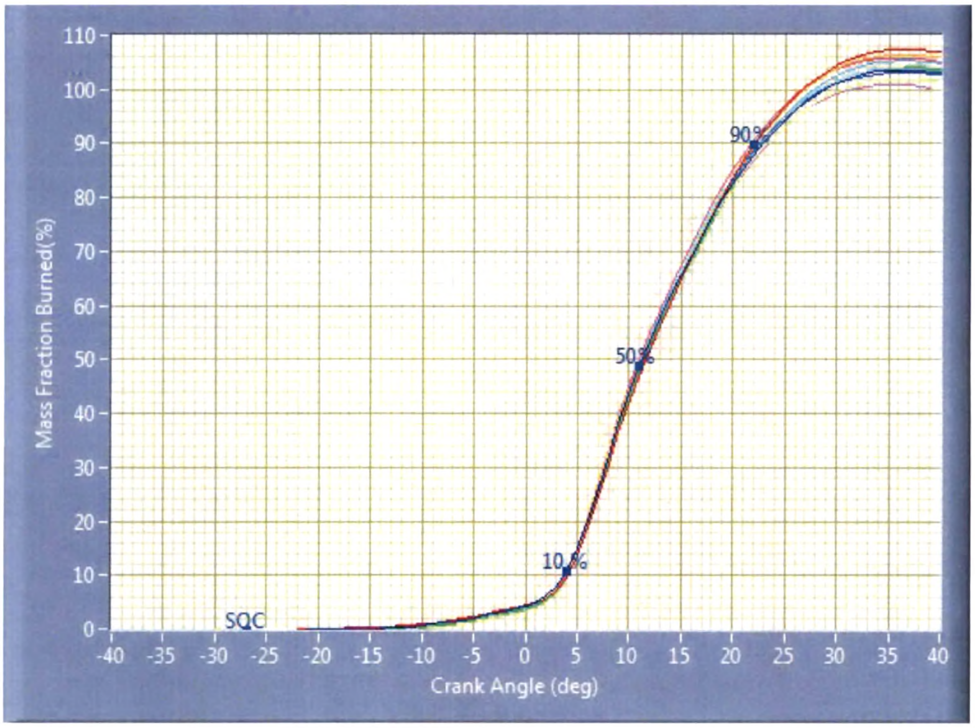

Figure 4.95 Variation of Mass Fraction Burnt with CA at CR of 18 for Karanja Biodiesel

It should be noted that curves of different colours are observed in all the figures of combustion analysis. The curves are the perturbations of repeated cycles of engine operation as mentioned earlier. Table 4.7 shows the comparison of fuel mass fraction burnt with the engine operated using Karanja biodiesel and Diesel oil as fuels. It can be observed that similar behaviour is found at higher CR of 16 and 18 between Karanja biodiesel and Diesel oil at higher CRs of 16 and 18 with respect to mass fraction burnt. Although, at CR of 14 there is an earlier combustion for all mass fractions burnt by about 4^0 to 5^0 CA after TDC with Karanja biodiesel as compared to Diesel oil.

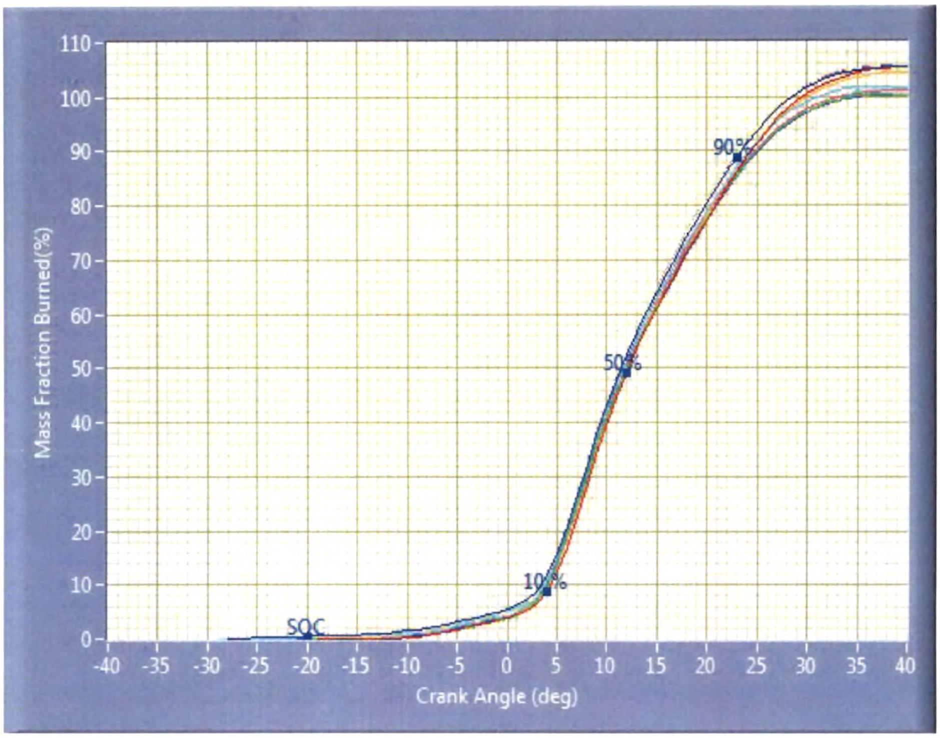

Figure 4.96 Variation of Mass Fraction Burnt With CA at CR of 18 for Diesel Oil

Table 4.7 Comparison of Mass Fraction of Fuel Burnt Between Diesel Oil and Karanja Biodiesel (Reproduced From Figures 4.91-4.96)

CR	Mass fraction burned (%)	Position (^{0}CA)	Fuel
14	10	7^0 after TDC	Karanja Biodiesel
	10	10^0 after TDC	Diesel oil
	50	11^0 after TDC	Karanja Biodiesel
	50	17^0 after TDC	Diesel oil
	90	21^0 after TDC	Karanja Biodiesel
	90	27^0 after TDC	Diesel oil
16	10	6^0 after TDC	Karanja Biodiesel
	10	6^0 after TDC	Diesel oil
	50	11^0 after TDC	Karanja Biodiesel
	50	11^0 after TDC	Diesel oil
	90	23^0 after TDC	Karanja Biodiesel

	90	22^0 after TDC	Diesel oil
18	10	4^0 after TDC	Karanja Biodiesel
	10	4^0 after TDC	Diesel oil
	50	11^0 after TDC	Karanja Biodiesel
	50	12^0 after TDC	Diesel oil
	90	23^0 after TDC	Karanja Biodiesel
	90	23^0 after TDC	Diesel oil

4.2.4.5 Mean Gas Temperature

Variation of mean gas temperature with CA for the engine operated with Karanja biodiesel and Diesel oil at CRs of 14, 16 and 18 are given in Figures 4.97 to 4.102. The average value of burned & unburned gas temperatures existing in the combustion chamber during a cycle is called mean gas temperature. The gas in the cylinder is the mixture of burnt and unburnt fuel air mixture. Mean gas temperature decides the rate of reaction during burning of fuel and it is desirable that the value be closer to the adiabatic flame temperature. Adiabatic flame temperature is the temperature achieved for the products of combustion if the reaction is adiabatic and no loss of thermal energy takes place in any other manner, ensuring that all the heat evolved helps in increasing the products of combustion to a maximum possible value.

The variation of mean gas temperature with CA at CR of 14 for Karanja biodiesel and Diesel oil are shown in Figures 4.97 and 4.98 respectively. It is observed that the minimum value of mean gas temperature is 40 ^{0}C less for Karanja biodiesel compared to Diesel oil at 40^0 CA before TDC. It remains almost constant and then rises to 1060^0C at 25^0 CA after TDC in case of Karanja biodiesel whereas the same is around 1430^0C at 35^0 CA after TDC for Diesel oil. It can be noted that the maximum mean gas temperature for Karanja biodiesel is about 25% less as compared to that of Diesel oil. The lower mean gas temperature for Karanja biodiesel may be due to the fact that heat release is less as calorific value of Karanja biodiesel is about 6% less than that of Diesel oil. It is observed that for Karanja biodiesel, the sudden rise in the mean gas temperature takes place at 5^0 after TDC and at 10^0 after TDC for Diesel oil. The earlier rise for Karanja biodiesel may be due to its lesser ignition delay.

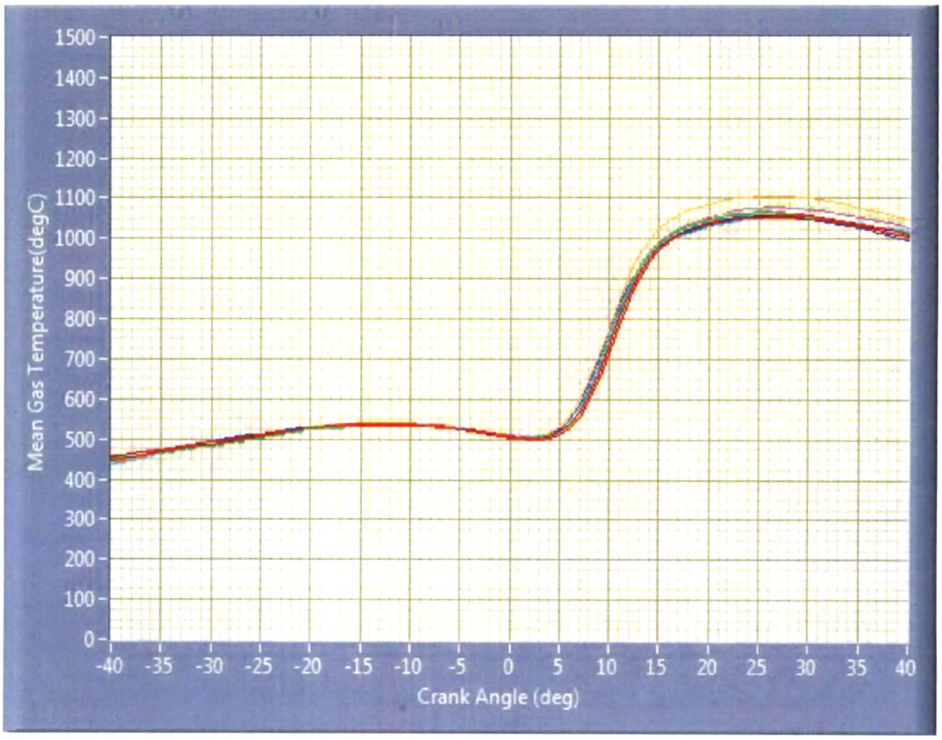

Figure 4.97 Variation of Mean Gas Temperature With CA at CR of 14 for Karanja Biodiesel

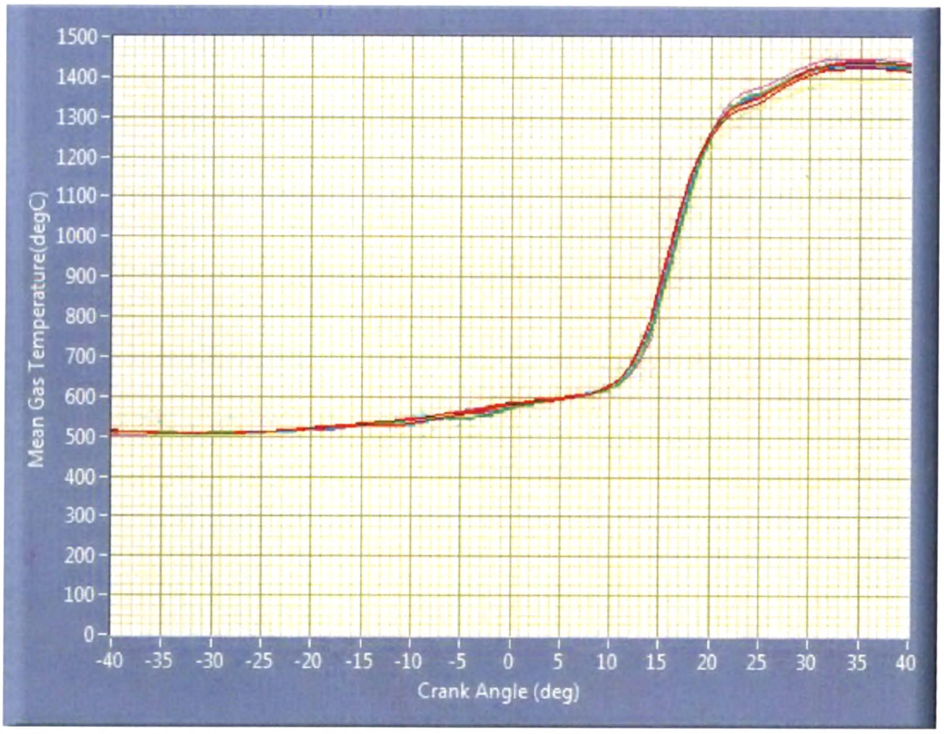

Figure 4.98 Variation of Mean Gas Temperature With CA at CR of 14 for Diesel Oil

The variation of mean gas temperature with CA at a CR of 16 for Karanja biodiesel and Diesel oil are shown in Figures 4.99 and 4.100 respectively. The minimum mean gas temperature is 421^0C and 500^0C for Karanja biodiesel and Diesel oil respectively at 40^0 before TDC. Mean gas temperature starts to increase at 5^0 CA after TDC for both the fuels tested reaching a value of 1130^0C and 1200^0C for Karanja biodiesel and Diesel oil respectively. The gap between the maximum value of mean gas temperature between the two fuels reduces as CR increases from 14 to 16.

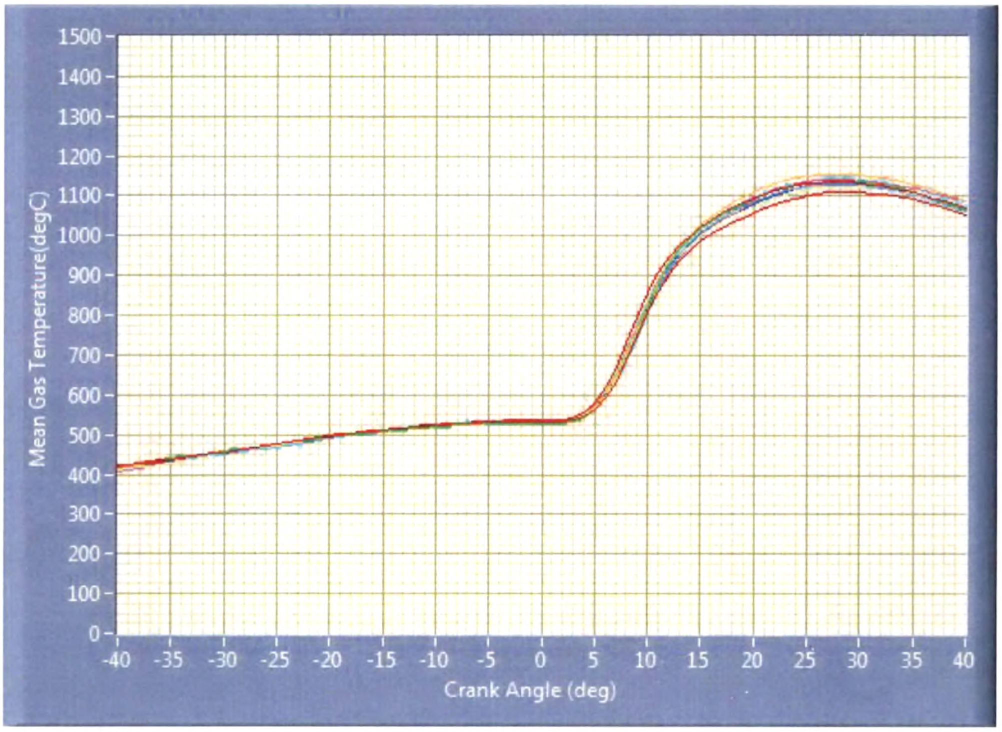

Figure 4.99 Variation of Mean Gas Temperature with CA at CR of 16 for Karanja Biodiesel

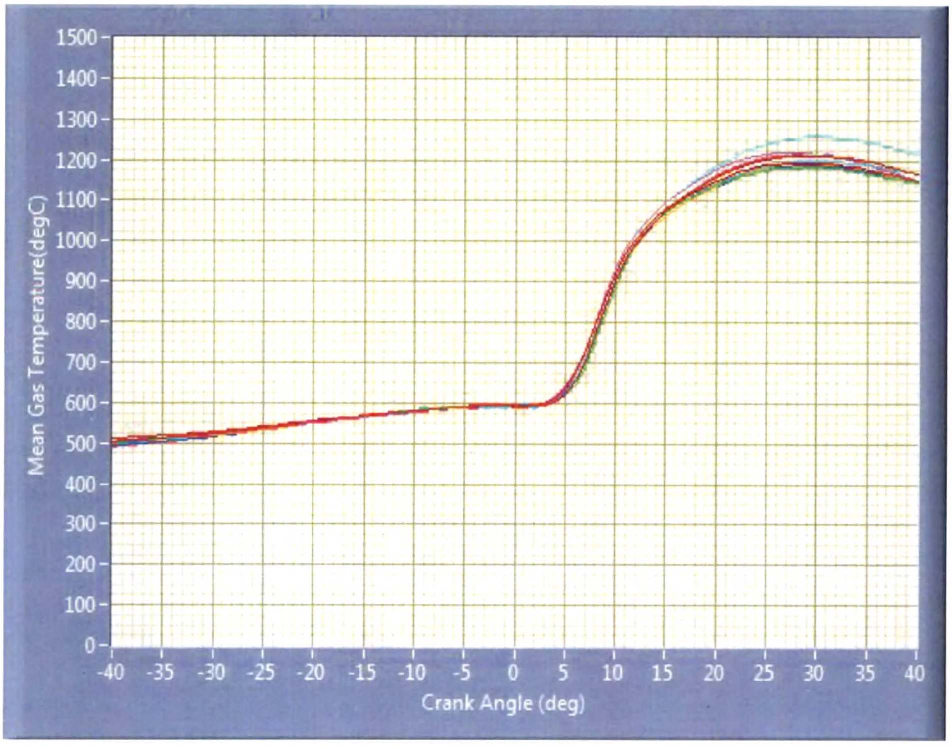

Figure 4.100 Variation of Mean Gas Temperature With CA at CR of 16 for Diesel Oil

The variation of mean gas temperature with CA at a CR of 18 for Karanja biodiesel and Diesel oil are shown in Figures 4.101 and 4.102 respectively. It is observed that the maximum mean gas temperature for Karanja biodiesel and Diesel oil are 1280^{0}C and 1275^{0}C respectively. The minimum temperatures achieved are identical and the crank angle positions at which it is observed are same for the fuels. Therefore, it can be inferred that Karanja biodiesel performs similar to Diesel oil at higher CR of 18 even though its calorific value is less and has a relatively higher viscosity.

Table 4.8 gives a comparison of mean gas temperatures for Karanja biodiesel with that of Diesel oil at CRs of 14, 16 & 18, full load of 12kg and IP of 200bar. It is observed that the mean gas temperature increases with increase in CR for Karanja biodiesel whereas the trend is opposite for Diesel oil. It can be attributed to the fact that more heat is released in diffusion burning (mixing controlled combustion) phase for Karanja biodiesel as compared to Diesel oil (Refer Table 4.5). Greater mass fraction is burnt at earlier CA for Karanja biodiesel as CR increases also results in increase of mean gas temperature (Refer Table 4.7). Delayed combustion and reduce in the peak net heat release rate with increase in CR account for the decrease in mean gas temperature with

Diesel oil. It can be noted that the behavior of Karanja biodiesel compared to Diesel oil are identical qualitatively at higher CR of 18.

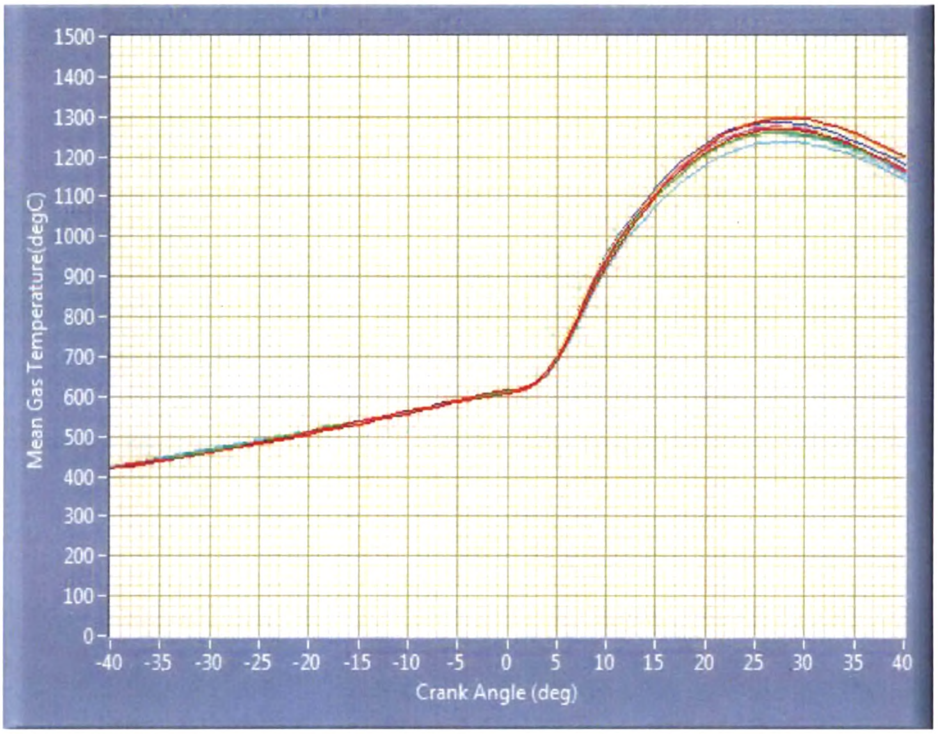

Figure 4.101 Variation of Mean Gas Temperature With CA at CR of 18 for Karanja Biodiesel

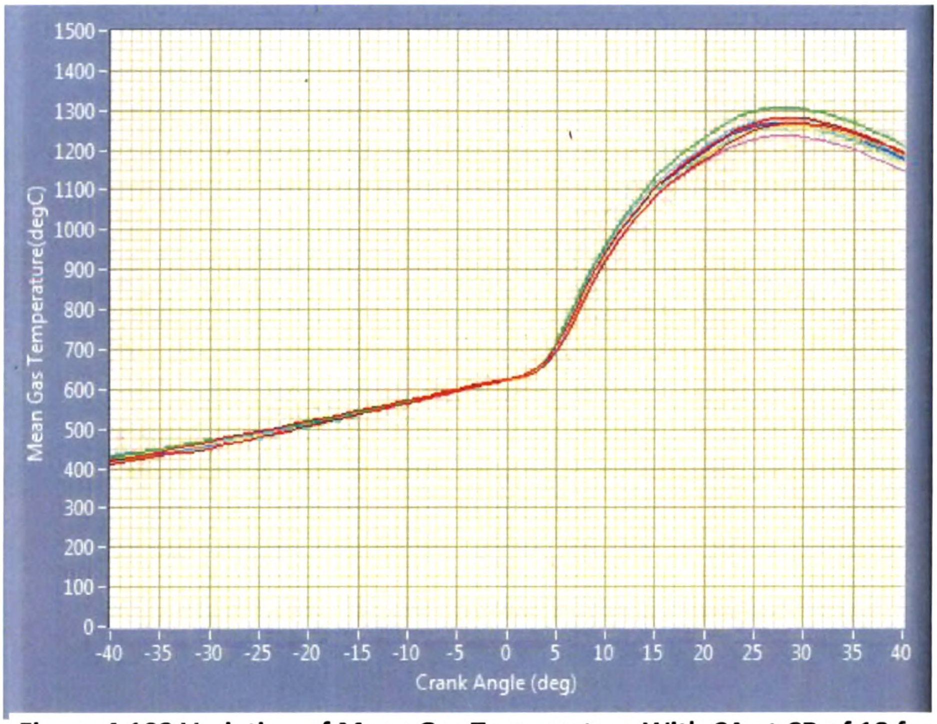

Figure 4.102 Variation of Mean Gas Temperature With CA at CR of 18 for Diesel Oil

A comparison between Table 4.7 and Table 4.8 shows that the mean gas temperature is highest when more than 90% of mass fraction is burnt for both fuels. It is obvious as mean gas temperature, is the result of thermal energy released during combustion of fuel. So more fuel burnt results in higher mean gas temperature.

Table 4.8 Comparison of Mean Gas Temperature of Karanja Biodiesel With that of Diesel Oil (Reproduced From Figures 4.97-4.102)

CR	Fuel	Mean Gas Temperature (^{0}C)		Position (^{0}CA)	
		Max	Min	Max	Min
14	Karanja biodiesel	1060	460	25^0 after TDC	40^0 before TDC
	Diesel oil	1430	500	35^0 after TDC	40^0 before TDC
16	Karanja biodiesel	1130	421	27^0 after TDC	40^0 before TDC
	Diesel oil	1200	500	28^0 after TDC	40^0 before TDC
18	Karanja biodiesel	1280	425	28^0 after TDC	40^0 before TDC
	Diesel oil	1275	425	27^0 after TDC	40^0 before TDC

4.2.4.6 PV characteristics

Variation of CP with cylinder volume for the engine operated with Karanja biodiesel and Diesel oil at CRs of 14, 16 and 18 are given in Figures 4.103 to 4.108. Cylinder pressure changes with crank angle as a result of cylinder volume change during combustion of fuel.. Since both the compression of the unburned mixture prior to combustion and the expansion of burned gases following the end of combustion are close to isentropic processes, the observed behaviour is as expected (Heywood [96]).

It can be inferred from the figures that peak value of cylinder pressure at lower compression ratio (CR 14) is lower for Karanja biodiesel (38 bar) by about 2bar as compared to that of Diesel oil (40 bar). As CR increases to 16, CP increases to 44bar and 46bar for Karanja biodiesel and Diesel oil respectively. However, as CR increases to 18, cylinder pressure increases to 50bar for both the fuel runs on the engine implying that identical performance exists at higher compression ratio of 18 exists for both fuels. For CR of 14, the areas of the PV plots for Karanja biodiesel are found to be less by about 30% as compared to Diesel oil which means work done during the cycle is comparatively less for Karanja biodiesel than Diesel oil. At CR of 16 the area is only 3% less for Karanja biodiesel. This is observed by area measurements of PV plots. As the CR increases to 18, the areas are almost identical , indicating same performance for both fuels. Between CR of 16 to 18 peak CP increases by 31% (38 to 50 bar) and 25% (40 to 50 bar) for Karanja biodiesel and Diesel oil respectively. The results obtained are interpreted earlier from the figures of CP with CA.

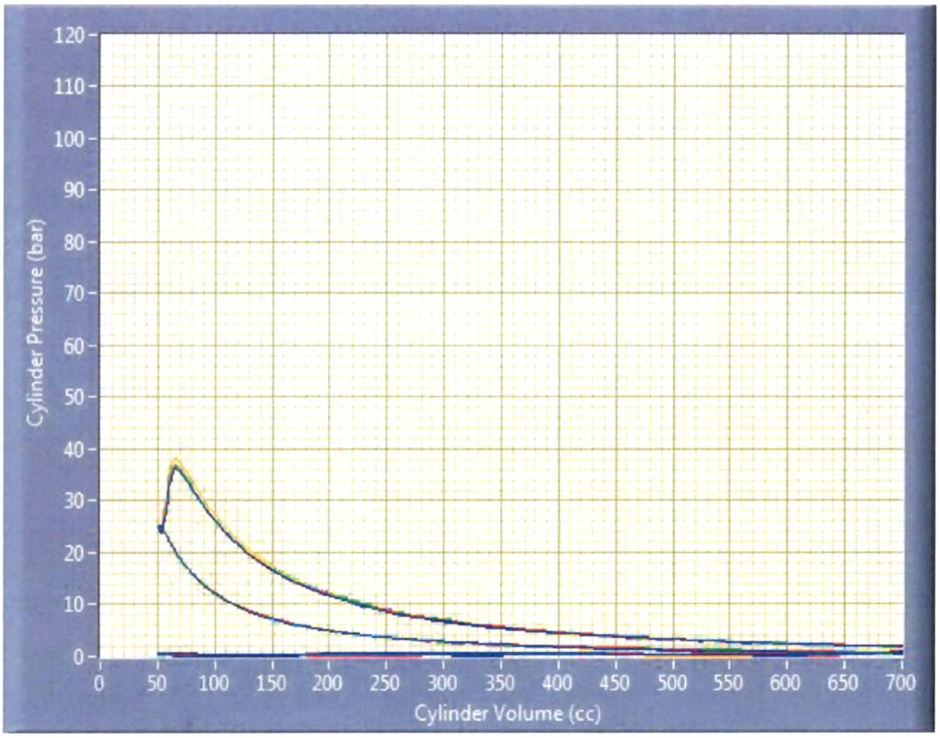

Figure 4.103 Variation of CP With Cylinder Volume at CR of 14 for Karanja Biodiesel

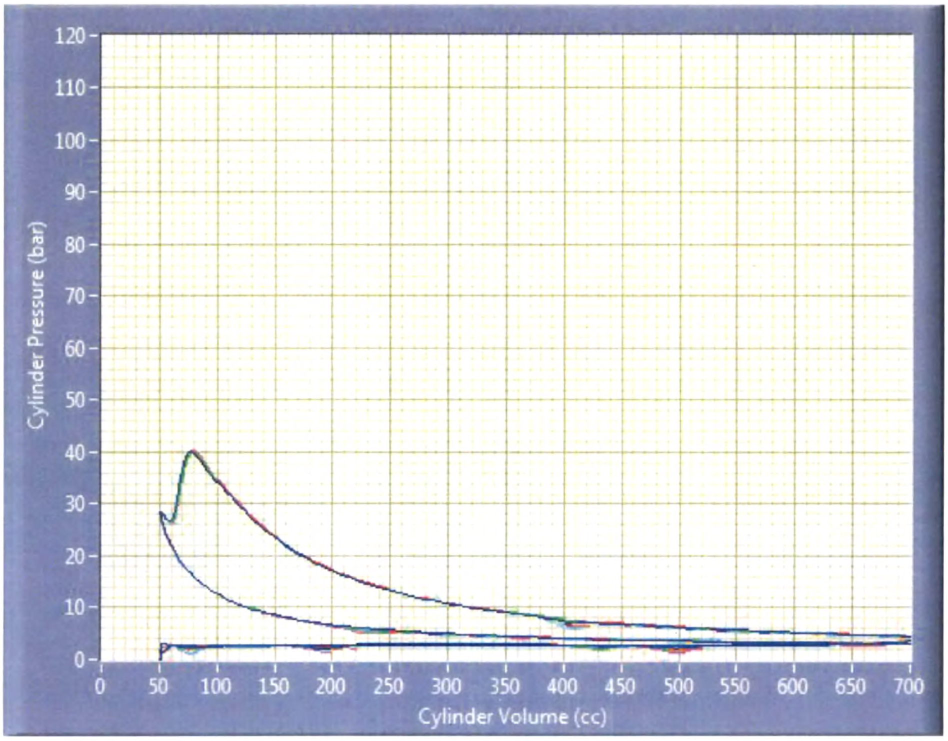

Figure 4.104 Variation of CP With Cylinder Volume at CR of 14 for Diesel Oil

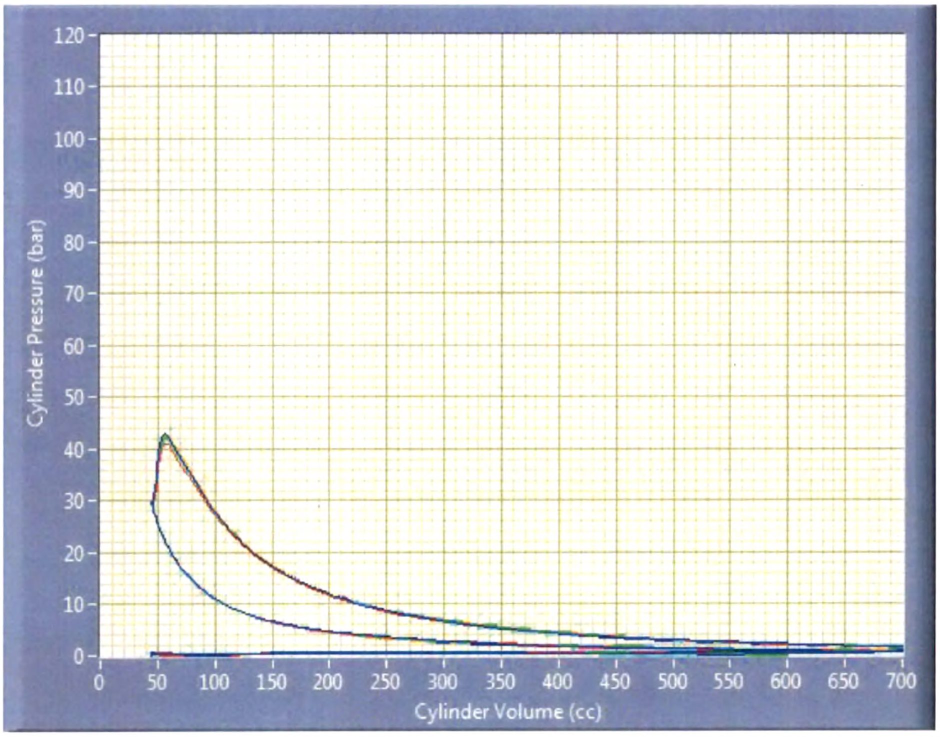

Figure 4.105 Variation of CP With Cylinder Volume at CR of 16 for Karanja Biodiesel

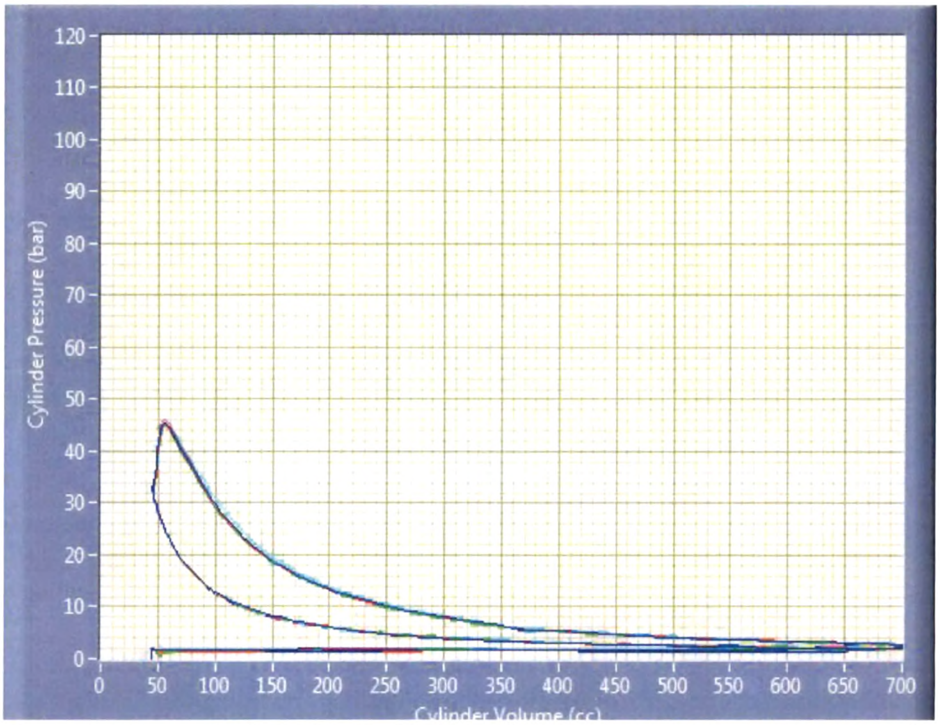

Figure 4.106 Variation of CP With Cylinder Volume at CR of 16 for Diesel Oil

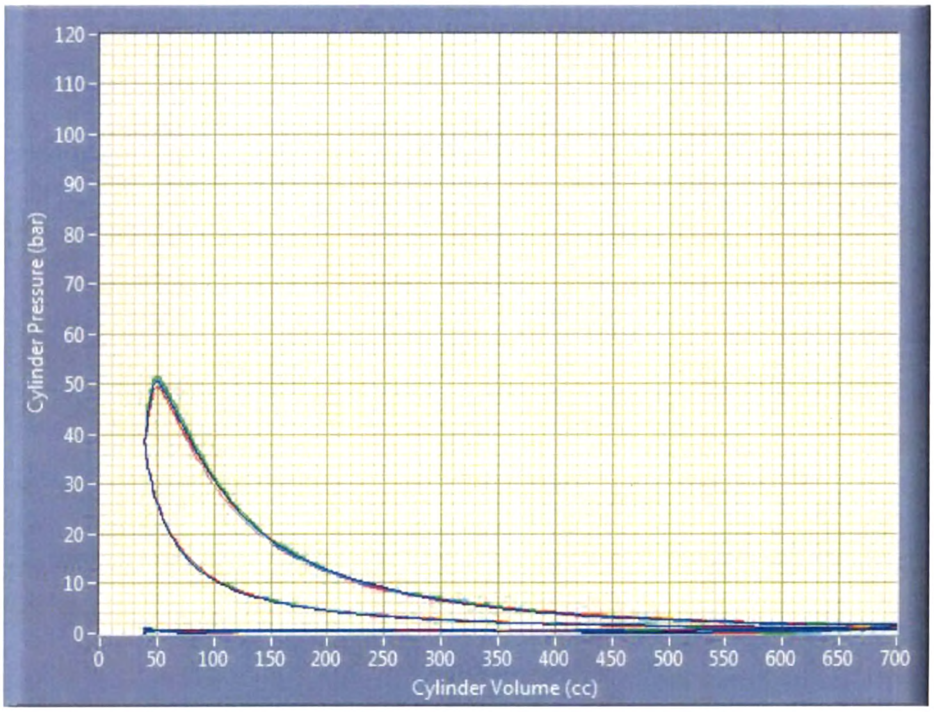

Figure 4.107 Variation of CP With Cylinder Volume at CR of 18 for Karanja Biodiesel

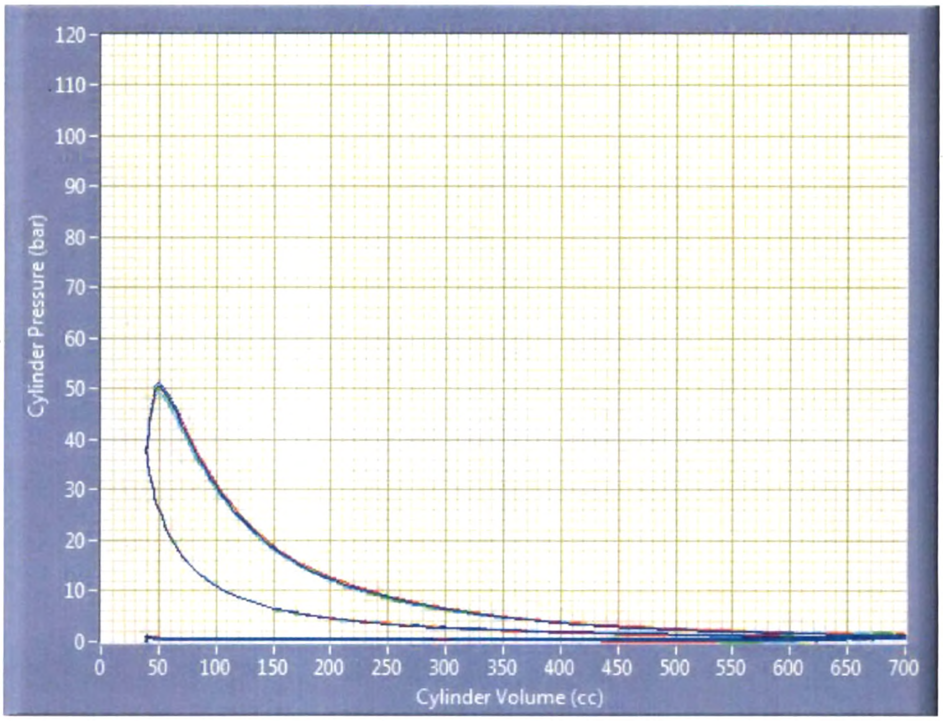

Figure 4.108 Variation of CP With Cylinder Volume at CR of 18 for Diesel Oil

4.2.4.7 Cumulative Heat Release

Variation of cumulative heat release with CA for the engine operated with Karanja biodiesel and Diesel oil at CRs of 14, 16 and 18 are given in Figures 4.109 to 4.114. Cumulative heat is the total chemical energy of the fuel released by combustion process. This is indicated by Q_{ch} in the equation.

$$(dQ_n)/dt = (dQ_{ch})/dt - (dQ_{ht})/dt = p\,dV/dt + (dU_s)/dt$$

The cumulative heat release is the sum of net heat release and heat transfer to the walls of the combustion chamber. It is also the sum of the sensible internal energy of the cylinder contents, the heat transfer rate to the walls and the rate at which the work is done on the piston (Heywood [96]).

The variation of cumulative het release with CA at a CR of 14 for Karanja biodiesel and Diesel oil are shown in Figures 4.109 and 4.110 respectively. It is observed that the cumulative heat release is about 0.02 kJ less at 40^0 before TDC for Karanja biodiesel as compared to Diesel oil.

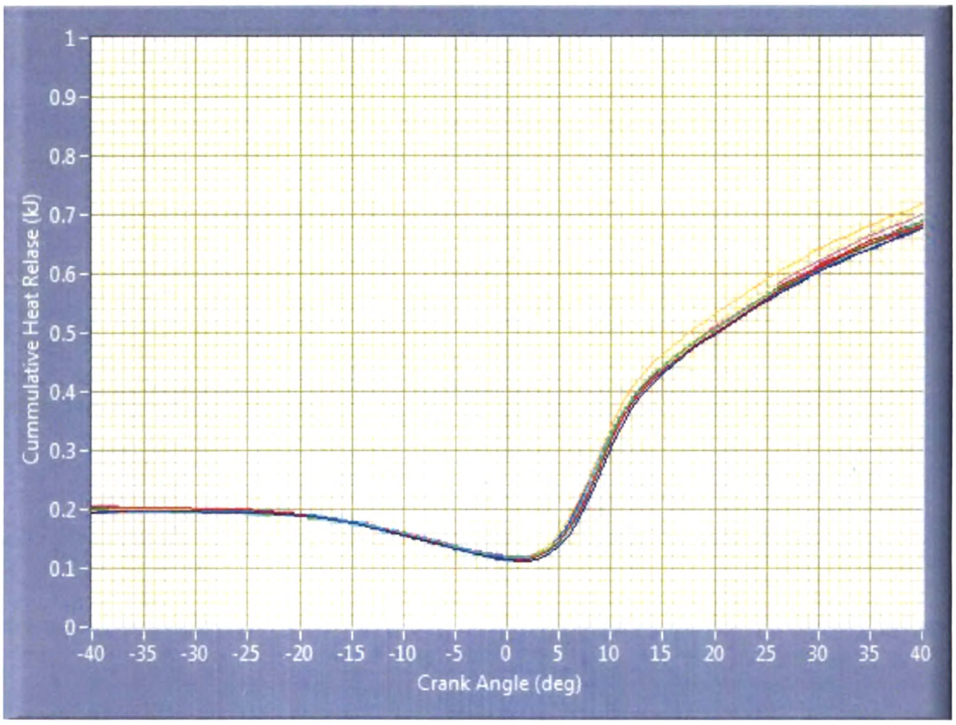

Figure 4.109 Variation of Cumulative Heat Release With CA at CR of 14 for Karanja Biodiesel

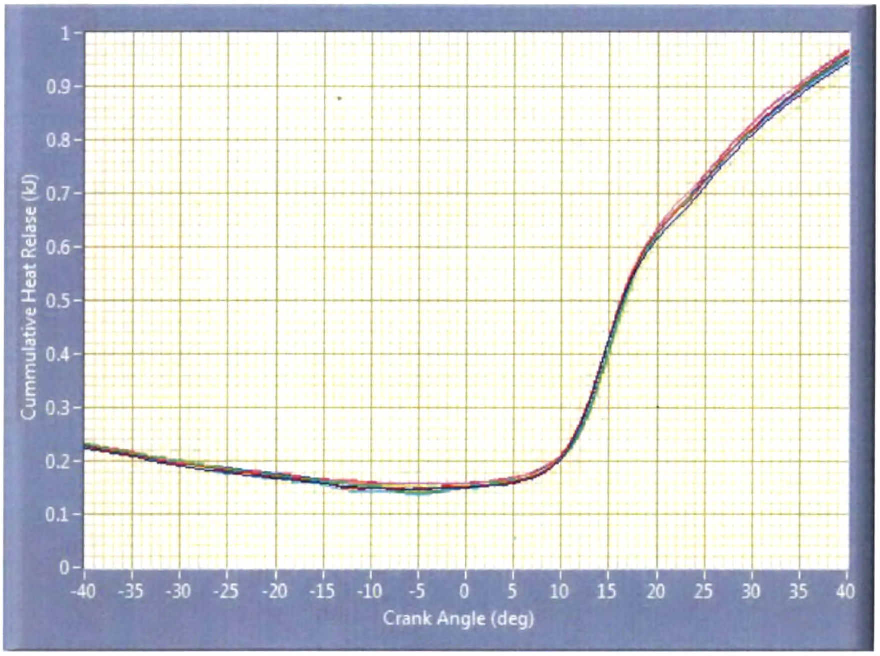

Figure 4.110 Variation of Cumulative Heat Release With CA at CR of 14 for Diesel Oil

Heat release drops to a minimum of 0.12 kJ at 1.5^0 CA after TDC for Karanja biodiesel and 0.14 kJ at 5^0 CA before TDC for Diesel oil. The drop in the curve is more noticeable for Karanja biodiesel than Diesel oil. The highest value of cumulative heat release achieved is 0.7 kJ for Karanja biodiesel and 0.97 kJ for Diesel oil which occurs at 40^0 after TDC for both fuels tested.

The variation of cumulative heat release with CA at a CR of 16 for Karanja biodiesel and Diesel oil are shown in Figures 4.111 and 4.112 respectively. The lowest value of cumulative heat release at a CR of 16 is about 0.13 kJ for Karanja biodiesel and 0.14 kJ for Diesel oil. The cumulative heat release raises to a maximum of 0.75 kJ at 40^0 CA after TDC for Karanja biodiesel whereas it is about 0.82 kJ at 40^0 CA after TDC for Diesel oil. The lower value of heat release for Karanja biodiesel may be due to its lower calorific value as compared to Diesel oil.

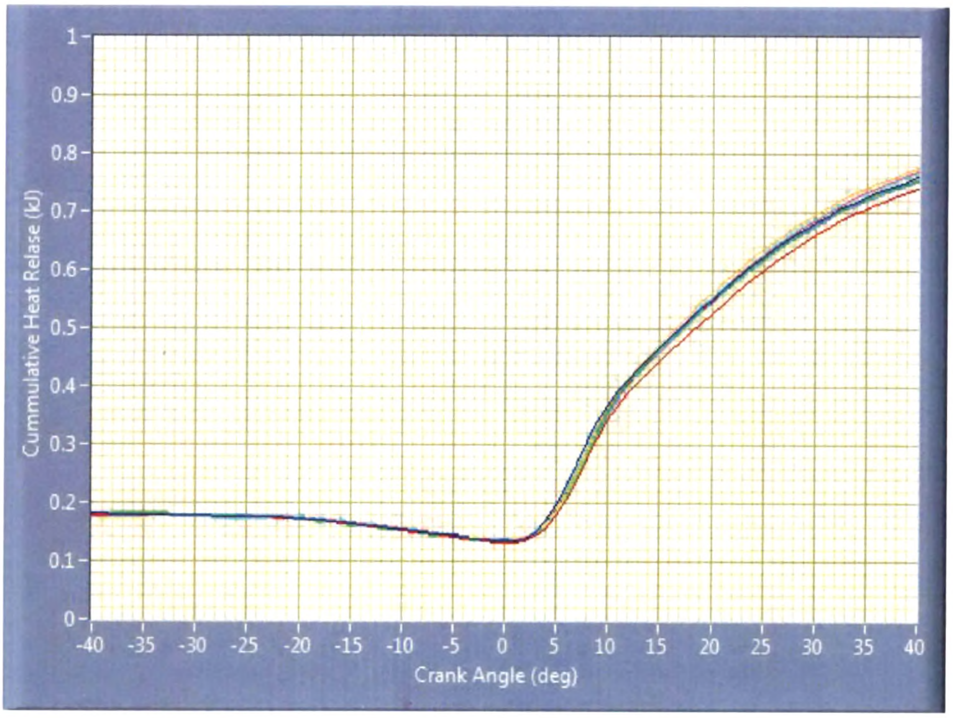

Figure 4.111 Variation of Cumulative Heat Release With CA at CR of 16 for Karanja Biodiesel

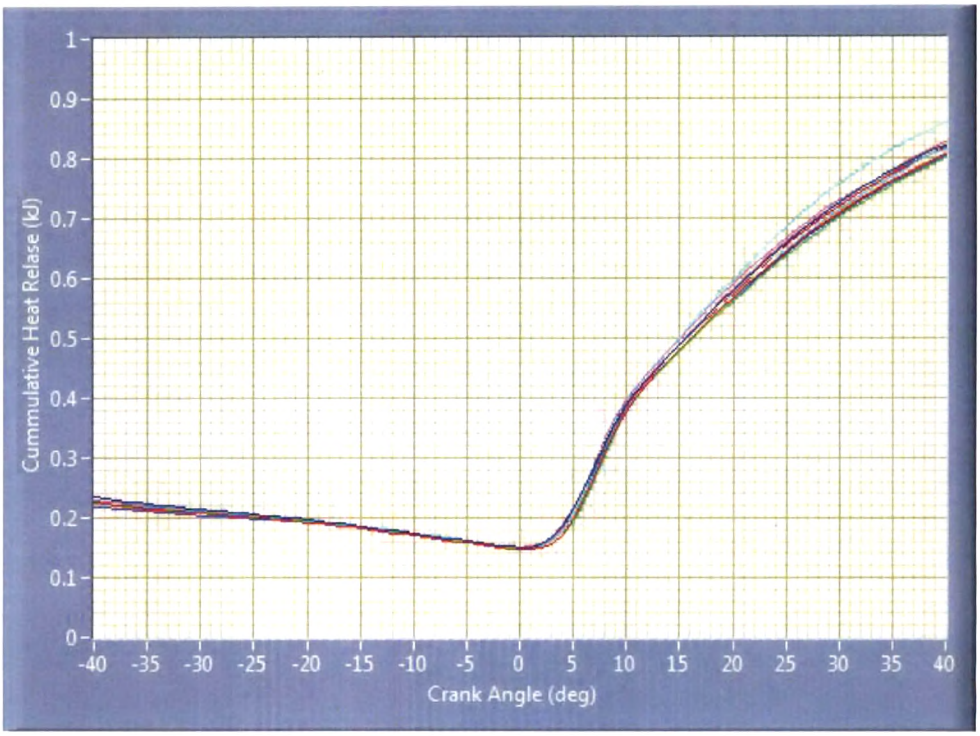

Figure 4.112 Variation of Cumulative Heat Release With CA at CR of 16 for Diesel Oil

The variation of cumulative heat release with CA at a CR of 18 for Karanja biodiesel and Diesel oil are shown in Figures 4.113 and 4.114 respectively. It can be observed that the trends for Karanja biodiesel and Diesel oil are the same with respect to cumulative heat release. The maximum value achieved is around 0.86kJ for both Karanja biodiesel and Diesel oil and it occurs at 40^0 CA after TDC. The minimum cumulative heat release value of 0.18kJ are identical for both the fuels. Hence, it can be noted that the performance of Karanja biodiesel is comparable to that of Diesel oil at higher CRs.

Table 4.9 gives the comparison of cumulative heat release of Karanja biodiesel with that of Diesel oil. It can be noted that cumulative heat release increases with increase in CR for Karanja biodiesel (22%) while an opposite trend is observed for Diesel oil (11%). Cumulative heat release is the integrated or ensemble average of the total number of cycles over the duration of combustion period.

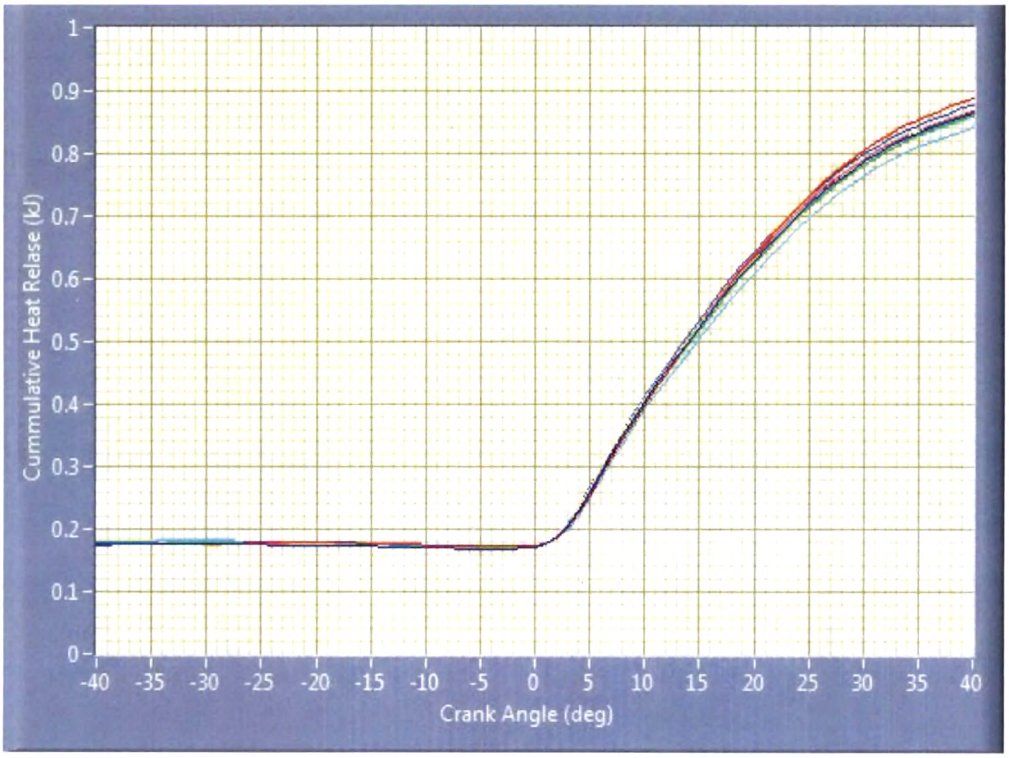

Figure 4.113 Variation of Cumulative Heat Release With CA at CR of 18 for Karanja biodiesel

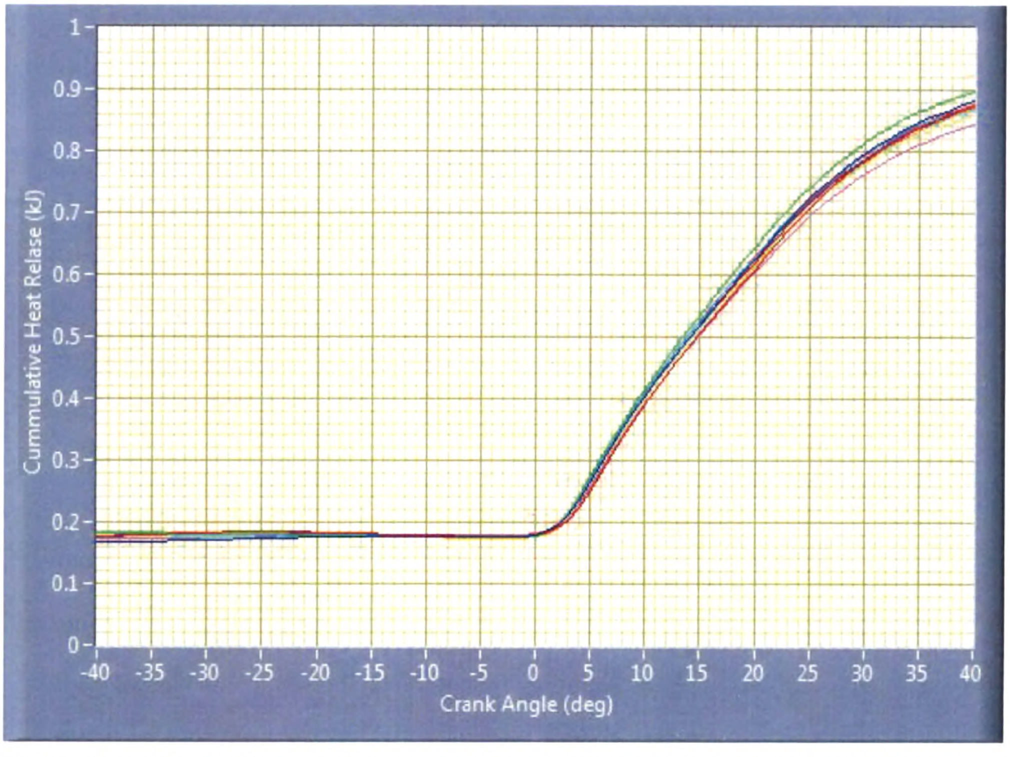

Figure 4.114 Variation of Cumulative Heat Release With CA at CR of 18 for Diesel oil

Table 4.9 Comparison of Cumulative Heat Release of Karanja Biodiesel With that of Diesel Oil (Reproduced From Figures 4.106-4.111)

CR	Fuel	Cumulative Heat Release (kJ)		Crank Angle (^{0} CA)	
		Max	Min	Max	Min
14	Karanja biodiesel	0.7	0.12	40^0 after TDC	1.5^0 after TDC
	Diesel oil	0.97	0.14	40^0 after TDC	5^0 before TDC
16	Karanja biodiesel	0.75	0.13	40^0 after TDC	TDC
	Diesel oil	0.82	0.14	40^0 after TDC	TDC
18	Karanja biodiesel	0.86	0.18	40^0 after TDC	TDC
	Diesel oil	0.86	0.18	40^0 after TDC	TDC

4.2.4.8 Injection Pressure

Variation of injection pressure and cylinder pressure data for the engine in one cycle of operation are shown superposed at full load of 12kg and CR of 14 in Figures 4.115, 4.116 and 4.117.

A typical data for cylinder pressure and fuel line pressure (IP) with crank angle is as shown in Figures 4.115, 4.116 and 4.117 for injection pressure settings of 150, 200 and 250bar at full load and CR of 14. The injection pressure rise was observed over a crank angle of 25^0CA and cylinder pressure rise over 175^0CA for one cycle of operation. The fuel line pressure plot is an indicator of the rate of fuel injection into the cylinder. The cylinder pressure varies between 0 to 40 bar and injection pressure varies from 0 to 150, 200 and 250 bar. The same trend is observed at all different values of injection pressures tried. The duration of fuel injection remains same in all cases at around 25^0CA. The value concurs with the duration of injection as mentioned in the available literature for diesel running on a CI engine (Ferguson & Kirkpatrick, Chapter Thermodynamic Analysis). The injection line pressure can be selected above or below the standard value 210 bar based on the type of fuel and its properties such as compressibility and viscosity. Generally, the injection pressure value selected for biodiesel is more than that for Diesel oil because of higher rate of fuel injection required to achieve the same pressure rise and hence the power output.. It should be noted that due to software limitation the injection pressure is indicated as diesel pressure on the ordinate of the plot indicates here (Figures 4.115, 4.116 and 4.117).

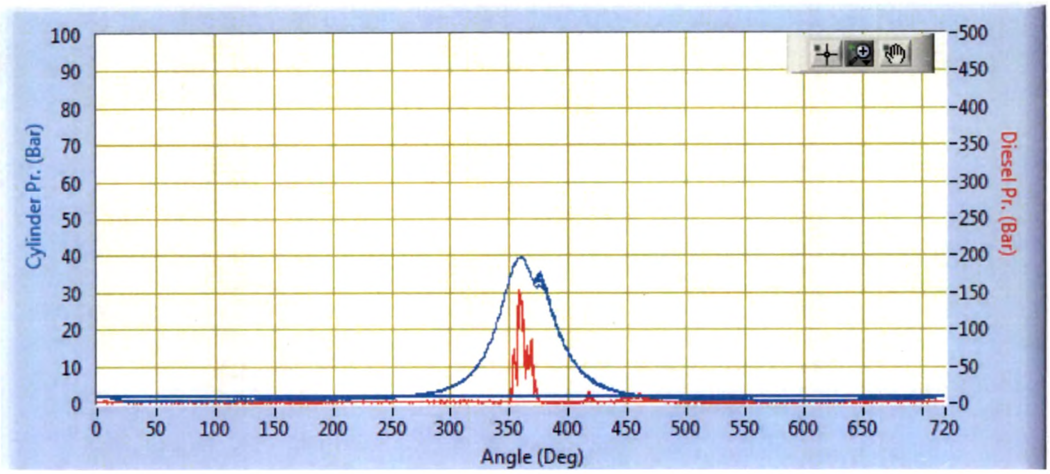

Figure 4.115 Variation of Cylinder and Injection Pressures with CA (150bar)

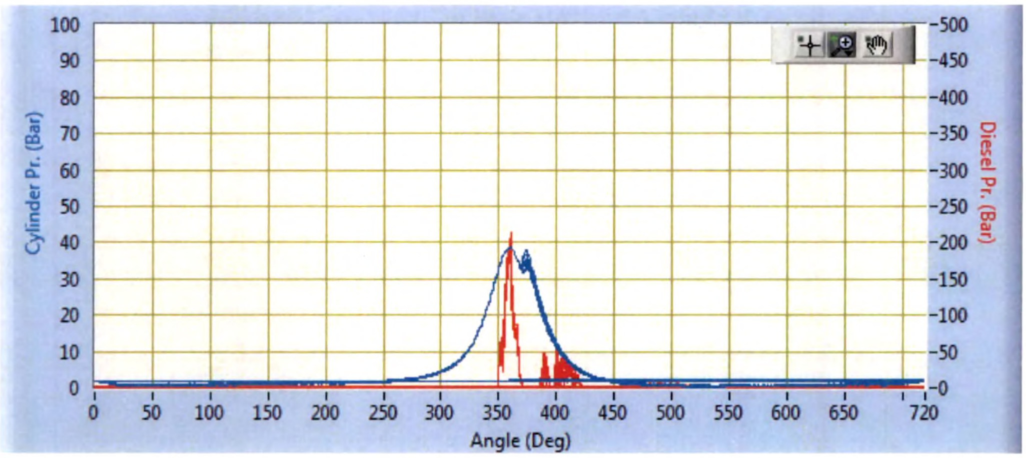

Figure 4.116 Variation of Cylinder and Injection Pressures with CA (200bar)

The cylinder peak pressure is almost same in all cases (around 40 bar) as seen from Figures 4.115 to 4.117. The attainment of the desired injection pressure takes place over crank advancement of 22-25^0 of CA in all cases. Higher IP is desirable for biodiesels as reported from thermal performance and emissions. Some experimental perturbation is noticed in the form of a small second peak cannot be substantiated.

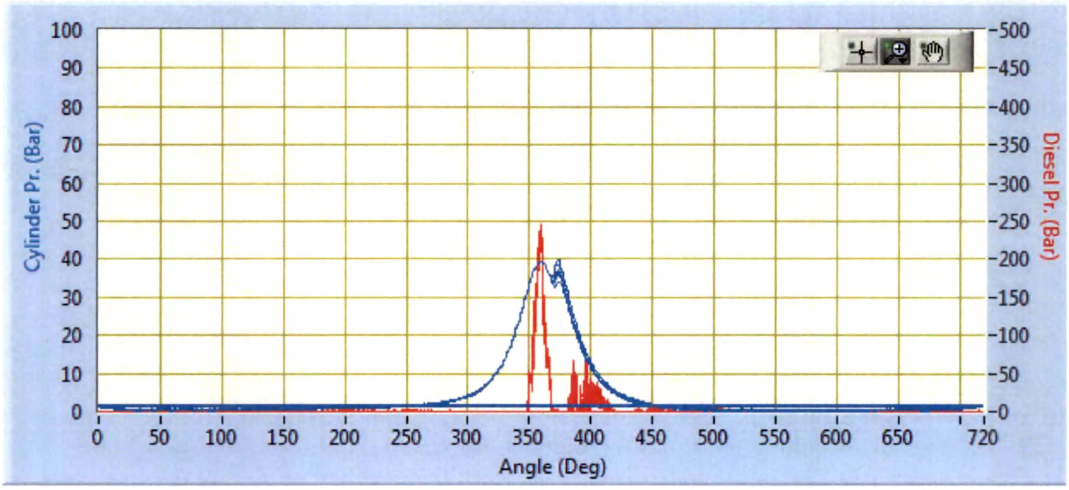

Figure 4.117 Variation of Cylinder and Injection Pressures with CA (250 bar)

4.3 Summary

In the earlier sections the thermal performance and emissions characterictics evaluated by operating a four stroke, variable compression ratio diesel engine using Karanja biodiesel and its blends with diesel are given. The experiments are performed using combinations of different preset compression ratios of 14, 15, 16, 17, 17.5 and 18, different injection pressures of 150 bar, 200 bar and 250 bar, and varying loads from 0kg to 12 kg in steps of 3kg. The thermal performance parameters evaluated are BTHE, BSFC, BMEP, Volumetric Efficiency, HBP and HGas, EGT. The emission constituents measured are CO, HC, NO_x, CO_2, O_2 and SO_x. Along with emission constituents, the smoke intensity is also measured in terms of HSU (%) & K (m^{-1}). A detailed combustion analysis of the engine running on pure diesel and Karanja biodiesel at different preset compression ratios of 14, 16 and 18 and full load is also conducted. The combustion parameters considered for analysis are cylinder pressure, net heat release, rate of pressure rise, mass fraction burnt, mean gas temperature, cylinder pressure-volume (PV) plot and cumulative heat release rate (follow same order). Prior to carrying out the exhaustive experimental study, a validation test is conducted on the engine using Diesel oil alone as fuel to check/ascertain the readiness of the experimental setup at standard rated conditions of 12kg, IP of 200 bar, CR of 17.5. The data from the validation test are also used as a base line for further comparison of the results with Karanja biodiesel & its blends.

4.3.1 Thermal Performance

Even though the rated CR of the engine used for experimentation is 17.5, the variation of thermal performance parameters is studied at different preset CRs maintaining a constant load of 12kg and IP of 200bar in order to determine the optimum CR for Karanja biodiesel and its blends. It is observed that with the increase in CR the performance with Karanja biodiesel and its blends approach to that of Diesel oil. At a CR of 18, BTHE, BSFC and EGT for Karanja biodiesel are about 8% less, 18% more and 2% less respectively as compared to Diesel oil which indicates that Karanja biodiesel performs close to Diesel oil at CR of 18. Due to this reason CR of 18 is selected for comparison of variation of other thermal performance parameters with load and IP for further analysis.

The difference of performance of blends from Diesel oil increases with increase in blend proportion. It is observed that the variation in CR and blend proportion does not have an effect on volumetric efficiency and BMEP of the engine. Volumetric efficiency is marginally (2%) higher for Karanja biodiesel as compared to Diesel oil. However HBP increases with increase in CR and decrease in blend proportion. It is noted that the increase in HBP with CR is (linear) continuous for Karanja biodiesel while it increases upto CR of 16 then remains almost constant upto CR of 17 and subsequently decreases for other blends. Therefore, it can be inferred that combustion is better at CR of 16 for the blends and at CR of 18 for Karanja biodiesel. The change in CR does not have much effect on the HGas of the engine. However, at most of the CRs it is less for Karanja biodiesel than Diesel oil.

The thermal performance evaluation indicates that the blend B20 operates closest to Diesel oil with respect to thermal performance. However, there is not much deviation between the performance of Karanja biodiesel and Diesel oil at higher CRs. Hence higher CRs particularly CR of 18 should be the mode of operation when engine is fuelled with Karanja biodiesel. Also, higher IP of 250bar is preferable for Karanja biodiesel due to its higher viscosity.

As load on engine is increased from 0kg to 12kg, BMEP, BTHE, HBP, EGT are found to increase while BSFC decreases. The variation in load did not have any effect on HGas and Volumetric efficiency of the engine. Higher volumetric efficiency is desirable since it is an indication of greater fuel economy for engine and higher volumetric efficiency is noted with both fuels (more than 90%). As the injection pressure is increased, BMEP, volumetric efficiency and HGas remained unaffected, whereas, BSFC decreases. The BTHE, EGT and HBP are found to be higher at higher injection pressure. It is observed that for Karanja biodiesel as fuel, load of 12kg and IP of 250 bar result in highest BTHE of 31% and lowest BSFC of 0.33 kg/kWh which are 6% lower and 17% higher as compared to that of Diesel oil respectively at same operating conditions.

The variation of BTHE and BSFC with CR of the present study are compared with that found in the literature. There are no reported studies available on variation of BTHE and BSFC with CR except Jindal et al. [66] and Raheman & Ghadge [40]. It should be noted that Jatropha and Mahua biodiesels are using by the investigators while Karanja biodiesel is used in the present study. An attempt also is made to compare the results reported by Banapurmath et al. [44] and Raheman and Phadatare [17] who conducted studies at constant CRs of 17.5 and 16 respectively. Banapurmath et al. [44] has reported a 10% higher value of BTHE at a constant CR of 17.5 while 14% lesser BTHE has been reported by Raheman and Phadatare [17] at a constant CR of 16 using Karanja biodiesel as compared to the present study. Further, comparison is made for BTHE at a constant CR of 18 for different fuels i.e., Jatropha and Mahua biodiesels are lesser by 12% for Jatropha biodiesel (Jindal et al. [66]) and 17% for Mahua biodiesel (Raheman & Ghadge [40]) with that of Karanja biodiesel used in the present study. Similar comparison is also made for BSFC at constant CR. About 3% higher value of BSFC at a constant CR of 16.5 is reported by Sureshkumar et al. [52] while 21% higher BSFC has been reported by Raheman and Phadatare [17] at a constant CR of 16 using Karanja biodiesel as compared to the present study. It is seen that the value of BSFC at 18 CR is 9% more for Jatropha biodiesel (Jindal et al. [66]) and 56% more for Mahua biodiesel (Raheman & Ghadge [40]) as compared to that of Karanja biodiesel used in the present study.

4.3.2 Emission Constituents

At higher CRs of 16 to 18, it is found that the fuel gets combusted in a much efficient way due to high temperature of compressed air. Therefore, most of the exhaust emissions are found to decrease at higher CRs. Also at higher CRs, smoke is less due to complete combustion of fuel. The engine may be operated with any higher CR ranging from 16 to 18 as far as the emission constituents of CO, HC, CO_2, O_2 and SO_x are concerned. The reason is that the mentioned emission constituents are least and remain constant in the CR range of 16 to 18. However, the NO_x emissions are found to be more at higher CRs with Karanja biodiesel as compared to Diesel oil. There is a trade off between NO_x and smoke emission as NO_x emissions are found to decrease with increase in smoke as lesser flame temperature decreases the amount of soot oxidised with the result higher smoke & relatively lesser NO_x levels. Therefore, the selection of CR can be made based on the relative combined effect on thermal performance and emission characteristics. It is preferable to operate the engine at CR of 18, as selected earlier for optimum thermal performance evaluation. If NO_x is considered then we have to operate at CR 16 but it is found that the decrease in BTHE of about 13% and increase of BSFC of about 13% are not affordable just for the sake of NOx emissions.

Higher oxygen content of Karanja biodiesel influences the exhaust emissions considerably. At a CR of 18, load of 12kg and IP of 200bar, it is observed that CO_2 emissions are more by 24% for Karanja biodiesel than that of diesel. It may be noted that due to higher oxygen content in the biodiesel more of the carbon gets oxygenated during combustion inside the cylinder which results in higher CO_2 emission. Higher CO_2 emissions lead to lower CO emissions as more of carbon is already oxygenated. CO emission is less by 67% for Karanja biodiesel as compared to that of Diesel oil. Also it can be noticed that the NO_x emissions are higher by 33% for Karanja biodiesel as compared to that of Diesel oil. The percentage reduction in HC emissions for Karanja biodiesel is 60% as compared to that of Diesel oil. The content of O_2 with exhaust increased with increase in blend proportion as it is an oxygenated fuel. Karanja biodiesel is sulphur free fuel and hence, fine traces of SO_x found in the exhaust may be from atmospheric air. In the context of NO_x emissions selection of suitable blends instead of pure Karanja biodiesel can be thought of, striking a balance between NO_x emissions on one end and all other emissions along with thermal performance on the other hand at the same point of time.

Among all the emission constituents measured, CO, CO_2, NO_x and HC are found to increase with increase in load, whereas O_2 and SO_x indicated a decrease. At higher loads, more fuel is burnt due to which more carbon is available from fuel to form CO_2 and CO. The unburnt HC are formed due to rich burning. At higher loads, the content of O_2 in the exhaust is less as a richer mixture is burnt inside the cylinder. At higher loads more fuel is burnt in rich zone and hence higher smoke level is observed. Smoke consists of solid carbon, organic fraction consisting of hydrocarbons and their partial oxidation products.

As the IP is increased, CO_2, O_2 and NO_x increase while, HC, CO and smoke opacity are decreased. A higher IP causes better atomisation which results in exposure of more surface area of fuel droplets to hot compressed air causing complete combustion of fuel as a result of which most of the harmful exhaust emissions reduce.

The emission characteristics evaluation indicates that the Karanja biodiesel (B100) gives minimum harmful emissions as compared to all other blends. Further, at a higher CR of 18 and IP of 250bar the fairly reduced exhaust emissions are observed irrespective of the fuel. Therefore, operating the diesel engine with Karanja biodiesel at a CR of 18 and IP of 250bar results in minimum emissions but for NO_x emissions.

The results of NO_x and smoke opacity (HSU) of the present study are compared with that found in the literature. Sureshkumar et al. [52] reported a 15% higher NO_x at a CR of 16.5 while 95% less NO_x at a CR of 16 is reported by Raheman & Phadatare [17] using Karanja biodiesel as compared to that of the present study. It is seen that NO_x emission at CR of 18 are higher by 32% for Jatropha biodiesel (Jindal et al. [66]) as compared to that of Karanja biodiesel used in the present study. Raheman & Phadatare [17] reported a 71% reduction in HSU at a constant CR of 16 respectively using Karanja biodiesel as compared to that of the present study. It is seen that HSU at a CR of 18 is almost double for Jatropha biodiesel (Jindal et al. [66]) as compared to that of Karanja biodiesel used in the present study.

4.3.3 Combustion Analysis

The peak CP development for Karanja biodiesel takes place at an earlier CA at 14 CR as compared to Diesel oil. However, the peak pressures at all CRs using both the fuels always takes place after TDC which ensures safe and efficient operation as peak pressure at or before TDC causes knocking which affects engine durability (Ganesan [97]). The peak CP attained for Karanja biodiesel is about 2 and 4 bar less at CR of 14 and 16 respectively, whereas at CR of 18 the peak CP is same for both the fuels. Peak cylinder pressure is an indicator of the intense premixed combustion. From the cylinder pressure data the location of peak pressure, the instantaneous heat release & the burn fraction can be identified. It has no direct bearing on the performance of the engine. Generally, with low cetane number fuels such as Diesel oil the peak CP is highest. It is the mean effective pressure which decides the performance parameters like the thermal efficiency and BSFC of the engine.

The double peak shape of the heat release rate curve which is the characteristic of Diesel oil combustion is observed only for Diesel oil at CR of 14. It is observed that the first peak of heat release curve occurs early in case of Karanja biodiesel than Diesel oil. The point of occurrence of first peak net heat release shifts closer to TDC with increase in CR for both the fuels. At 14 CR no significant second peak observed for Karanja biodiesel. At CR of 16 the second peak heat release for Karanja biodiesel is 10% less as compared to Diesel oil. As CR increases from 16 to18, the second peak net heat release rate increases for Karanja biodiesel and it is same as that of Diesel oil at 18CR. The trend observed corroborates the closeness of thermal performance of Karanja biodiesel as compared to Diesel.

At CR of 14, the maximum rate of pressure rise takes place closer to TDC in case of Karanja biodiesel as fuel than Diesel oil. With the increase in CR from 14 to 16 the point of occurrence of peak rate of pressure rise shifts by about 2^0 towards TDC for both the fuels. The peak rate of pressure rise at CR of 14 and 16 is about 2.5bar $/^0$CA for both the fuels. However, at CR of 18 it occurs at same CA and has same magnitude of 2 bar$/^0$CA for both the fuels.

The behaviour of Karanja biodiesel in terms of mass fraction burnt is similar to that of Diesel oil at CRs of 16 and 18. At CR of 14, however, there is an earlier combustion by about 4^0 to 5^0 CA after TDC with Karanja biodiesel as compared to Diesel oil. It is noted that the mean gas temperature (average of burned and unburned gas temperatures in cylinder) is highest when more than 90% of the fuel mass fraction is burnt for both fuels. It is obvious as mean gas temperature is the result of thermal energy released during combustion of fuel. So more fuel burnt results in higher mean gas temperature. The mean gas temperature increases with increase in CR for Karanja biodiesel and its behaviour is identical compared to Diesel qualitatively at higher CR of 18. The analysis of PV characteristics and cumulative heat release also indicate that Karanja performs identical to Diesel oil at a CR of 18.

It is inferred from the combustion analysis that as the CR increases from 14 to 18 at full load and IP of 200bar, the difference in performance between Karanja biodiesel and diesel reduces i.e. the operation of the engine fuelled with Karanja biodiesel tends towards that fuelled with diesel. The combustion characteristics of diesel engine using Karanja biodiesel is similar to that using pure diesel at higher CR of 18 which is very promising as far as Karanja biodiesel as an alternative fuel in diesel engines is concerned.

From the thermal performance, emission characteristics and combustion analysis, it is observed that Karanja biodiesel operates closer to Diesel oil at a CR of 18. Proper combustion ensures reduced emission levels and optimum thermal performance. Although B20 blend gives better thermal performance compared higher blends of Karanja, it is not recommended as it poses problems of higher levels of exhaust emissions. It is observed that harmful emissions such as CO, HC are 81% and 75% higher for B20 blend as compared that of Karanja biodiesel. Hence Karanja biodiesel can be successfully used without any hardware modifications on the engine.

4.3.4 Limitations of the Experimental Study

The experimental study conducted provides large number of results. But, it is impossible to select the input parameters such as CR, IP and blend for obtaining optimum thermal performance and emissions from the engine. Hence, a suitable computational study is required to be carried out in order to meet the objective of finding the optimum combination of the input parameters under different preset priorities. The preset priorities is a combination of weightages in proportions of performance and emissions like 50-50, 80-20, 20-80, etc. A balance can be struck as to what could be the suitable combination of optimum input parameters which will result in maximising the thermal performance while minimising the emission constituents.

Multi-objective optimization using genetic algorithm technique is one of the suitable tools available that can be used to optimize the thermal performance and exhaust emissions. Genetic algorithms are computerized search and optimization algorithms based on the mechanics of natural genetics and natural selection. GAs are radically different from most of the traditional optimization methods. GAs work with a string-coding of variables instead of the variables. The advantage of working with the coding of variables is that the coding discretizes the search space, even though the function may be continuous. On the other hand, since GAs require only function values at various discrete points, a discrete or discontinuous function can be handled with no extra cost. This allows GAs to be applied to a wide variety of problems. Another advantage is that the GA operators exploit the similarities in string-structures to make an effective search.

Further, ANN can be used to obtain the output parameters using the optimized input parameters by modeling. ANN is a theoretical simulation of actual engine behaviour. ANNs don't rely upon a pre-defined mathematical equation to relate system input/output. A proper ANN structure is developed for each system to capture the system behavior of a complex system. With high complexity of combustion relations and emission phenomena it is suitable to model by ANN. ANNs have been used for two main tasks: 1) function approximation and 2) classification problems. Neural networks offer a general framework for representing non-linear mappings. The application of neural networks to predict thermal performance and exhaust gas constituents belongs to the class of function approximation applications. Suitable software is to be used for modeling an ANN model. The software that can be selected for neural network modeling is EasyNN purely because of its simplicity in developing and training models involving feed forward multilayered neural networks with back-propagation training algorithm.