CHAPTER 6

STUDY ON PERFORMANCE AND EMISSIONS OF DIESEL ENGINE FOR BIODIESEL BY VARYING DIFFERENT PARAMETERS

6.1 INTRODUCTION

The calorific value and cetane number of the non-edible oils in their pure form are comparable to diesel oil, the changeover is considered relatively simple; however, the impediments are their high viscosity. In the light of this, the present study is conducted in order to investigate engine performance and the exhaust emissions using non-edible oils (karanja) as fuel, in pure form as well as their blends, in direct injection (DI) diesel engine. The primary aim is to arrive at a basic strategy that can be adopted for reducing emission levels using these fuels.

Engine performance testing of bio-diesels and their blends is essential for evaluating their relevant properties. Several research groups have investigated the properties of a bio-diesel blend with soybean oil methyl esters in diesel engines and found that particulate matter (PM), CO, and soot mass emissions decreased, while NO\textsubscript{x} increased. Labeckas et al. (2006) examined the performance and exhaust emissions of rapeseed oil methyl esters in direct injection diesel engines, and found that there were lower emissions of CO, CO\textsubscript{2} and HC. Similar results were reported by Kalligeros et al. (2003) for methyl esters of sunflower oil and olive oil when they were blended with marine diesel and tested in a stationary diesel engine.
Lin et al. (2006) confirmed that emission of polycyclic aromatic hydrocarbons (PAH) decreased when the ratio of palm biodiesel increased in a blend with petroleum diesel.

Vegetable oils (palm, sunflower, and soyabean) present a very promising alternative to diesel oil since they are renewable and have similar properties. Vegetable oils offer almost same power output with slightly lower thermal efficiency when used in diesel engines. Reduction of engine emissions is a major research aspect in engine development with the increasing concern on environmental protection and the stringent exhaust gas recirculation. The tremendous growth of vehicular population of the world has led to a steep rise in the demand for petroleum products. Biodiesel such as jatropha, karanja, sunflower, and rapeseed are some of the popular biodiesels currently considered as substitute for diesel. These are clean burning, renewable, non-toxic, biodegradable and environmentally friendly transportation fuels that can be used in neat form or in blends with petroleum derived in diesel engines.

Agrawal et al. (2007) found out that when biodiesel is used as a substitute for diesel, it is highly essential to understand the parameters that affect the combustion phenomenon which will in turn have direct impact on thermal efficiency and emission. In the present energy scenario lot of efforts is being focused on improving the thermal efficiency of IC engines with reduction in emissions. Sahoo et al. (2009) analysis reveals that biodiesel from unrefined jatropha, karanja and polanga seed oil is quite suitable as an alternative to diesel.

Cenk sayin et al. (2011) has been observed that engine parameters such as injection timing, compression ratio have considerable effects on the performance and emissions of diesel engine running on biodiesel blends.
Many innovative technologies are developed to tackle these problems. Modification is required in the existing engine designs.

It has been concluded that the performance characteristics can be improved with biodiesel by re-designing the injection system and determining the optimum biodiesel diesel blend. To develop a good injection system, a parameter search to determine the influence of design parameters on both the performance and exhaust emissions should be performed.

Some optimization approach has to be followed so that the efficiency of the engine is not comprised. As far as the internal combustion engines are concerned the thermal efficiency and emission are the important parameters for which the other design and operating parameters have to be optimized.

In this study, bio-diesel produced from karanja was tested on a diesel engine by varying different parameters. The engine performance and emissions were evaluated and compared with that obtained using standard diesel fuel.

6.2 OBJECTIVE

The objective of this study is to

1. Determine experimentally the performance and emissions of diesel engine by varying different parameters, for different blends of karanja biodiesel (B10,B20,B30,B50) and karanja oil (non edible oil).

2. Determine experimentally the influences of compression ratio, injection timing, injection pressure and power on the
performance, and emission characteristics of the diesel engine.

3. Find out the parameters (compression ratio, injection timing, injection pressure and power) of diesel engine that gives maximum efficiency and minimum fuel consumption and emissions.

6.3 MATERIALS AND METHODS

Various experiments, experimental procedure, used to characterize and to undergo various engine performance test of karanja oil is explained.

Table 6.1 shows the change in input parameters in diesel engine and the experiments were done according to this design.

**Table 6.1 Setting levels for design parameters**

<table>
<thead>
<tr>
<th>Controlled factors</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
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<tr>
<td>Compression ratio (CR)</td>
<td>17.5</td>
<td>17.7</td>
<td>17.9</td>
<td>18.1</td>
</tr>
<tr>
<td>Static Injection Pressure (bar) (IP)</td>
<td>230</td>
<td>220</td>
<td>210</td>
<td>190</td>
</tr>
<tr>
<td>Injection Timing (Btdc) (IT)</td>
<td>23</td>
<td>25</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>Biodiesel fuel fraction % (B)</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Power (kW) (P)</td>
<td>3.64</td>
<td>4.16</td>
<td>4.68</td>
<td>5.2</td>
</tr>
</tbody>
</table>

6.3.1 Experimental Procedure

Before starting the test run all the modifications for four parameters are made as per the specification for each test. Then for each test, following procedure was adopted. Cooling water circulation was ensured for eddy current dynamometer and piezo sensor, engine and calorimeter. The engine
soft is opened and the set up is run. Gradually the power on the engine is increased and is set as per the requirement for the test runs. Steady state conditions are attained before the readings are taken and data is logged in the engine soft.

The water flow is set at 60 LPH for the calorimeter and 300 LPH for the engine. Then the power is decreased gradually.

The result and the performance plots are viewed in the engine soft and recorded for further analysis.

6.4 EXPERIMENTAL ANALYSIS

6.4.1 Selection of Control Parameters

The following control parameters as given in Table 6.1 were selected for the investigation since they have influence on the objectives of improving brake power and fuel economy. More parameters are related to the fuel injection and these parameters were found to be suitable for the experiment and could be done with available engine configuration. Four levels were chosen for this investigation. Karanja biodiesel is used as a fuel and the experiments were done in a single cylinder diesel engine. The experimental results are shown in Table 6.2.

In this study five input parameters were varied one by one and five output responses were obtained.

First the effect of compression ratio CR (17.5, 17.7, 17.9 and 18.1) was analyzed on engine performance and emissions by varying the other input parameters (IP, IT, B and P).
Secondly the effect of injection pressure IP (190, 210, 220 and 230 bar) was analyzed on engine performance and emissions by varying the other input parameters (CR, IT, B and P).

Next the effect of injection parameters IT (23°, 25°, 27° and 29° btdc) was analyzed on engine performance and emissions by varying the other input parameters (CR, IP, B, P).

Next the effect of karanja biodiesel blend (B10, B20, B30 and B50) was analyzed on engine performance and emissions by varying the other input parameters (CR, IP, IT and B).

Next the effect of power P (3.64, 4.16, 4.68 and 5.2 kW) was analyzed on engine performance and emissions by varying the other input parameters (CR, IP, IT and B).

### Table 6.2 Experimental results

<table>
<thead>
<tr>
<th>Run No.</th>
<th>CR (bar)</th>
<th>IP (bar)</th>
<th>IT (° btdc)</th>
<th>B (%)</th>
<th>Power (kW)</th>
<th>BSFC (kg/kWh)</th>
<th>BTE (%)</th>
<th>CO (%)</th>
<th>HC (PPM)</th>
<th>NOx (PPM)</th>
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<tr>
<td>1</td>
<td>17.5</td>
<td>230</td>
<td>23</td>
<td>10</td>
<td>3.64</td>
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<td>34</td>
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<td>25</td>
<td>20</td>
<td>4.16</td>
<td>0.275</td>
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<td>0.25</td>
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<td>4</td>
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<td>50</td>
<td>5.2</td>
<td>0.34</td>
<td>27</td>
<td>0.60</td>
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<tr>
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<td>9</td>
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<td>220</td>
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<td>190</td>
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<td>30</td>
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<td>27</td>
<td>0.59</td>
<td>260</td>
<td>625</td>
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</table>
6.5 RESULTS AND DISCUSSION

The experimental results obtained from the tests carried out on engine performance and exhaust emissions are presented in this section. These include results at different compression ratio, injection timing, injection pressure and power for the different fuels i.e. standard diesel fuel, nonedible oil (karanja oil) and the four biodiesel products. The results are discussed from the point of view of using biodiesel as an alternate fuel for compression ignition engines.

6.5.1 Engine Performance for Karanja Methyl Ester Blends (B10, B20, B30 and B50)

After the engine reached the stabilized working condition, the readings for each test, fuel consumption, torque applied were measured from which BSFC, BTE were computed.

First the brake specific fuel consumption and brake thermal efficiency for karanja biodiesel blends for different input parameters were discussed, next emissions from diesel engine (CO, HC, NOx) for different input parameters were analyzed and it’s compared with diesel fuel. Finally engine performance parameters (BSFC, BTE) were found out for karanja oil (B 100).

6.5.1.1 Brake specific fuel consumption (BSFC)

The variation of BSFC at different CR, IT, IP,B and P is shown in Figure 6.1 – Figure 6.5. For all cases BSFC reduces with increase in power. The reverse trend in the BSFC may be due to increase in biodiesel percentage ensuring lower calorific value of fuel. Another reason for the change in BSFC in biodiesel in comparison to petro diesel may be due to a change in the combustion timing caused by the biodiesel’s higher cetane number as well as injection timing.
6.5.1.1.1 Effect of compression ratio

The variation in the BSFC of the engine is shown in Figure 6.1. The best results were obtained at increased CR 17.9. The maximum percentage increase of BSFC from the overall mean is 4.9 % when the compression ratio is 18.1. This shows that increasing the CR had more benefits with biodiesel than with high speed diesel. Due to their low volatility and higher viscosity, biodiesel might be performing relatively better at higher compression ratios.

The possible reason for this trend could be that with an increase in compression ratio, the peak cylinder pressure increases, and better combustion takes place due to the fuel injected in hotter combustion chamber and this leads to more power. Therefore, fuel consumption per output power shall decrease compare with diesel. When the compression ratio is 18.1 there is a increase in the fuel consumption due to low calorific value of biodiesel, because at CR18.1, the power produced is more compare to other compression ratio.

![Figure 6.1 The Brake specific fuel consumption for different compression ratios](image-url)
6.5.1.1.2 Effect of injection timing

Retarding the start of the fuel delivery yields a reduction in peak combustion pressure and temperature. It can be seen from Figure 6.2 when start of injection has been advanced from 23° to 29° before TDC of which 23° gives the best value. Start of injection meant the combustion occurred earlier in the cycle and more fuel burnt before TDC and the peak pressure move closer to TDC. The fuel consumption is more at 25° and 29° bTDC, if the IT is advanced too much a decrease from the overall mean value is observed. This is due to pressure and temperature in the cylinder may be too low to cause auto ignition.

With the start of injection, the ignition delay will be longer and speed of the flame will be shorter. These cause reductions in the engine output power. Thus, fuel consumption per output power will increase. But, decreasing IT means later combustion, and therefore pressure rises only when the cylinder volume is expanding rapidly. These results reduced more pressure to do work. As a result, minimum BSFC was obtained at original IT 23° for all fuel blends.

![Figure 6.2 The Brake specific fuel consumption for different Injection timing](image-url)
6.5.1.1.3 Effect of nozzle pressure

The injection pressures 230 bar, 220, 210, 190 bars were chosen to investigate their influence on BSFC. At high injection pressures, the fuel coming out of the nozzle undergoes a throttling process and droplets end up almost in the vapour phase aiding sparingly good combustion, hence an improvement in the BSFC. Thus it may be concluded that 210 bar has a little influence in improving fuel economy. Figure 6.3 demonstrates the change in BSFC at different IPs. The minimum BSFC values were obtained with the decreased IPs because of improved atomization and better mixing process.

The decrease in BSFC can be attributed to the more efficient utilization of the fuel at higher injection pressures because of better atomization associated with slight delay in admission due to high needle lift pressure with same period and hence lesser fuel going into the cylinder.

![Figure 6.3 The Brake specific fuel consumption for different Pressures](image-url)
6.5.1.1.4 Effect of Biodiesel fuel fraction

We can see from the Figure 6.4 that as the amount of karanja biodiesel increases in the blend, the premixed heat release part becomes less dominant. However, with further increase in blend ratio, the oxygen content in biodiesel molecules increases, and results in better combustion. The fuel consumption is less for B10 and a slight increase as the fraction of the blend increases. It is maximum at B30 and drop in fuel consumption with increase in blend.

This lower fuel consumption of B20 as compared to pure HSD might be due to the possible synergy effect of biodiesel with diesel in various ways, e.g. the oxygen present in biodiesel might have helped in improved combustion of the blend.

However, as the blending proportion was increased to B30 and beyond, this effect was probably negated due to reduced calorific value and higher densities of these blends. As the BSFC was calculated on weight basis, obviously higher densities of B50 resulted in higher values for BSFC. The higher densities of biodiesel blends caused higher mass injection for the same volume at the same injection pressure. The calorific value of B50 was lower than HSD by about 12%. Hence, the combustion of biodiesel blends in the engine may not be similar to that of diesel. Therefore, any additional increase in BSFC of B50 might be ascribed to the improper combustion of biodiesel blends inside the cylinder.
6.5.1.1.5 Effect of power

For all cases BSFC first decreased then increased with increase in power. The reverse trend in the BSFC may be due to increase in biodiesel percentage ensuring lower calorific value of fuel. Another reason for the change in BSFC in biodiesel in comparison to diesel may be due to a change in the combustion timing caused by the biodiesel’s higher cetane number as well as injection timing.
Figure 6.5 The brake specific fuel consumption for different power

6.5.2 Brake Thermal Efficiency (BTE)

The variation of brake thermal efficiency of the engine with diesel fuel and karanja biodiesel is shown in Fig.6.6- Fig 6.10 compared with the brake thermal efficiency obtained with diesel fuel. From the test results, it was observed that there were considerable increases in efficiencies with the karanja and its blends with increase in power. This is due to reduction in heat loss and increase in power with increase in power. It was observed that all the karanja blends developed similar trend to that of conventional diesel, even at higher engine power 50:50 diesel fuel/ karanja blends produced higher brake power than diesel fuel. This can be expected due to the slightly larger fuel droplets, and oxygen content in karanja which contribute better atomization and as a result complete combustion occurs, even though viscosity of B50 is higher than ND, high air to fuel ratio and high IOP improves atomization, vaporization, mixing with air leading to better combustion. It indicates improved pre mixed combustion phase when the IOP is increased. This improves BTE. It is also to be noted that the oxygen contained in the B50 takes part in combustion which enhances the combustion process.
(Prem anand et al. 2011). The brake thermal efficiency of an engine depends on number of factors but the most meaningful property is heating value and specific gravity. The combination of heating value and mass flow rate indicates energy input to the engine. The energy input or consumption to the engine in case of higher proposition of karanja is more compared to diesel which results in reduction in efficiency at all powers.

6.5.2.1 Effect of compression ratio

From Figure 6.6 it is observed by increasing the compression ratio of the engine, the brake thermal efficiency also gets increase for all the fuel types tested. Brake thermal efficiency is directly proportionate to the compression ratio.

In general, increasing the CR improved the efficiency of the engine. The mean BTE of the engine increased by more than 6% when CR was raised from 17.5 to 18.1. This improved performance of the engine at higher compression ratio may be due to reduced ignition delay. The CR 18.1 was the best and it is minimum at 17.5. In general if the compression is high there is increase in brake thermal efficiency. This could be due to the fact that biodiesel blends had lower volatility as compared to diesel and therefore the improvement in their combustion characteristics might have been relatively more at higher temperatures resulting from higher CR than the improvement in case of diesel with the same rise in CR.

The improvement of thermal efficiency with biodiesel can be attributed to the oxygen content and higher cetane number of biodiesel. These properties lead to favorable effects on the combustion process and a slight improvement in thermal efficiency for biodiesel operation in spite of the lower calorific value of biodiesel.
6.5.2.2 Effect of injection timing

From the experimental data, it was found that the rated static injection timing of 23° bTDC was the best subsequently test were done to optimize the injection timing. Figure 6.7 indicates, that karanja biodiesel has lower ignition delay than diesel, as the combustion starts earlier. Hence, it is suggested that in case of karanja biodiesel, the injection timing has to be regarded as compare to base diesel operation to compensate for the lower ignition delay. On the other hand, the lower combustion rates with karanja biodiesel can warrant advancing the injection timing. Since karanja biodiesel has a higher viscosity and a lower burning rate, the efficiency with karanja biodiesel is always less than diesel, regardless of the injection timing. The best injection timing for biodiesel is determined to be 23° BtDC, on account of higher efficiency.

The brake thermal efficiency of karanja biodiesel is 31 % at 23° bTDC while for diesel at full power it is 33 % and occurs at 25° bTDC.
6.5.2.3 Effect of nozzle pressure

The BTE was found to decrease at maximum pressure 230 bar whereas at 210 bar it gives the maximum efficiency as shown in Figure 6.8 because of better combustion due to finer breakup of fuel droplets providing more surface area and better mixing with air compared to minimum pressure 190 bar.
6.5.2.4 Biodiesel fuel fraction

The brake thermal efficiency is shown in Figure 6.9, from this figure, it is clear that the brake thermal efficiency slightly decreases with an increase in the blend ratio. With an increase in blend ratio, the mass flow rate of fuel increases but the calorific value of the blends decrease and hence not much variation in efficiency is observed for lower blends of karanja biodiesel. As the blend ratio increases, the combustion rate decreases and the combustion duration increases and this lower the efficiency it can be seen the brake thermal efficiency is high at lower blends and low as the percentage of the blend increases. It is maximum at B10. This lower brake thermal efficiency obtained for B50 could be due to reduction in calorific value and increase in fuel consumption as compared to B20.

This could be attributed to better burning of biodiesel blends partly due to favorable conditions inside the cylinder at those engine settings and also due to the presence of extra oxygen in biodiesel as compared to diesel.

Karanja oil itself has relatively low energy content, but the biodiesel fuel produced from it has a value (about 35.9 MJ/kg) close to that of diesel; this means that efficiency and output is lower but only by a small percentage.

The energy content of the blend can be calculated, using simple formulae. Energy content of blend = (% diesel \times 42.5 + % bio-diesel \times 35.9). It can be seen from Figure 6.9 that the loss in power is close to the value predicted. At 20% bio-diesel the calculated power is 41.8 MJ/kg, a decrease of 1.6% compared to diesel.
6.5.2.5 Effect of power

Figure 6.10 shows the variation of brake thermal efficiency for the blends at all powers. From the experiment it was observed that BTE increases with increasing in power up to 4.12 kW for biodiesel blends and then reduces as the power is increased and slightly increases at maximum power.
6.6 ENGINE EMISSIONS

The engine operating parameters such as air-fuel equivalence ratio, fuel type, combustion chamber design and atomization ratio have an influence on emissions emitted by internal combustion engines. Especially, emissions of CO and unburned HC in the exhaust are very important since they represent the low chemical energy that cannot be totally used in the engine. Emissions such as CO$_2$, NO$_x$ emitted by diesel engine have important effects on ozone layer and human health.

The engine emissions with karanja biodiesel have been evaluated in terms of CO, HC and NO$_x$ at various CR, IP, IT and blend at different powering conditions of the engine.

6.6.1 Hydrocarbon

It is seen from Figures 6.11 -6.15 that there is a significant decrease in the HC emission level blends of methyl ester of karanja oil as compared to pure diesel. These reductions indicate that more complete combustion of the fuels and thus HC level decreases significantly. The reduction in HC emission was linear with the addition of biodiesel for the blends .Advanced injection and combustion timing lower the HC emissions this is due to higher Cetane number of biodiesel reduces the combustion delay and such a reduction has been related to decrease in HC emissions. HC emissions tend to increase with increase in compression ratio and also on reduction in injection pressure. Lowest HC emissions (64 ppm) were found for compression ratio of 17.7 with injection pressure of 200 bar At lower compression ratio, insufficient heat of compression delays ignition whereas at high compression ratio, dilution by residual gases hampers the combustion. The un-burnt emissions are higher for low injection pressure (190 bar) for all compression ratios supporting the argument that at lower injection pressures, atomization is poor.
and large droplets are formed leading to more unvaporised hydrocarbons in the exhaust.

**Figure 6.11 Variation of HC for different Compression ratio**

**Figure 6.12 Variation of HC for different Injection timing**
Figure 6.13 Variation of HC for different Injection Pressure

Figure 6.14 Variation of HC for different Biodiesel fuel fraction
The NO\textsubscript{x} values for different fuel blends are shown in Figures 6.16 - 6.20. The amount of NO\textsubscript{x} produced for B10 to B50 is in the range of 627 -1730 ppm. It can been seen that the increasing proportion of biodiesel in the blends increases NO\textsubscript{x} emissions as compared with diesel. This could be attributed to the increased exhaust gas temperatures and the fact that biodiesel had some oxygen content in it results in the promotion of NO\textsubscript{x} formation. In general the NO\textsubscript{x} concentration varies linearly with the power of the engine. As the power increases the overall fuel –air ratio increases resulting in an increase in the average gas temperature in the combustion chamber and hence NO\textsubscript{x} formation, that is sensitive to the temperature increase. During advancement of injection timing from 23° to 29° Btdc the NO\textsubscript{x} emissions first decreased then increased. This could be due to the following fact: in-cylinder charge temperature and pressure decreased with an advancement of the injection timing resulting in extended ignition delay of the injected fuel. Increasing the injection pressure from 190 bar-230 bar increases the NO\textsubscript{x} formation.
The emission of NO$_x$ is more sensitive to compression ratio at lower injection pressures as compared to higher compression ratios. With low injection pressure, increase in compression ratio facilitates the combustion of larger droplets because of high temperature of compression, whereas, high injection pressure breaks the fuel into smaller droplets with good combustion suppressing the effect of compression pressure. The highest emissions were observed for high compression ratio and low injection pressure and this is due to greater availability of fuel inside the cylinder.

In bio-diesel operation, an average of 7.5% increase in the NO$_x$ emission was observed compared to standard diesel operation.

![Figure 6.16 Variation of NOx for different compression ratio](image-url)
Figure 6.17 Variation of NOx for different Injection timing

Figure 6.18 Variation of NOx for different Biodiesel fuel fraction
6.6.3 Carbon Monoxide Emission

Carbon monoxide emission is mainly due to the lack of oxygen, poor air entrainment, mixture preparation and incomplete combustion during the combustion process. Carbon Monoxide in the diesel emission is formed
due to intermediate combustion stage. In diesel engine operating on the lean side of stochiometric ratio, CO emissions are low. Figures 6.21-6.25 show the variation of CO emission. For biodiesel operation, CO emissions were low compared to the diesel. The emission has decreased with increase in amount of biodiesel B50 compared to B30. In the blend the additional amount of oxygen in the biodiesel accounts for better combustion inside the cylinder and hence for reduced CO emission. At lower CR, insufficient heat of compression delays ignition and so CO emissions increase. The possible reason for this trend could be that the increased CR actually increases the air temperature inside the cylinder therefore reducing the ignition lag which causes better and more complete burning of the fuel. From the equations of combustion, it was clear to see that the addition of bio-diesel fuel to the petroleum diesel provides more oxygen which allows for a more complete reaction and combustion, with less dissociation. Since CO was a main by-product of dissociation more complete combustion causes this to decrease as was seen in the data. Bio-diesel has both a higher cetane number (ignition quality) and a higher oxygen content which contribute to a shorter ignition delay period which is important in reducing CO emission.

![Figure 6.21 Variation of CO for different compression ratio](image-url)
Figure 6.22 Variation of CO for different Injection pressure

Figure 6.23 Variation of CO for different Injection timing
Figure 6.24 Variation of CO for different Power

Figure 6.25 Variation of CO for different Biodiesel fuel fraction
6.7 CONCLUSION

Based on the results of this study, the following conclusions were drawn, in terms of fuel properties and exhaust emission characteristics.

In the current study, experiments were done to evaluate the effects of engine parameter values (compression ratio, injection pressure, injection timing and power) while working with karanja methyl ester as fuel.

Trials with four values of compression ratio, injection pressures, injection timing and blend as against the standard values set by manufacturer for diesel as fuel (210 IP and 17.5 CR)

Karanja oil methyl ester can be regraded as an alternative to diesel fuel. This experimental design, considerably reduced the time required by minimizing the number of experiments to be performed and provided statistically proven models for all response.

Out of the five design and operating parameters compression ratio, injection pressure and injection timing are having a very high influence on the response.

Compression ratio is having the strongest influence on BTE. The performance of BTE increases as compression ratio increases, at CR 18.1 the value of BTE was 32% whereas at 17.5 it was 30.5%. The increase in BTE is due to complete combustion of fuel.

When the CR was high (18.1) the fuel consumption was high compared to original CR (17.5).
When the injection pressure increases there is a decrease in bsfc, due to better atomization of karanja biodiesel and more effective utilization of fuel.

All the other parameters are having very little influence over bsfc. Advancing the compression ratio from 17.5 to 17.9 helped to decrease HC emissions, but at 18.1 it was slightly high. Increasing the compression ratio also have positive impact on NO\textsubscript{x} emissions. At CR 17.9 it was 1038 PPM. Increasing the compression ratio decreases CO emissions at CR 17.9 it was 0.26 %, whereas it was 0.345 % at CR 17.5.

For all CR, the emissions of HC and CO with karanja biodiesel blends are lower than that of diesel fuel. With the increase in CR, the temperature reached is also high and so less CO and HC emissions are exhausted in engine.

Increasing the pressure from 190 bar to 230 bar, HC emissions decrease from 167 ppm to 37 ppm, since karanja biodiesel has oxygen content in it, which helps in better combustion of the fuel inside the cylinder. When the injection timing was advanced from 23\textdegree{} to 27\textdegree{} btdc the HC emissions were decreased from (114 to 70 ppm), but increases at 29\textdegree{} (94 ppm).

Lower injection pressure decreases NOx emissions, at 190 bar it was 651 ppm whereas at higher injection pressure 230 bar it was 1539 ppm, much higher than diesel fuel (1432 ppm).

Variation of injection pressure do not have significant effect on the BTE and BSFC. Increasing the injection pressure contributed for better BTE with lesser BSFC at all injection timings with lower CO, HC and higher NOx.
Advancing the injection timing from 23 $^\circ$bTDC to 29 $^\circ$bTDC helped to reduce the CO, HC increase in NOx emission. Increase in compression ratio associated with increase in injection pressure improves the performance of the engine used in study with regard to the engine performance measured in terms of BSFC and BTE.

It is clear from this research that HC emissions have been reduced when biodiesel is fueled instead of diesel. Decreasing the fuel blend ratios, contributed for better BTE with lesser BSFC with lower CO, HC and NO$_x$ values. However when too low was the blend ratio, the results were good.

For all combinations of Compression ratio and injection pressure, the emissions of HC, NO$_x$, are lower with pure bio-diesel against that of diesel fuel. Looking to the advantage of improved performance of the engine with higher compression ratio and injection pressure, marginal deterioration of some emissions, which are still lower than that with diesel fuel, can be accepted.

The engine when operated at 3.64 kW gives better fuel economy and less emissions. The maximum brake thermal efficiency for B20 (35.42 %) was higher than that of diesel at full power.

By implementing the modifications in the design and control parameters based on this research work the BTE can be increased and fuel economy and emissions can be reduced. The usage of biodiesel has the significance in the economical growth of world.

It was very clear from these study different combinations of input parameters gives different results, therefore to obtain an optimum solution to achieve our objective we have to go for optimization of engine parameters, that gives a solution of better efficiency and minimum emissions.
In the next chapter optimization of input parameters was done using design of experiments (Taguchi and Response surface methodology) techniques.