CHAPTER 3

EXPERIMENTAL INVESTIGATION OF
DIESEL ENGINE WITH BIODIESEL

Biofuels will mitigate the vulnerability and the adverse effects of use of fossil fuels. Several developed countries have introduced policies encouraging the use of biofuels made from grains, vegetable oil or biomass to replace part of their fossil fuel use in transport in order to achieve the following goals; to prevent environmental degradation by using cleaner fuel, to reduce dependence on import, finite fossil supplies by partially replacing them with renewable, domestic sources and to provide new demand for crops to support producer income and rural economics.

In the present research, biodiesel (pongamia pinnata methyl ester (PPME)) is prepared from the raw pongamia oil by the transesterification process. The kinematic viscosity value of raw Pongamia oil is 37.12 mm²/s compared to the kinematic viscosity of 2.6 mm²/s for diesel at 40°C. Thus kinematic viscosity of the biofuel is 14 times that of diesel. This leads to many problems in pumping, atomization and others necessitating the transesterification process. Further, investigations are made to study the various effects of the use of the blends of PPME and diesel in diesel engines. The experiments are conducted in a diesel engine coupled with an exhaust gas analyzer to study the performance and exhaust emission characteristics and the extent to which the PPME could replace mineral diesel.

Further, in order to ascertain the environment friendly nature of PPME as compared to diesel, it is essential to theoretically investigate the quantity and quality of energy transfer during the combustion process through
energy and exergy analysis. Hence a thermodynamic energy and exergy analysis was carried out on the use of diesel and biodiesel in a diesel engine to compare the environmental destruction effects of these fuels.

3.1 BIODIESEL PREPARATION AND CHARACTERIZATION

Pongamia pinnata is a non-edible species capable of growing in almost all types of land (sandy, rocky including oolitic limestone). It grows even in salt water and can withstand extreme weather conditions with a temperature range of $0^\circ$C to $50^\circ$C and annual rainfall of 50 to 250 cm. The annual production potential is about 9000 kg per hectare. In India the estimated oil from seeds is about 50,000 tones. The yield from a single tree varies from 25 to 100 kg of seed containing approximately 27 to 50% of oil. The comparison of various properties of raw pongamia oil with respect to other raw oils is presented in table 3.1 (Ramadhas et al 2005a).

The characteristics of these oils fall within a fairly narrow band and are quite close to those of diesel. The pongamia oil has less calorific value than diesel due to the oxygen content in their molecules. Previous research works (Zejewski et al 1986, Pryde 1983 and Ziejewski and Kaufman 1983) show that high viscosity, density, iodine value and poor non volatility are the problems associated with the use of vegetable oils in diesel engines leading to problems in pumping, atomization and gumming, injector fouling, piston and ring sticking and contamination of lubricating oils in the long run operation. Hence it is essential to reduce the viscosity of the vegetable oils by methods such as preheating, thermal cracking and transesterification. Transesterification is the best way to convert the vegetable oils to suit for the use in diesel engines (Srivastsva and Prasad 2000, Yusuf et al 1995, Freedman et al 1984 and Bala 2005).
Table 3.1  Properties of raw pongamia oil in comparison with other raw oils

<table>
<thead>
<tr>
<th>Property</th>
<th>Ponagamia oil*</th>
<th>Diesel</th>
<th>Soya bean oil</th>
<th>Cotton seed oil</th>
<th>Sun Flower oil</th>
<th>Rap seed oil</th>
<th>Rubber seed oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatty acid composition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palmitic acid C₁₆₀</td>
<td>3.7-7.9</td>
<td>11.75</td>
<td>11.67</td>
<td>6.8</td>
<td>3.49</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>Stearic acid C₁₈₀</td>
<td>2.4-8.9</td>
<td>3.15</td>
<td>0.89</td>
<td>3.26</td>
<td>0.85</td>
<td>8.7</td>
<td></td>
</tr>
<tr>
<td>Oleic acid C₁₈:1</td>
<td>44.5-71.3</td>
<td>13.26</td>
<td>13.27</td>
<td>16.93</td>
<td>64.4</td>
<td>24.6</td>
<td></td>
</tr>
<tr>
<td>Linoleic acid C₁₈:2</td>
<td>10.8-18.3</td>
<td>55.33</td>
<td>57.51</td>
<td>73.73</td>
<td>22.3</td>
<td>39.6</td>
<td></td>
</tr>
<tr>
<td>Linoleic acid C₁₈:3</td>
<td>---</td>
<td>6.31</td>
<td>0</td>
<td>0</td>
<td>8.23</td>
<td>16.3</td>
<td></td>
</tr>
<tr>
<td>Specific gravity</td>
<td>0.912</td>
<td>0.830</td>
<td>0.92</td>
<td>0.912</td>
<td>0.918</td>
<td>0.914</td>
<td>0.91</td>
</tr>
<tr>
<td>Kinematic Viscosity (mm²/s at 40°C)</td>
<td>37.12</td>
<td>2.4</td>
<td>65</td>
<td>50</td>
<td>58</td>
<td>39.5</td>
<td>66.2</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>263</td>
<td>49</td>
<td>230</td>
<td>210</td>
<td>220</td>
<td>280</td>
<td>198</td>
</tr>
<tr>
<td>Calorific Value (MJ/kg)</td>
<td>34.0</td>
<td>41.86</td>
<td>39.6</td>
<td>39.6</td>
<td>39.5</td>
<td>37.6</td>
<td>37.5</td>
</tr>
<tr>
<td>Acid Value (mg KOH/gm)</td>
<td>0.62</td>
<td>---</td>
<td>0.2</td>
<td>0.11</td>
<td>0.15</td>
<td>1.14</td>
<td>34</td>
</tr>
</tbody>
</table>

*Experimentally determined property values

3.1.1  Transesterification process

Transesterification of pongamia oil was carried out by heating of oil, addition of KOH and methyl alcohol, stirring of mixture, separation of glycerol, washing with distilled water and heating for removal of water. The complete process of transesterification of raw vegetable oil into biodiesel (methyl ester) of the corresponding vegetable oil is clearly indicated in Figure 3.1.

The commercially available Pongamia Pinnata oil is procured and transesterified at “M/S. Jetropha oil seed Development and Research Centre”,...
Vanasthalipuram, Hyderabad, India. The biodiesel (PPME) so produced was mixed with diesel in varying proportions from 20%, 40%, 60% and 80% by volume (B20, B40, B60 and B80) with the help of a magnetic stirrer. The blends were stirred continuously to achieve stable property values. Fuel properties such as flash point, fire point, kinematic viscosity and calorific value were determined for the PPME and the different blends.

Figure 3.1 Transesterification of vegetable oil
3.2 EXPERIMENTAL SET UP AND TEST PROCEDURE

The experimental set up consists of a single cylinder four stroke, water-cooled and constant speed (1500 rpm) compression ignition (CI) engine and an exhaust gas analyzer as shown in Figure 3.2. The detailed specification of the engine is given below.

3.2.1 Engine Specification

- Manufacturer: Kirloskar
- Rated speed: 1500 rpm
- Brake power: 3.68 kW
- Stroke length: 110 mm
- Cylinder Bore: 87.5 mm
- Compression ratio: 16.5 : 1
- Fuel used: Diesel

3.2.2 Generator Specification

- Rated voltage: 220 V
- Efficiency: 82 %

The engine is equipped with a D.C swinging field generator and a salt-water rheostat in order to apply the required load. An exhaust gas analyzer is coupled to this engine for measuring the various emission parameters. This analyzer is capable of measuring CO, HC, CO\textsubscript{2} using NDIR technique with the range of 0-20%, 0-10,000 ppm, 0-20% respectively. The analyzer can also measure O\textsubscript{2} and NO\textsubscript{x} using electrochemical technique in the
range of 0-25% and 0-5000 ppm respectively. A separate fuel tank of capacity 5 liters is fitted with the diesel engine for the biodiesel and its blends. The photographic view of the experimental set up is shown in Figure 3.3.

A series of experiments was carried out using diesel, biodiesel and the various blends. As there was slight deviation among the values of different trials, the average value of the trials has been taken into consideration. All the blends were tested under varying load conditions (no load to 75% of the rated maximum load) at the rated speed. During each trial, the engine was started and after it attained the rated speed, important parameters related to thermal performance of the engine such as the time taken for 20 cm³ of fuel consumption, the ammeter and voltmeter readings were measured and recorded. Also the engine emission parameters like CO, CO₂, HC and NOₓ from the online exhaust gas analyzer were noted and recorded.

Figure 3.2 Schematic representation of the experimental set up
3.3 ERROR ANALYSIS

The errors associated with various primary experimental measurements and the calculations of important parameters are detailed in Appendix 1. Also the summary of estimated uncertainties is given in the form of a table in the Appendix 1.

3.4 THERMODYNAMIC ANALYSIS

For better utilization of energy, it is important to take into account of the quantity and quality of energy. This can be accomplished by employing the first and second laws of thermodynamics. Both are required, one complements the other. The methodology, which utilizes both laws, is called availability or exergy analysis. First law analysis might indicate no loss in
energy for some processes, but actually there is a real loss in the value or quality of energy (Najem and Diab 1992). Exergy analysis of biomass combustion is an important tool to measure the environmental degradation. Exergy analysis identifies accurately the margin available to design more efficient energy systems by reducing inefficiencies and can represent a measure of environmental impact potential. Engineers and researchers suggest that the thermodynamic performance of a process is best evaluated by performing exergy analysis rather than conventional energy analysis as exergy analysis provides more insight towards efficiency improvements than energy analysis.

In the present work, analysis has been carried out by estimating the adiabatic flame temperature (AFT), stoichiometric air requirement (SAR), energy produced, exergy destructed, exergy loss index for both diesel and biodiesel (PPME) and the exergy destruction during the specific energy generation in an engine through diesel and biodiesel (PPME) to compare the environmental destruction level of the fuels.

The chemical analysis of the fuels diesel and the biodiesel (PPME) used is given in Table 3.1 (NREL 2003 and Raheman and Phadatare 2004).

A combined first and second law supplies the information about the reversible work or availability change associated with the chemical processes and also the irreversibility or losses. The analysis is based on the assumption that the complete combustion occurs inside the combustion chamber at 1000K and the reactants enter at room temperature.
Table 3.2 Chemical analysis of fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Constituent</th>
<th>Mass fraction (%)</th>
<th>Mole fraction (k mol / kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>C</td>
<td>86.60</td>
<td>0.0721</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>14.35</td>
<td>0.144</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>0.042</td>
<td>1.31X 10^{-5}</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>C</td>
<td>76.63</td>
<td>0.0639</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>12.05</td>
<td>0.1205</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>11.26</td>
<td>0.00704</td>
</tr>
</tbody>
</table>

3.4.1 Energy Analysis

A steady state control volume is considered where the fuel is taken at the restricted dead state, air (oxidant) from the atmosphere and the product gases are returned to the unrestricted dead state. Heat release during a steady flow process is given by the difference in enthalpies of the products and reactants. It is given in Equation 3.2.

\[
Q = H_p - H_R = \sum_p N_i h_i^p - \sum_R N_i h_i^R = \sum_{p-R} N_i h_i \\
\]

Heat release during constant volume combustion process is given by

\[
Q = \sum_p N_i [h_f,298 + \tilde{h}_T - \tilde{h}_{298} - p \tilde{v} - \sum_R N_i [h_f,298 + \tilde{h}_T - \tilde{h}_{298} - p \tilde{v}]] \\
\]

Adiabatic combustion Temperature and heating value of fuel

It is desirable to measure the adiabatic flame / combustion temperature \( T_{ad} \) of the reacting mixture and is evaluated by equating \( H_r \) and \( H_p \) as given in Equation 3.3.
\[
\sum_p N_i [\Delta h_{f,298}^0 + h_T - h_{298}] = \sum_R N_i [\Delta h_{f,298}^0 + h_T - h_{298}]
\] (3.3)

The adiabatic flame temperature is taken as the theoretical upper limit of the product gas temperature due to improper insulation of the reactor and dissociation of some of the products into other chemical species due to high temperature. The higher heating value of the fuels is theoretically derived from the fuel chemical analysis using the following formula with a correlation coefficient of 0.996.

\[
(HHV)_{DAF} = [152.19H + 98.767 \bar{C}/3 + H - (O - S)/8]
\] (3.4)

### 3.4.2 Exergy Analysis

Exergy analysis is a useful tool for achieving more efficient energy resource utilization through determination of location, types and magnitude of wastes and loses. It can reveal clearly whether or not and to what extent it would be possible to design more efficient energy systems by reducing the inefficiencies in the existing system.

**Chemical Availability (exergy)**

The availability or exergy of a substance in a given state is a measure of the maximum obtainable work, as it proceeds to the dead state while exchanging heat solely with the environment.
The absolute entropy ($S_{DAF}$) is given by,

$$S_{DAF} = \left[ 37.1653 - 31.4767 \exp \left(-0.564682 \frac{h}{c+n} \right) \right]$$

$$+ \left( 20.11454 \frac{o}{c+n} + 54.3111 \frac{n}{c+n} + 44.6712 \frac{s}{c+n} \right)$$

(3.5)

The chemical exergy is given by

$$e^{CH}_{DAF} = (HHV)_{DAF} - T_0 \left[ S_{DAF} + V_{o_2} - V_{CO_2} \bar{S}_{CO_2} - V_{H_2O} \bar{S}_{H_2O} - V_{SO_2} \bar{S}_{SO_2} - V_{N_2} \bar{S}_{N_2} \right]$$

$$+ \left[ V_{CO_2} e_{CO_2} + V_{H_2O} e_{H_2O} + V_{SO_2} e_{SO_2} + V_{N_2} e_{N_2} - V_{o_2} e_{o_2} \right]$$

(3.6)

From the above Equations (3.2, 3.3, 3.5 and 3.6) the energy produced, adiabatic flame temperature and chemical exergy are calculated (Kennath Wark 2002 and Haribaskaran and Saravanan 2007).

**Exergy loss index (ELI)**

The exergy loss index is a measure to compare the potential of a fuel to destruct the surrounding environment during the combustion process. This index would be an useful measure to compare diesel and the biodiesel by taking into account both qualitative and quantitative energy accountability.

$$ELI = \frac{\text{exergy destructed (MJ/kg)}}{\text{energy produced (MJ/kg)}}$$

**Exergy destruction for specific energy generation (EDSE)**

In order to evaluate the exergy destructed during the specific energy generation in a diesel engine using diesel and biodiesel, some data from the experiment have been used. For a given fuel the exergy destructed per unit energy generation is given by

$$EDSE = \frac{\text{exergy destructed (MJ/kg)}}{\text{BSFC (kg/kWh)}}$$
3.5 RESULTS AND DISCUSSION

In the section, the results of the biodiesel characterization, performance and exhaust emission analysis and the energy and exergy analysis are reported in detail.

3.5.1 Characteristics of biodiesel and its blends

After the transesterification process, the colour of the biodiesel (PPME) changed from deep brown to reddish yellow. Transesterification decreased the kinematic viscosity by a factor of 3.5. The calorific value of PPME was slightly increased and specific gravity was slightly decreased. The comparison of the measured property values of PPME with those of biodiesel derived from other vegetable oils is presented in Table 3.2 (Ramadhas et al 2005a).

Table 3.3 Properties of PPME, and esters (biodiesel) of other vegetable oils

<table>
<thead>
<tr>
<th>Property</th>
<th>PPME*</th>
<th>Soya bean</th>
<th>Cotton seed</th>
<th>Sun Flower</th>
<th>Rap seed</th>
<th>Rubber seed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>0.878</td>
<td>0.885</td>
<td>0.874</td>
<td>0.878</td>
<td>0.882</td>
<td>0.874</td>
</tr>
<tr>
<td>Calorific Value (MJ/kg)</td>
<td>35.56</td>
<td>39.76</td>
<td>40.32</td>
<td>40.56</td>
<td>37.0</td>
<td>36.5</td>
</tr>
<tr>
<td>Kinematic Viscosity at 40ºC (mm²/s)</td>
<td>10.64</td>
<td>4.08</td>
<td>4.0</td>
<td>4.5</td>
<td>4.5</td>
<td>5.81</td>
</tr>
<tr>
<td>Flash point (ºC)</td>
<td>172</td>
<td>69</td>
<td>70</td>
<td>85</td>
<td>170</td>
<td>130</td>
</tr>
</tbody>
</table>

*Experimentally determined property values
It is seen from the table that the specific gravity and calorific values of PPME are in closer agreement with the other biodiesel and the kinematic viscosity and flash points are comparatively higher. In comparison with diesel, the flash point and fire point were found to be around three times more than that of pure diesel, facilitating safe transport and storage. The calorific value of PPME was measured to be 36 MJ/kg, which is less than that of diesel (41.86 MJ/kg) and greater than that of raw Pongamia oil (34.0 MJ/kg). The kinematic viscosity of the PPME was measured to be four times that of diesel at 40°C.

The property values of the different blends of diesel and biodiesel (PPME) in varying proportions from 0 to 100% (pure diesel to 100 % PPME) are shown in Figures 3.4 and 3.5. It is observed that increasing concentration of PPME in the diesel resulted in the corresponding increase in the kinematic viscosity.

![Graph showing variation of kinematic viscosity and specific gravity with percentage of PPME in the blend](image)
Figure 3.5  Variation of calorific value and flash point with percentage of PPME in the blend

A similar phenomenon in specific gravity is also noted. The flash point of the various blends with increasing PPME concentration is found to increase, due to the higher value of flash point for the PPME than diesel. Conversely, a decreasing trend is observed for the calorific value in the fuels with increasing PPME concentration.

The variation of kinematic viscosity with temperature for the different blends is shown in Figure 3.6. It is observed that for all the blends, the kinematic viscosity decreases with increase in temperature. The kinematic viscosity of the blends B20, B40 and B60 are closer to that of diesel at 70° C. In the case of B80 and B100, the kinematic viscosity is very high at lower temperature and this value decreases appreciably at higher temperature.
3.5.2 Engine performance

The engine performance was evaluated based on brake specific fuel consumption (BSFC) and brake specific energy consumption (BSEC) to compare the effects of various biodiesel (PPME) blends and diesel. BSFC is the amount of fuel required to develop unit brake power and BSEC is the energy input required to develop unit brake power. BSEC is independent of the fuel used and hence the brake specific energy consumption is a good measure to compare the performance of the engine with different fuels.

3.5.2.1 BSFC and BSEC

The variation of BSFC and BSEC with load for different blends and diesel are presented in Figures 3.7 and 3.8. It is observed from Figures 3.7 and 3.8 that the BSFC and BSEC for all the fuel blends and diesel tested decrease...
with increase in load. This is due to higher percentage increase in brake power with load as compared to increase in the fuel consumption. For all loads except the full load, the BSFC is lower than that of diesel for B20 and is equal to that of diesel for B40. The BSEC is less than that of diesel for both B20 and B40 at all loads except initial load. This could be due to the presence of dissolved oxygen in the PPME that enables complete combustion and the negative effect of increased viscosity would not have been initiated. However as the PPME concentration in the blend increases further, the BSFC increases at all loads and the percentage increase is higher at low loads. Whereas the BSEC increases initially at low loads and at higher load conditions, its value is less than that of diesel for all the blends except PPME (B100).

![Figure 3.7 Variation of BSFC with load for different blends](image)

**Figure 3.7 Variation of BSFC with load for different blends**
Figure 3.8 Variation of BSEC with load for different blends

This could be due to the lower calorific value of the PPME and the high mass flow of fuel entering into the engine (specific gravity of PPME is 6% more than that of diesel). Also the engine has been designed only for diesel fuel and has been used for PPME in an unmodified condition. In addition, the high viscosity of the blends may also inhibit the proper atomization of the fuel, which in turn affects the combustion process.

The efficiency of the generator employed in the experimental set up is 0.82. The variation of the generator efficiency with load is shown in Figure 3.9. As the efficiency of the generator is not 100%, it is appropriate to incorporate the same in the calculation of BSFC and BSEC in order to arrive at the true / actual BSFC and BSEC. The curves of true BSFC and true BSEC are shown in Figures 3.10 and 3.11. The graphs exhibit the same trend as those of BSFC and BSEC.
Figure 3.9 Variation of generator efficiency with load

Figure 3.10 Variation of true BSFC with load for different blends
3.5.3 Engine emission studies

The engine emission study was evaluated based on CO, CO$_2$, unburnt hydrocarbon (UBHC), NO$_x$ emissions and the exhaust gas temperature. The emissions of CO, CO$_2$, UBHC and NO$_x$ are very critical from environmental degradation point of view.

3.5.3.1 CO emission

It is interesting to note that excepting no load condition, the engine emits more CO for diesel as compared to biodiesel blends under all loading conditions. It is seen from Figure 3.12 that the CO concentration is totally absent for the blends B40 and B60 at all loading conditions and as the PPME concentration in the blend increases above 60%, presence of CO is observed. At lower PPME concentration, the oxygen present in the PPME aids for complete combustion. However as the PPME concentration increases, the
negative effect due to high viscosity and small increase in specific gravity suppresses the complete combustion process, which produces small amount of CO. The reason explained above is also confirmed from the effects shown in Figures 3.7 and 3.8 for BSFC and BSEC.

![Figure 3.12 Variation of CO emission with load](image)

### 3.5.3.2 CO₂ emission

Figure 3.13 depicts the CO₂ emission of various fuels used. The CO₂ emission increased with increase in load for all blends. The lower percentage of PPME blends emits less amount of CO₂ in comparison with diesel. Blends B40 and B60 emit very low emissions. This is due to the fact that biodiesel in general is a low carbon fuel and has a lower elemental carbon to hydrogen ratio than diesel fuel. Using higher content PPME blends, an increase in CO₂ emission was noted, which is due to the incomplete combustion as explained earlier. Though at higher loads, higher biodiesel (PPME) content blends emit CO₂ almost at par with diesel, in general
biodiesels themselves are considered carbon neutral because, all the CO$_2$ released during combustion had been sequestered from the atmosphere for the growth of the vegetable oil crops.

![Figure 3.13 Variation of CO$_2$ emission with load](image)

**Figure 3.13** Variation of CO$_2$ emission with load

### 3.5.3.3 UBHC emission

The UBHC emission variation for different blends is indicated in Figure 3.14. It is seen from the figure that the UBHC emission decreases with increase in load for diesel and it is almost nil for all PPME blends except B20 where some traces are seen at no load and full load. As the Cetane number of ester based fuel is higher than diesel, it exhibits a shorter delay period and results in better combustion leading to low UBHC emission. Also the intrinsic oxygen contained by the PPME was responsible for the reduction in UBHC emission.
3.5.3.4 Exhaust gas temperature

The variation of exhaust gas temperature for different blends with respect to the load is indicated in Figure 3.15. The exhaust gas temperature for all the fuels tested increase with increase in the load. The amount of fuel injected increases with the engine load in order to maintain the power output and hence the heat release and the exhaust gas temperature rise with increase in load. Exhaust gas temperature is an indicative of the quality of combustion in the combustion chamber.

At all loads, diesel was found to have the highest temperature value and the values for the different blends showed a downward trend with increasing concentration of PPME in the blends. This is due to the improved combustion provided by the PPME on account of its 11% dissolved oxygen content.
3.5.3.5 NO$_x$ emission

The variation of NO$_x$ emission for different blends is indicated in Figure 3.16. The NO$_x$ emission for all the fuels tested followed an increasing trend with respect to load. The reason could be the higher average gas temperature at higher load conditions. A reduction in the emission for all the blends as compared to diesel was noted. With increase in the PPME content of the blends, corresponding reduction in emission was noted and the reduction was remarkable for B40 and B60.
The most significant factor that causes NO\textsubscript{x} formation is the maximum combustion temperature. Since injection particles of the vegetable oils were greater than those of diesel, the combustion efficiency, maximum combustion temperature, and hence the NO\textsubscript{x} emissions were lower. The maximum and minimum amount of NO\textsubscript{x} produced were 230 ppm and 48 ppm corresponding to B20 and B60.

3.5.4 Exergy analysis

The adiabatic flame temperature, exergy destructed, exergy loss index, and exergy destructed per unit energy produced are reported in this section.
3.5.4.1 Adiabatic flame temperature and stoichiometric air requirement

The theoretically estimated values of adiabatic flame temperature (AFT) and the stoichiometric air requirement (SAR) are shown in Figures 3.17 and 3.18. The Adiabatic flame temperature for PPME (2400 K) is less than that of diesel (2500 K). The Stoichiometric air requirement is less for PPME as compared to that of diesel. It is due to the presence of 11% free dissolved oxygen, which facilitates to achieve complete combustion and necessitates less amount of oxygen from atmospheric air.

![Figure 3.17 Adiabatic flame temperature](image)
Figure 3.18  Stoichiometric air requirement

3.5.4.2 Energy produced and exergy destructed

The energy produced and the exergy destructed for diesel and PPME are shown in Figure 3.19. The energy produced is more for diesel in comparison with biodiesel (PPME).

Though the energy produced per kg is more for the diesel fuel as compared to PPME, the exergy destructed (irreversibility) is considerably less for the PPME. The exergy destruction is a measure of environment friendly nature of a fuel and hence PPME is an eco friendly fuel capable of protecting the environment.
3.5.4.3 Exergy loss index

The exergy loss index with respect to diesel and PPME is represented in Figure 3.20. For a given fuel, exergy loss index is the ratio of exergy destructed in kJ/kg and the energy produced in kJ / kg. The exergy loss index is less for PPME as compared to diesel indicating the importance of use of PPME and other biodiesel fuels for any combustion process. From the estimated values of exergy destruction and the exergy loss index, it is clearly evident that biodiesel (PPME) usage for diesel engine application serves a lot towards environmental protection.
3.5.4.4 **Exergy destructed per unit energy produced**

The variation of the exergy destructed per kWh of energy produced by diesel, PPME and the different blends of PPME and diesel at various engine loads is shown in Figure 3.21. As seen from the figure, though the exergy destruction per kWh of energy produced is more for PPME (B100) as compared to diesel, the value is less for all the blends of PPME at all loads. This is an appreciable feature of use of eco-friendly biodiesel (PPME).
Figure 3.21 Variation of exergy destruction per unit energy produced

The reason for the higher value of exergy destruction per unit energy generation in the case of 100% PPME, is that the increased viscosity plays a significant role to increase the BSFC through reduced flow. Moreover, the engine is designed for diesel fuel and has been used for PPME application without any modification, thereby resulting in higher BSFC.