CHAPTER 5

EXPERIMENTAL RESULTS AND DISCUSSION

5.1 INTRODUCTION

In this chapter various experimental analyses are discussed elaborately. Initially the different properties of various biodiesels, diesel and raw vegetable oils were found through experimentation. These results are discussed in detail in the section 5.2. The performance analysis, emission analysis and exergy analysis of different dual biodiesels are discussed in the section 5.3, 5.4 and 5.5 respectively. The optimum dual biodiesel was discussed in the section 5.6. The optimum dual biodiesel performance was further increased by adding additives to the dual biodiesel and their results are discussed in the section 5.7. The diesel engine combustion parts such as piston and cylinder head were coated with the ceramic material of Al₂O₃ - TiO₂. The results of the optimum dual biodiesel with LHR engine were discussed in the section 5.8. The diesel engine exhaust gas had waste heat energy which was recovered by the double pipe heat exchanger and preheated the dual biodiesel. The heat exchanger augmentation was performed with circular plate inserts. The effects of the heat exchanger with inserts were discussed in the section 5.9.1. The performance analysis of the preheated dual biodiesel was discussed in the section 5.9.2.
5.2 PROPERTY ANALYSIS

The various properties like kinematic viscosity, density, calorific value, flash point temperature, surface tension, corrosiveness and cetane number of four raw vegetable oils, four single biodiesels, diesel fuel and thirty six dual biodiesel blends were calculated experimentally and shown in the Figures 5.1 to 5.13.

5.2.1 Calorific Value of Fuels

Calorific value of a fuel measures the energy content in a fuel determines the suitability of the biodiesel as an alternative to diesel fuel. Digital bomb calorimeter was used to find out the calorific value of fuels. The calorific values of any fuel need to be high for complete combustion or for burning process.

The calorific value of the raw vegetable oils of pongamia pinnata oil, cotton seed oil, neem oil, jatropha oil, biodiesel of pongamia pinnata, Cotton seed biodiesel, neem biodiesel, jatropha biodiesel and diesel fuel are shown in Figure 5.1. The calorific values of biodiesels are higher than those of the raw vegetable oils due to the transesterification process.

The calorific values of pongamia pinnata biodiesel, cotton seed biodiesel and jatropha biodiesel are 1.82%, 2.3% and 10.8% respectively and they are higher than those of raw pongamia pinnata vegetable oil, cotton seed oil and jatropha oil. From Figure 5.1, it is clearly shown that the calorific values of the diesel are higher than those of the raw vegetable oils and biodiesel.
The Calorific values of pongamia pinnata biodiesel blends and cotton seed biodiesel blends are shown in Figure 5.2. The cotton seed biodiesel blends are 0.5% to 0.72% higher than pongamia pinnata biodiesel.
The Calorific values of the neem biodiesel blends and jatropha biodiesel blends are shown in Figure 5.3. The jatropha biodiesel blends are 3.9% to 8.1% higher than neem biodiesel.

![Figure 5.3 Calorific value for neem and jatropha biodiesel](image)

The Calorific values of the DPN dual biodiesel blends and DPJ dual biodiesel blends are shown in Figure 5.4. The calorific values of DPN bends are closer to those of DPJ blends. The calorific values of DPN biodiesel blends are 0.02% to 0.2% higher than those of DPJ biodiesel. This is due to higher volatility and low viscosity of the DPN blends than those of DPJ blends.
The Calorific values of DPC dual biodiesel blends and DCJ dual biodiesel blends are shown in Figure 5.5. The calorific values of DPC biodiesel blends are 0.02% to 0.48% higher than those of DCJ biodiesel.

The Calorific values of DNJ dual biodiesel blends and DNC dual biodiesel blends are shown in Figure 5.6. The calorific values of DPC biodiesel blends are 0.22% to 1.2% higher than those of DCJ biodiesel.
Figures 5.4 - 5.6 show that the calorific values of DPN 1, DPJ 1, DPC 1, DCJ 1 and DNJ 1 are higher than those of the other dual biodiesel blends. Figure 5.7 shows the optimum dual biodiesel mixtures of all the tested dual biodiesel blends and diesel. The Table 5.1 shows the calorific values of the optimum dual biodiesel blends. The calorific value of DPN 1 and DPJ 1 are 1% and 1.1% lower than those of diesel.

Figure 5.6 Calorific value for DNJ and DNC dual biodiesel

Figure 5.7 Calorific value of optimum dual biodiesel
Table 5.1 Calorific value for optimum dual biodiesel blends

<table>
<thead>
<tr>
<th>Optimum dual biodiesel blends</th>
<th>Calorific value, kJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPN 1</td>
<td>46100</td>
</tr>
<tr>
<td>DPJ 1</td>
<td>46090</td>
</tr>
<tr>
<td>DPC 1</td>
<td>46050</td>
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<td>DCJ 1</td>
<td>46040</td>
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<tr>
<td>DNJ 1</td>
<td>46000</td>
</tr>
<tr>
<td>Diesel</td>
<td>46580</td>
</tr>
</tbody>
</table>

5.2.2 Viscosity of Fuels

Kinematic viscosity is measured using Redwood viscometer. It is a major factor of consequence in exhibiting its suitability for the mass transfer and metering requirements of engine operation. Higher viscosity results in low volatility and poor atomization of oil during injection in CI engine, that results in incomplete combustion and ultimately carbon deposits on injector nozzle as well as in the combustion chamber.

The kinematic viscosities of dual biodiesel blends vary from 4.1 to 5.85 mm²/s and are higher than those of diesel fuels. The kinematic viscosity of the raw oil is very high compared to diesel. The use of neat vegetable oils generates some problems, when they are subjected to prolonged usage in CI engines. These problems are attributed to the high viscosity and low volatility.

Kinematic viscosity of raw vegetable oils, diesel fuel and biodiesels is shown in Figure 5.8. The kinematic viscosities of the vegetable oils were higher than those of diesel. However, the kinematic viscosities of vegetable oils were reduced after the transesterification process. The pongamia pinnata
biodiesel, cotton seed biodiesel, neem biodiesel and jatropha biodiesel had 32%, 31%, 30% and 20% higher viscosity than diesel. This is due to the biodiesel, which had higher density and specific gravity than diesel.

Figure 5.8 Kinematic viscosities for raw vegetable oil, biodiesel and diesel

The kinematic viscosities of the DPN dual biodiesel and DPJ dual biodiesel are shown in Figure 5.9. The kinematic viscosity of diesel was 4 mm²/s. The DPN 1, DPN 2 and DPN 6 had the viscosities of 4.13 mm²/s, 4.26 mm²/s and 5.3 mm²/s whereas DPJ 1, DPJ 2 and DPJ 6 had the viscosities of 4.125 mm²/s, 4.25 mm²/s and 5.25 mm²/s. The DPN and DPJ blends had 3% to 24% higher viscosity than diesel. The biodiesel was prepared from vegetable oils so that it has higher volatility and viscosity than diesel.

Figure 5.9 Kinematic viscosities for DPN and DPJ dual biodiesel
The kinematic viscosities of DPC dual biodiesel and DCJ dual biodiesel are shown in Figure 5.10. The kinematic viscosity of the DPC blends was lower than that of DCJ blends. DCJ blends had 1% to 7% higher viscosity than DPC blends.

![Figure 5.10 Kinematic viscosities for DPC and DCJ dual biodiesel](image1)

The kinematic viscosities of the DNJ dual biodiesel and DNC dual biodiesel are shown in Figure 5.11. The kinematic viscosities of the DNC blends were higher than that of the DNJ blends. DNC 1, DNC 2 and DNC 6 blends have 0.23%, 0.22% and 0.8% higher viscosity than DNJ blends.

![Figure 5.11 Kinematic viscosities for DNJ and DNC](image2)
Figure 5.12 shows the comparison of the optimum biodiesel of all the combinations. From the Figures 5.9 - 5.11, it is clear that the kinematic viscosity of DPN 1, DPJ 1, DPC 1, DCJ 1, DNJ 1 and DNC 1 is closer to that of diesel fuel. The Table 5.2 shows the kinematic viscosity of the optimum dual biodiesel blends. The kinematic viscosity of DPN 1 and DPJ 1 is 3.1% and 3% higher than that of diesel fuel.

Figure 5.12 Kinematic viscosities of optimum dual biodiesel

Table 5.2 Kinematic viscosity for optimum dual biodiesel blends

<table>
<thead>
<tr>
<th>Optimum dual biodiesel blends</th>
<th>Kinematic viscosity, mm²/s</th>
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<tr>
<td>DPN 1</td>
<td>4.13</td>
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<tr>
<td>DPC 1</td>
<td>4.135</td>
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<td>DCJ 1</td>
<td>4.18</td>
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<td>DNJ 1</td>
<td>4.18</td>
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<td>DNC 1</td>
<td>4.19</td>
</tr>
<tr>
<td>Diesel</td>
<td>4</td>
</tr>
</tbody>
</table>
5.2.3 Fuel Density

The density of different biodiesels, dual biodiesel blends, raw vegetable oil and diesel is calculated. The density of a fluid defines mass per unit volume, denoted in cubic meters. The density of biodiesel is related to the combustion process, which is highly dependent on the quality of atomization. In turn, fuel atomization is dependent on fuel properties such as viscosity, surface tension and specific gravity.

Higher density, specific gravity and viscosity of fuel bring out the lower volatility and poor atomization of biodiesel during fuel injection in the combustion chamber causing incomplete combustion and carbon deposits in the combustion chamber.

The density of raw vegetable oils, pongamia pinnata biodiesel, cotton seed biodiesel, neem biodiesel, jatropha biodiesel and diesel is shown in Figure 5.13. The densities of various biodiesels are higher than those of diesel.

![Figure 5.13 Density for raw oil, biodiesels and diesel](image)
The density of DPN and DPJ dual biodiesel blends is shown in Figure 5.14. The DPN blends have lower density than DPJ dual biodiesel blends. This is due to the fact that the DPN blends have lower viscosity than the other blends. The lower density of DPN improves the volatility of the fuel.

**Figure 5.14 Density for DPN and DPJ dual biodiesel**

The density of DPC and DCJ dual biodiesel blends is shown in Figure 5.15. The densities of DPC blends are lower than those of the DCJ blends. The density of DPC 1 is better than the other DPC and DCJ dual biodiesel blends.

**Figure 5.15 Density for DPC and DCJ dual biodiesel**
The density of DNJ and DNC dual biodiesel blends is shown in Figure 5.16. The densities of DNJ blends are lower than those of the DNC blends. The density of DNJ 1 is better than the other DNJ and DNC dual biodiesel blends.

![Figure 5.16 Density for DNJ and DNC dual biodiesel](image)

The density of various optimum dual biodiesel is shown in Figure 5.17. Figures 5.14 - 5.16 show that the density of DPN 1, DPJ 1, DPC 1, DCJ 1 and DNJ 1 are lower than that of the other dual biodiesel blends. The Table 5.3 shows the density of the optimum dual biodiesel blends. The density of DPN 1 blend is lower than that of the other dual biodiesel blends. The density of DPN 1 is comparable to that of the diesel fuel whereas DPJ 1 has 0.2% higher density than diesel.
Figure 5.17 Density for optimum dual biodiesel

Table 5.3 Density for optimum dual biodiesel blends

<table>
<thead>
<tr>
<th>Optimum dual biodiesel blends</th>
<th>Density, Kg/m$^3$</th>
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<tr>
<td>DPN 1</td>
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<tr>
<td>DPJ 1</td>
<td>831.5</td>
</tr>
<tr>
<td>DPC 1</td>
<td>832.25</td>
</tr>
<tr>
<td>DCJ 1</td>
<td>832.3</td>
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<tr>
<td>DNJ 1</td>
<td>832.55</td>
</tr>
<tr>
<td>Diesel</td>
<td>830</td>
</tr>
</tbody>
</table>

5.2.4 Flash Point Temperature of Fuels

The flash point temperature of a fuel is the minimum temperature at which the fuel will ignite or flash when an ignition source is applied. The flash point temperature was measured using Pensky Marten’s closed cup apparatus.
In terms of shipping and safety regulations, the flash point is generally used to define the flammable or combustible properties of biodiesel. Although flash point is not directly related to the engine performance, it is important for legal requirements and safety precautions involved in the handling and storage of biodiesel for insurance and fire regulations.

The flash point temperatures of the raw vegetable oil and various biodiesel are as shown in Figure 5.18. The flash point temperature of pongamia pinnata biodiesel, cotton seed biodiesel, neem biodiesel and jatropha biodiesel is 172ºC, 150ºC, 165ºC and 125ºC whereas that of the diesel is 58ºC. The dual biodiesel blends have higher flash point temperature value than diesel. These results show that the selected biodiesels could be safely stored due to their higher flash point temperatures.

![Figure 5.18 Flash point temperatures for raw oil and biodiesel](image)

The flash point temperatures of DPN and DPJ dual biodiesel are shown in Figure 5.19. The flash point temperature of DPN 1, DPN 2, DPJ 1 and DPJ 2 is 69ºC, 80.1ºC, 67.1ºC and 76.1ºC. DPN 1 blend has 3% higher flash point temperature than the DPJ 1 blend. The DPN dual biodiesel blends have higher flash point temperature than DPJ blends.
The flash point temperatures of DPC and DCJ dual biodiesel are as shown in Figure 5.20. The DPC blends have higher flash point temperature than DCJ blends. DPC 1 blend, DPC 2 blend and DPC 3 blend have 3.4%, 6% and 8% higher flash point temperature than DCJ 1, DCJ 2 and DCJ 3 respectively.

The flash point temperatures of DNJ and DNC dual biodiesel are shown in Figure 5.21. The DNC dual biodiesel blends have higher flash point temperature than DNJ blends. The flash point temperature of DNC 1 is 1.8% higher than that of DNC 1.
Figure 5.21 Flash point temperatures for DNJ and DNC

The flash point temperatures for the various optimum dual biodiesel blends are shown in Figure 5.22. The higher flash point temperature is better for any liquid fuel. Figures 5.19 - 5.21 show that DPN blends, DPJ 6, DPC 6, DCJ 6, DNJ 6 and DNC 6 have higher flash point temperature than the other dual biodiesel blends. This ensures safety in handling, storage and transport of the DPN dual biodiesel blends compared to the other blends. The Table 5.4 shows the flash point temperature of the optimum dual biodiesel blends.

Figure 5.22 Flash point temperatures for optimum dual biodiesel
Table 5.4 Flash point temperatures for optimum dual biodiesel

<table>
<thead>
<tr>
<th>Optimum dual biodiesel blends</th>
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<tbody>
<tr>
<td>DPN 6</td>
<td>168.25</td>
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<tr>
<td>DPJ 6</td>
<td>148</td>
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<tr>
<td>DPC 6</td>
<td>161</td>
</tr>
<tr>
<td>DCJ 6</td>
<td>137.5</td>
</tr>
<tr>
<td>DNJ 6</td>
<td>145</td>
</tr>
<tr>
<td>DNC 6</td>
<td>157</td>
</tr>
<tr>
<td>Diesel</td>
<td>58</td>
</tr>
</tbody>
</table>

5.2.5 Cetane Number

The cetane number is an important fuel property of diesel engines. The cetane number of a fuel is a measure of the ignition delay, that is, the time that passes between injection of the fuel into the cylinder and ignition. The shorter the ignition delay, the higher the cetane number. Higher cetane numbers in diesel fuel have been associated with lower NOx emissions.

Despite the fact that biodiesels generally have higher cetane numbers, emissions of NOx from these fuels are slightly higher than those of petroleum diesel. The higher cetane number of biodiesel is still considered positive. Studies have shown that as levels of unsaturation increase, cetane number decreases, and as the chain length increases the cetane number increases.

The characteristics of the feed stock also influence the cetane number of biodiesel. The number of carbon atoms in the fatty acids and the
number of double bonds in the biodiesel affect the cetane number and this was reported by Sivaramakrishnan & Ravikumar (2012).

The Cetane numbers of raw vegetable oils and biodiesel are shown in Figure 5.23. The cetane number of diesel is 47. The raw vegetable oils have lower cetane number than diesel. But after the transesterification process, the cetane number is improved for the biodiesel. The cetane number of pongamia pinnata biodiesel, cotton seed biodiesel and jatropha biodiesel are 2%, 9.6%, 7.8% higher than that of diesel. This is due to the fact that oxygen content available in the biodiesels is higher than diesel.

![Figure 5.23 Cetane number for raw oil and biodiesel](image)

The Cetane numbers of DPN and DPJ dual biodiesel blends are shown in Figure 5.24. The cetane numbers of DPJ blends are slightly higher than those of DPN blends. The DPJ 1, DPJ 2 and DPJ 3 are 4%, 3%, 1.6% higher than DPN 1, DPN 2 and DPN 3 blends. DPN 4 blend and DPJ 4 are comparable to each other.
The Cetane numbers of DPC and DCJ dual biodiesel blends are shown in Figure 5.25. The cetane numbers of DCJ blends are higher than DPC blends. The DCJ 1, DCJ 2 and DCJ 3 are 0.3%, 0.6% and 0.9% higher than DPC 1, DPC 2 and DPC 3 blends.

The Cetane numbers of DNJ and DNC dual biodiesel blends are shown in Figure 5.26. The cetane numbers of DNC blends are higher than DNJ blends. The DNC 1, DNC 2 and DNC 6 are 0.1%, 0.2% and 1% higher than DNJ 1, DNJ 2 and DNJ 6 blends.
The cetane numbers of optimum dual biodiesel combinations are shown in Figure 5.27. Figures 5.24 - 5.26 show that DPN 6, DPJ 6, DPC 6 and DCJ 6 have higher cetane numbers than other dual biodiesel blends. The cetane number of DPN 6, DPJ 6, DPC 6 and DCJ 6 is 6%, 5%, 6% and 9% higher than that of diesel. The Table 5.5 shows the cetane number of the optimum dual biodiesel blends.
Table 5.5 Cetane number for optimum dual biodiesel

<table>
<thead>
<tr>
<th>Optimum dual biodiesel blends</th>
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<td>50</td>
</tr>
<tr>
<td>DPJ 6</td>
<td>49.5</td>
</tr>
<tr>
<td>DPC 6</td>
<td>50</td>
</tr>
<tr>
<td>DCJ 6</td>
<td>51.5</td>
</tr>
<tr>
<td>Diesel</td>
<td>47</td>
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</table>

5.2.6 Surface Tension

Surface tension affects the spray characteristics and atomization of fuel droplets leading to significant effect on combustion efficiency. The surface tension is determined by the drop counting method in a Stalagmometer.

This property is important to the fuel spray process in the diesel engine combustion chamber. Higher surface tension creates larger droplet sizes, allowing the biodiesel to be pushed into the engine oil sump with greater frequency. The comparison of the surface tension of pongamia pinnata biodiesel, cotton seed biodiesel, neem biodiesel, jatropha biodiesel and diesel is shown in Figure 5.28. The surface tension of diesel is lower than those of the other fuels and this is due to the low viscosity and density of diesel fuel.
Figure 5.28 Surface tension for various biodiesel

The surface tensions of DPN and DPJ dual biodiesel blends are shown in Figure 5.29. The surface tension of DPJ 1 is 3% higher than that of DPN 1 blend.

Figure 5.29 Surface tension for DPN and DPJ

The surface tensions of DPC and DCJ dual biodiesel blends are shown in Figure 5.30. The surface tension of DPC blends is lower than that of the DCJ blends.
The surface tensions of DNJ and DNC dual biodiesel blends are shown in Figure 5.31. The surface tension of DNJ blends is lower than that of the DCJ blends.

The surface tensions of optimum dual biodiesel combinations are as shown in Figure 5.32. From the Figures 5.29 - 5.31, it is shown that the surface tensions of DPN 1, DPJ 1 and DPC 1 are lower than those of the other dual biodiesel blends. The surface tensions of DPN 1, DPJ 1 and DPC 1 are 6%, 9% and 11.7% higher than that of diesel. The surface tension results show that the dual biodiesel blends of DPN 1 and DPJ 1 have closer surface tension value with the diesel but the other blends have higher surface tension than diesel.
Figure 5.32 Surface tension for optimum dual biodiesel

Table 5.6 Surface tension for optimum dual biodiesel

<table>
<thead>
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<th>Optimum dual biodiesel blends</th>
<th>Surface tension</th>
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<td>DPJ 1</td>
<td>33</td>
</tr>
<tr>
<td>DPC 1</td>
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</tbody>
</table>

5.2.7 Corrosion Test

The copper corrosion test measures the corrosion tendency of fuel. Free fatty acids that exist in biodiesel may cause corrosion. The corrosion results show that all the samples tested are classified as 1a (as per ISO-2160 international standard manual), which is a suitable classification from the point of view of corrosion.

5.3 PERFORMANCE ANALYSIS

The diesel engine runs with diesel fuel and various dual biodiesel combinations (DPN, DPJ, DPC, DCJ, DNJ and DNC). From the experimental
analysis, brake power, brake specific fuel consumption, brake specific energy consumption, thermal efficiency and exhaust gas temperature are analyzed.

### 5.3.1 Specific Fuel Consumption

The total fuel consumption is determined by measuring the volume of fuel consumed by the engine under the given test condition in a given time. The fuel consumption of an engine depends principally upon the heating value of the fuel, the air-fuel ratio and the efficiency of the engine process (Srivastava & Verma 2008). Specific fuel consumption is defined as the amount of fuel consumed per unit of power developed per hour (Mathur & Sharma 1989).

The specific fuel consumptions (SFC) with load for DPN, DPC and DNC blends are as shown in Figure 5.33. From the test results, the SFC of DPN blends show lower values than those of the DPC and DNC blends. For all the fuels tested, SFC value decreased with increase in the engine load. This reduction is due to the higher percentage of increase in the brake power with load as compared to fuel consumption (Raheman & Phadatare 2004).

![Figure 5.33 Variations of SFC with load for DPN, DPC and DNC blends](image)

**Figure 5.33 Variations of SFC with load for DPN, DPC and DNC blends**
The variations of SFC with load for DPJ, DCJ and DNJ blends are shown in Figure 5.34. The SFC of the DPJ blends is lower than those of the DCJ and DNJ blends. The low proportions of dual biodiesel blends have closer value of SFC with diesel. The high proportions of dual biodiesel blends have higher SFC than diesel. This is due to the decrease in the calorific value of fuel with an increase in dual biodiesel percentage in the blends.

**Figure 5.34 Variations of SFC with load for DPJ, DCJ and DNJ blends.**

Figures 5.33 and 5.34 show that DPN 1, DPN 2 and DPJ 1 are closer to diesel fuel shown in Figure 5.35. The variations of DPN 1 give 9% lower SFC with diesel in minimum load and gives 2% lower SFC with diesel in maximum load. This is due to the lower calorific value with an increase in the biodiesel percentage in the blends. The same trend was in good agreement with the previous literature (Raheman & Phadatare 2004).
5.3.2 Brake Specific Energy Consumption

Brake specific energy consumption (BSEC) is used to evaluate the engine performance of fuels having dissimilar calorific values. BSEC is an ideal variable because it varies with the calorific value of the particular fuel. It is a more reliable parameter to compare the volumetric consumption of the two fuels.

The brake specific energy consumption of DPN, DPC and DNC dual biodiesel blends is shown in Figure 5.36. It shows that the BSEC is lower for all dual biodiesel blends compared to diesel. The same trend was in good agreement with the previous literature (Agarwal & Rajamanoharan 2009). The BSEC of DPN 1, DPC 1 and DNC 1 is 3.7%, 2.2% and 1.4% lower than that of diesel.

The low specific energy consumption is due to the high oxygen content available with the dual biodiesel and the lower energy content of the dual biodiesel as shown in Figure 5.4, Figure 5.5 and Figure 5.6. Hence, the
brake specific energy consumption of the dual biodiesel blends increases as compared to that of diesel.

Figure 5.36 Variations of BSEC with load for DPN, DPC and DNC

The brake specific energy consumption of DPJ, DCJ and DNJ dual biodiesel blends is shown in Figure 5.37. The BSEC of DPJ 1, DCJ 1 and DNJ 1 is 2.4%, 2% and 1.5% lower than that of diesel.

Figure 5.37 Variations of BSEC with load for DPJ, DCJ and DNJ
Figure 5.38 shows the comparison of BSEC for optimum dual biodiesel blends. The brake specific energy consumption of DPN 1 is lower than those of the other dual biodiesel blends.

![Figure 5.38 BSEC for optimum dual biodiesel](image)

### 5.3.3 Brake Thermal Efficiency

Brake thermal efficiency is the ratio between the brake power output and the energy introduced through fuel injection. The effect of the brake power on the brake thermal efficiency of the single biodiesels of pongamia pinnata biodiesel (PB), jatropha biodiesel (JB), cotton seed biodiesel (CB) and neem biodiesel (NB) is shown in Figure 5.39. The results show that the thermal efficiency of jatropha biodiesel is higher than those of the other single biodiesels.
Figure 5.39 Effect of thermal efficiency with BP for PB, JB, CB and NB

The effect of the brake power on the brake thermal efficiency of DPN, DPC and DNC dual biodiesel blends is shown in Figure 5.40. It is observed that the brake thermal efficiency increases with increase in the brake power. There is a steady increase in the efficiency as the brake power increases in the diesel and the blends of the dual biodiesel operations. The thermal efficiency of dual biodiesel is higher than that of any single biodiesel. The thermal efficiency of the DPN blends is higher than those of DPC and DNC blends. This is due to the better combustion and additional lubricity of the dual biodiesel. The molecules of the dual biodiesels contain some amount of oxygen, which takes active part in the combustion process.

Figure 5.40 Effect of thermal efficiency with BP for DPN, DPC and DNC
The thermal efficiency of the DPJ, DCJ and DNJ dual biodiesel blends is shown in Figure 5.41. The thermal efficiency of DPJ dual biodiesel blends is higher than that of DCJ and DNJ blends. The DCJ and DNJ blends have lower thermal efficiency. This is due to the poor mixture formation caused by the low volatility, higher viscosity and density of the tested fuels.

The brake thermal efficiency of DPJ and DPN blends is higher than that of other dual biodiesel blends and this is due to its higher calorific value. The other dual biodiesel blends have lower brake thermal efficiency than diesel fuel which is due to a reduction in the calorific value and an increase in the fuel consumption as compared to DPJ 1 and DPN 1.

![Figure 5.41 Effect of thermal efficiency with BP for DPJ, DCJ and DNJ](image)

The thermal efficiency of the optimum dual biodiesel blends is shown in Figure 5.42. The thermal efficiency of DPN 1, DPN 2, DPJ 1 and DPJ 2 is 2.6 %, 4.9%, 1.1% and 4.2% lower than that of diesel. The same trend was in good agreement with the previous literature (Pramanik, 2003). DPJ 1 and DPN 1 are closer to the diesel values.
5.3.4 Exhaust Temperature

The exhaust gas temperature provides qualitative information about the progress of combustion in an engine. The exhaust temperatures of DPN, DPC and DNC blends are shown in Figure 5.43 and the exhaust temperatures of DPJ, DCJ and DNJ blends are shown in Figure 5.44. It is observed that exhaust gas temperature is increased with an increase in the brake power. The dual biodiesel blends have higher exhaust gas temperature than diesel fuel. The same trend was reported by Pramanik (2003). This is due to oxygen molecule present in the dual biodiesel which enhances the combustion process and thus increases the temperature.

The exhaust temperatures of DPN blends are lower than those of the DPC and DNC blends. The exhaust temperatures of DPJ blends are lower than those of the DCJ and DNJ blends. This is due to the lower viscosity and better volatility than the other dual biodiesel blends.
The exhaust temperature of the optimum dual biodiesel is shown in Figure 5.45. Figures 5.43 and 5.44 show that DPN 1, DPC 1, DNC 1, DPJ 1, DCJ 1, DNJ 1 have the optimum dual biodiesel blends. The exhaust temperature of the DPN 1 blend is lower than those of the other dual biodiesel blends. The exhaust temperature of DPN 1 blend is 1.6% higher than that of diesel.
5.4 EMISSION CHARACTERISTICS

The exhaust gas emissions emitted from the diesel engine with dual biodiesel blends as fuel are analyzed. In this section carbon monoxide emission, carbon dioxides, hydrocarbon, nitrogen oxides and smoke opacity are experimentally tested and discussed.

5.4.1 Carbon Monoxide Emission (CO)

The formation of CO is attributed to the fuel oxidation from combustion. The major contributor to CO formation is insufficient time for complete combustion and oxygen for the oxidation of CO to CO$_2$. The variations of carbon monoxide emission on the brake power of DPN, DPC and DNC dual biodiesel blends are shown in Figure 5.46. It can be noticed that CO emissions increases with increasing brake power. This is due to the increase in the peak combustion temperature with the associated increase in the rate of dissociation reaction.
The CO emission of DPN blends is lower than those of the DPC and DNC blends. This is due to the high oxygen content in the biodiesel which makes easy burning at higher temperature in the cylinder. The other blends give higher CO emissions than pure diesel and this is due to the high viscosity and higher engine load.

The test results indicate that DPN 1, DPN 2, DPN 3, DPN 4, DPN 5, DPN 6, DPC 1, DPC 2, DPC 3, DNC 1 and DNC 2 blends give low CO emissions than diesel fuel.

![Figure 5.46 Effect of CO on BP for DPN, DPC and DNC blends](image)

The effects of CO on the brake power of DPJ, DCJ and DNJ are shown in Figure 5.47. The CO emission of DPJ blends is lower than those of DCJ and DNJ blends. The test result indicates that DPJ 1, DPJ 2, DPJ 3, DPJ 4, DPJ 5, DCJ 1, DCJ 2 and DNJ 1 blends give low CO emissions than diesel fuel. This is also evident from the low CO emissions from the biodiesel engine (Raheman & Phadatare 2004).
Figure 5.47 Effect of CO on BP for DPJ, DCJ and DNJ blends

The effects of CO on the brake power for optimum dual biodiesels are shown in Figure 5.48. The DPN blends give 8% to 50% lower carbon monoxide emissions compared with diesel. The DPJ blends give 8% to 42% lower CO emissions than diesel.

Figure 5.48 Effect of CO on BP for optimum dual biodiesel
5.4.2 Carbon Dioxide Emission (CO$_2$)

The carbon cycle of biodiesel is dynamic through the photosynthesis process. The plants give the biodiesel which is absorbed by the CO$_2$ emission delivered by the engines. Hence, the dual biodiesel can minimize the CO$_2$ emission and shelter the global environment and keep the environmental stability.

The variations of carbon dioxide emission on load for DPN, DPC and DNC dual biodiesel blends are shown in Figure 5.49. It is inferred that all the tested dual biodiesel blends produce high amount of CO$_2$ in comparison with diesel, because it is an indication of efficient combustion. It is desirable in the combustion process to have higher CO$_2$ production and less HC and CO emissions since it is a measure of combustion efficiency.

The CO$_2$ emission of DPN blends is lower than that of DPC and DNC blends. DPN blends emit 2.4% to 9.6% higher carbon dioxide emission compared with diesel fuel.

Figure 5.49 Effect of CO$_2$ on load for DPN, DPC and DNC
The effects of CO\textsubscript{2} on load for DPJ, DCJ and DNJ are shown in Figure 5.50. The CO\textsubscript{2} emission of DPJ blends is lower than that of DCJ and DNJ blends.

![Figure 5.50 Effect of CO\textsubscript{2} on load for DPJ, DCJ and DNJ](image1)

The effects of carbon dioxide on load for optimized dual biodiesel are shown in Figure 5.51. The CO\textsubscript{2} of DPN 1, DPN 2 and DPJ 1 are 2.4%, 3.1% and 6% higher than that of diesel fuel. The similar trend was reported by Nwafor (2004). The test results show that the DPN blends are better than DPJ blends.

![Figure 5.51 Effect of CO\textsubscript{2} on load for optimum dual biodiesel](image2)
5.4.3 Hydrocarbon Emission (HC)

Unburnt hydrocarbon is also an important parameter for determining the emission behavior of the engines. Unburnt hydrocarbon emission is the direct result of incomplete combustion. It can be observed from Figure 5.52 and Figure 5.53 that the HC emission increases with an increase in load. Dual biodiesel blends create lower HC emission than diesel. The DPN blends produce 30% to 55% lower HC than diesel fuel. The HC emission of DPN blends is lower than that of the DPC and DNC blends.

Figure 5.52 Variations of HC on load for DPN, DPC and DNC blends

Figure 5.53 Variations of HC on load for DPJ, DCJ and DNJ blends

The HC emission of DPJ blends is lower than that of DCJ and DNJ blends. For the maximum load, the hydrocarbon emission is 9 ppm in
DPN 1, 12 ppm in DPC 1, 18 ppm in DNC 1, 10 ppm in DPJ 1, 13 ppm in DCJ 1 and 16 ppm in DNJ 1 whereas diesel gives 20 ppm.

The variations of hydrocarbon emission on the load for the optimum dual biodiesel blends are shown in Figure 5.54. The HC emission of DPN 1 and DPJ 1 blends is 55% and 50% lower than that of diesel fuel. The reduction in HC emission on biodiesel engine was reported by Sahoo et al (2007).

![Figure 5.54 Variations of HC on load for optimum dual biodiesel](image)

**5.4.4 Nitrogen Oxides**

The variations of NOx emission on brake power for DPN, DPC and DNC dual biodiesel blends are depicted in Figure 5.55 and the effects of NOx emission on the brake power of DPJ, DCJ and DNJ dual biodiesel blends are as shown in Figure 5.56. It conveys that the dual biodiesel blends show higher NOx emission than diesel. This is also evident from the higher exhaust temperature from the biodiesel engine (Srivastava & Verma 2008).
Oxides of nitrogen in the engine exhaust are a combination of nitric oxide (NO) and nitrogen dioxide (NO₂). Nitrogen and oxygen react at relatively high temperatures. Therefore, high temperatures and availability of oxygen are the two main reasons for the formation of NOx. Also, as the load increases, the temperature of the combustion chamber increases and NO formation also increases (Srivastava and Verma 2008), (Banapurmath et al 2008).

The NOx emissions of DPN blends are lower than those of DPC and DNC dual biodiesel blends. NOx emission of the DPN 1 is nearer to that of diesel. The NOx emissions of DPJ blends are lower than those of the DCJ and DNJ dual biodiesel blends.

Figure 5.55 Variations of BP on NOx for DPN, DPC and DNC

Figure 5.56 Variations of BP on NOx for DPJ, DCJ and DNJ
The DNJ and DNC dual biodiesel blends emit high temperature exhaust gases. The nitrogen oxide emissions emitted by DNJ and DNC blends are higher than those of the other dual biodiesel blends.

The nitrogen oxides for the optimum dual biodiesel blends are shown in Figure 5.57. The NOx emissions of optimum blends, DPN 1, DPN 2, DPJ 1 and DPC 1 are 1.2%, 3%, 1.5% and 2.4% higher than that of diesel fuel.

![Figure 5.57 NOx for optimum dual biodiesel](image)

5.4.5 Smoke Opacity

The variation of the smoke opacity of DPN, DPC and DNC dual biodiesel blends as a function of load is presented in Figure 5.58 and the effect of smoke opacity on the load for DPJ, DCJ and DNJ dual biodiesel blends is shown in Figure 5.59. It can be noticed that the smoke emissions of DPN 1, DPN 2, DPN 3, DPC 1, DPJ 1 and DPJ 2 blends are lower, while compared to that of diesel fuel. The smoke opacity of DPN 1 is 9% lower than that of diesel.
The reason for the lower smoke density for the dual biodiesel blends may be better and the complete combustion of fuel is due to oxygen atom present in the molecule of biodiesel itself. The other blends have higher smoke opacity than diesel. The heavier molecules of biodiesel, higher density and viscosity of dual biodiesel blends are the reason for more smoke emissions as compared to diesel.

Figure 5.58 Variations of smoke on load for DPN, DPC and DNC

Figure 5.59 Variations of smoke on load for DPJ, DCJ and DNJ

The variations of smoke on the load for the optimum dual biodiesel blends are shown in Figure 5.60. The DPN 1, DPN 2, DPN 3, DPJ 1, DPJ 2
and DPC 1 dual biodiesel blends give lower smoke than diesel fuel. This is also evident from the low smoke emissions on the biodiesel engine (Raheman & Phadatare 2004). The blends of DPN give lower smoke opacity than other dual biodiesel blends.

![Smoke opacity for optimum dual biodiesel](image)

**Figure 5.60 Smoke opacity for optimum dual biodiesel**

### 5.5 EXERGY ANALYSIS

The diesel engine is experimented with different kinds of dual biodiesel blends to evaluate the exergy. The exergy analysis of the engine is calculated from the principle of 2\textsuperscript{nd} law of thermodynamics. From the exergy analysis, the input exergy (availability) of the test fuel, engine shaft exergy, cooling water exergy, exhaust gas exergy, destructive exergy and exergy efficiency are calculated and analyzed in this section.
The input availability of DPN and DPJ fuel is shown in Figure 5.61. It provides the input exergy values of the dual biodiesel test fuels. The input availability of the dual biodiesel blends is calculated from the mass flow rate, heat content of the fuel, hydrogen to carbon ratio and oxygen to carbon ratio of the fuel. More input availability is required for any fuel. The input availability of the DPN fuel is higher than that of DPJ fuel. For the maximum load DPN fuel is 0.6% to 1.1% higher than DPJ fuel. From the results it is clear that DPN dual biodiesel provides better input availability than other dual biodiesel blends.

The input availability of DPC and DCJ fuel is shown in Figure 5.62. The input availability of DCJ dual biodiesel blends is higher than those of the DPC blends. For the low load conditions, the input availability of the DCJ blends are 0.7% to 1.4% higher than that of the DPC blends whereas at the maximum load conditions the input availability of DCJ blends are 0.3% to 0.6% higher than those of the DPC blends.
Figure 5.62 Input availability of DPC and DCJ fuel

The input availability of the DNJ and DNC dual biodiesel blends is shown in Figure 5.63. The input availability of the DNJ dual biodiesel blends is higher than those of the DNC blends. For the low load conditions, the input availability of DNJ blends is 0.14% to 1.5% higher than those of the DNC blends whereas at the maximum load conditions the input availability of the DNJ blends is 0.3% to 0.6% higher than those of the DNC blends.

Figure 5.63 Input availability of DNJ and DNC fuel

The destruction of exergy \((A_d)\) is the important factor of the system inefficiency. From the exergy analysis, it is found that the actual exergy losses are insignificant compared to the irreversibility losses in the engine. In
this study, the destructive availability of the DPN blends is higher than those of the other dual biodiesel blends. This is due to the fact that the net calorific values of DPN blends are greater than those of the other dual biodiesel blends.

Destructed availability (exergy) of DPN, DPJ and DPC dual biodiesel blends are shown in Figure 5.64. The destructed availability of the DPN dual biodiesel blends is higher than those of DPJ and DPC blends. The DPN blends have 2.4% to 2.7% higher than DPJ blends and 6.8% to 8.6% higher than DPC blends.

![Figure 5.64 Destructed availability of DPN, DPJ and DPC fuel](image)

The destructed availability of DCJ, DNJ and DNC fuel is shown in Figure 5.65. The destructed availability of the DCJ dual biodiesel blends is higher than those of the DNJ and DNC blends. The DCJ blends have 1.9% to 2.3% higher than DNJ blends and 3.3% to 3.7% higher than DNC blends.

![Figure 5.65 Destructed availability of DCJ, DNJ and DNC fuel](image)
The exergy efficiency takes into account of the first law and the second law of thermodynamics. It provides a better measure of the performance for a thermal system. The effects of load on the exergy efficiencies of DPN and DPJ dual biodiesel blends are shown in Figure 5.66. The DPN blends have 1.2% to 2% higher exergy efficiency than DPJ blends. This is due to the calorific values of the DPN blends which are higher than those of the DPJ dual biodiesel blends.

![Figure 5.66 Effect of load on exergy efficiencies for DPN and DPJ](image)

The effects of load on the exergy efficiencies for DPC and DCJ dual biodiesel blends are shown in Figure 5.67. The DCJ blends have higher exergy efficiency than DPC dual biodiesel blends. The DCJ blends have 1.3% to 1.6% higher exergy efficiency than DPC blends. This is due to the calorific values of the DCJ blends which are higher than those of the DPC dual biodiesel blends.
The effects of load on the exergy efficiencies for DNJ and DNC dual biodiesel blends are shown in Figure 5.68. The DNJ blends have higher exergy efficiency than DNC dual biodiesel blends. The DNJ blends have 2.1% to 2.7% higher exergy efficiency than DNC blends. This is due to the calorific values of the DNJ blends which are higher than those of the DNC dual biodiesel blends.

The DPN blends have higher exergy efficiency than all other dual biodiesel blends. This is due to the calorific values of the DPN blends which are higher than other dual biodiesel blends and it is discussed in the section 5.2.1.
5.6 OPTIMUM DUAL BIODIESEL

From the performance analysis, DPN dual biodiesel blends and DPJ dual biodiesel blends have performed better than the other tested blends. The thermal efficiency and specific fuel consumption of the DPN blends and DPJ blends are comparable to each other. However, from the emission analysis, DPN dual biodiesel blends have emitted less HC, CO, CO$_2$, NOx and smoke opacity emissions than DPJ blends and other tested dual biodiesel blends. Moreover, the exergy analysis shows that the DPN dual biodiesel blends have performed better than other blends. On the whole, DPN dual biodiesel blends have performed better than other blends. Hence, further experimental work to enhance the performance analysis and emission analysis is carried out only with DPN dual biodiesel blends.

The optimum dual biodiesel performance characteristics are further increased by (i) adding additives, (ii) using LHR engine, (iii) preheating the dual biodiesel using waste heat recovery heat exchanger.
5.7 PERFORMANCE AND EMISSION ANALYSIS WITH ADDITIVES

The performance analysis and the emission analysis of the DPN dual biodiesel blends (DPN 1, DPN 2, DPN 3 and DPN 4) with three different additives namely, i) Ethanol, ii) diethyl ether and iii) 2-methoxy ethyl acetate are carried out and discussed in this section.

5.7.1 Specific Fuel Consumption for Dual Biodiesel with Additives

The effect of additives on BSFC for DPN 1 and DPN 2 dual biodiesel is shown in Figure 5.69 and the variations of BSFC with the additives for DPN 3 and DPN 4 is as shown in Figure 5.70. As the engine load increases, the SFC is reduced for all the dual biodiesel blends with additives.

![Figure 5.69 Effect of additives on BSFC](image-url)
Figure 5.70 Variations of BSFC with additives

From the results, the SFC of DPN 1 blend combined with ethanol is 2.5% to 2.8% lower than that of DPN blends and 5.5% to 11% lower than that of diesel. Similarly, DPN 1 blend combined with diethyl ether (DEE) has 6.25% to 20% lower SFC than the DPN blends and 13.6% to 22% lower than diesel. The SFC of 2-methoxy ethyl acetate (MEA) blended DPN 1 is higher than those of the other fuels.

The SFC of DPN 1 with DEE additive is lower than those of all the other tested fuels. DEE and ethanol have higher volatility than MEA, which improves the combustion process and hence has lower SFC.

The SFC of DPN 4 blend combined with ethanol is 1.35% to 4.5% lower than those of the DPN blends and 2.7% to 3.4% lower than that of diesel. Similarly, DPN 4 blend combined with diethyl ether (DEE) has 7.8% to 9.5% lower SFC than DPN blends and 6.8% to 8.33% lower than diesel. The SFC of 2-methoxy ethyl acetate (MEA) blended DPN blends is higher than those of the other fuels. The similar trend was reported by Yanfeng et al (2007).
5.7.2 Thermal Efficiency for Dual Biodiesel with Additives

The effects of brake thermal efficiency of DPN 1 and DPN 2 dual biodiesel with different additives are shown in Figure 5.71. The DPN 1 with ethanol gives 4.8% higher thermal efficiency than DPN 1 dual biodiesel. The DPN 1 with DEE gives 17.4% higher thermal efficiency than DPN 1 dual biodiesel. The DPN 1 with MEA gives 20% higher thermal efficiency than DPN 1 dual biodiesel.

The DPN 2 with ethanol gives 19% higher thermal efficiency than DPN 2 dual biodiesel. The DPN 2 with DEE gives 21.3% higher thermal efficiency than DPN 2 dual biodiesel. The DPN 2 with MEA gives 24.5% higher thermal efficiency than DPN 2 dual biodiesel. The DPN 2 with MEA gives higher thermal efficiency than other other additives blended test fuels.

The brake thermal efficiency of the dual biodiesel has improved with the adding of oxygenated additives to the dual biodiesels in the blend. The similar trend was reported by Yanfeng et al (2007). This is due to the additional volatility provided by the additives. The molecules of the dual biodiesels and additives have contained some amount of oxygen, which takes active part in the combustion process.

![Figure 5.71 Effect of additives on thermal efficiency](image)

Figure 5.71 Effect of additives on thermal efficiency
The variations of brake thermal efficiency with additives for DPN 3 and DPN 4 dual biodiesel are shown in Figure 5.72. The DPN 3 with ethanol, DPN 3 with DEE and DPN 3 with MEA give 23%, 25% and 27% higher thermal efficiency than DPN 3 dual biodiesel. The DPN 4 with ethanol, DPN 4 with DEE and DPN 4 with MEA give 25%, 28% and 29% higher thermal efficiency than the DPN 4 dual biodiesel. The DPN 4 with MEA gives higher thermal efficiency than the other other additives blended test fuels.

![Figure 5.72 Variations of thermal efficiency with additives](image)

It can be also observed that MEA additive with dual biodiesel gives the maximum thermal efficiency compared to the other blends, DEE additive with dual biodiesel and ethanol additive dual biodiesel gives better brake thermal efficiency than the dual biodiesel and diesel at the same brake power.

5.7.3 Exhaust Temperature for Dual Biodiesel with Additives

The effects of additives on exhaust temperature for DPN 1 and DPN 2 are shown in Figure 5.73. The DPN 1 with ethanol and DPN 1 with MEA give 1% and 3% higher exhaust temperature than DPN 1 dual biodiesel. The DPN 2 with ethanol and DPN 2 with MEA give 0.3% and 3% higher
thermal efficiency than the DPN 2 dual biodiesel. DPN 1 with DEE gives lower exhaust temperature than DPN and its other additives.

![Diagram showing exhaust temperature variations with additives for DPN 3 and DPN 4.](image)

**Figure 5.73 Effect of additives on exhaust temperature**

The variations of exhaust temperature with additives for DPN 3 and DPN 4 are shown in Figure 5.74. The DPN 3 with MEA and DPN 4 with MEA give 2.7% and 1.2% higher exhaust gas than the DPN 3 and DPN 4 dual biodiesel. Exhaust temperature increases with increase in the engine load in all cases. Exhaust gas temperature is an indicative of the quality of combustion in the combustion chamber. Dual biodiesel with ethanol additive fuel and dual biodiesel with MEA additive fuel higher exhaust temperature than the dual biodiesel and diesel for all the loads. However, dual biodiesel with DEE have less exhaust gas temperature than the DPN dual biodiesel and other additive blended fuels.
5.7.4 Hydrocarbon Emission for Dual Biodiesel with Additives

The variations of HC on DPN 1 and DPN 2 with additives are shown in Figure 5.75. The results show that the DPN 1 and DPN 2 with MEA emit 11% and 10% lower HC than DPN 1 and DPN 2 respectively. Hydrocarbon emission for DPN 1 and DPN 2 with ethanol and DEE are higher than those for standard DPN dual biodiesel blends.
The effects of additives on HC for DPN 3 and DPN 4 are shown in Figure 5.76. DPN 3 and DPN 4 with ethanol and DEE emit higher HC than the DPN blends. The results show that the DPN blends with MEA give lesser HC than the other blends. Similar trend is reported by Yanfeng et al (2007).

![Figure 5.76 Effect of additives on hydrocarbon emission](image)

5.7.5 Carbon Monoxide Emission for Dual Biodiesel with Additives

The effects of brake power on carbon monoxide for DPN 1 and DPN 2 blends with additives are shown in Figure 5.77 and the variations of CO emission with additives for DPN 3 and DPN 4 are shown in Figure 5.78 respectively. The CO emission for DPN 1+ MEA is 16% lower than that for DPN 1. However, DPN 1+E and DPN 1+DEE have emitted 14% and 33% higher CO than DPN 1. Similar trend is followed in all the other DPN blends. The similar trend was reported by Qi et al (2011) and Yanfeng et al (2007). On the whole, DPN blends with MEA give lower CO than diesel and all other tested fuels. The ethanol mixed DPN blends and DEE mixed DPN blends give higher CO emission than the standard DPN blends. Moreover, ethanol and DEE mixed DPN blends emit lower emission than
diesel. This is due to the oxygen content in the dual biodiesel and additives, which make easy burning at higher temperature in the cylinder.

![Figure 5.77 Effect of additives on carbon monoxide emission](image1)

![Figure 5.78 Variations of carbon monoxide with additives](image2)

**Figure 5.77 Effect of additives on carbon monoxide emission**

**Figure 5.78 Variations of carbon monoxide with additives**

### 5.7.6 Carbon dioxide emission for dual biodiesel with additives

Figure 5.79 depicts the CO$_2$ emission of DPN 1 and DPN 2 with additives and Figure 5.80 shows the CO$_2$ emission of DPN 1 and DPN 2 with additives. From the results it is clear that DPN 1+DEE, DPN 2+DEE, DPN 3+DEE and DPN 4+DEE have emitted 5.4%, 6.6%, 8.4% and 9.8% lower
CO2 than DPN 1. It is also inferred that CO2 emission for the DPN blends with ethanol, DPN blends with DEE and DPN blends with MEA have emitted lower CO2 than those for DPN blends. Moreover, DPN blends with DEE have emitted lower CO2 emission than the other two additive mixed DPN blends. This is due to the oxygen content in the dual biodiesel with DEE additive blends and they also have higher calorific value than the other blends making easy burning at higher temperature in the cylinder.

![Graph](image)

**Figure 5.79** Effect of additives on Carbon dioxide emission

![Graph](image)

**Figure 5.80** Variations of CO2 with additives
5.7.7 Nitrogen Oxides Emission for Dual Biodiesel with Additives

The effects of engine load on Nitrogen oxides for DPN 1 and DPN 2 with additives are shown in Figure 5.81 and the variations of NOx on DPN 3 and DPN 4 with additives are shown in Figure 5.82. The Nitrogen oxides (NOx) are increased by increasing the load for each blend. For the maximum load, DPN 1 gives 324 ppm whereas diesel gives 320 ppm, DPN 1+E gives 330 ppm, DPN 1+DEE gives 322 ppm and DPN 1+MEA gives 340 ppm for the same maximum load. DPN 2+DEE, DPN 3+DEE and DPN 4+DEE emit 1.5%, 1.4% and 1.7% lower NOx than the standard DPN blends.

Figure 5.81 Effect of additives on Nitrogen Oxides

Figure 5.82 Variations of NOx with additives
The results show that the DPN blends with DEE give lesser NOx than DPN blends and the other additive mixed DPN blends. The similar trend was reported by Pugazhvadivu & Rajagopan (2009). The vegetable oil-based biodiesel contains a small amount of nitrogen. This contributes towards NOx production. The average gas temperature, the presence of fuel oxygen and residence time at higher load conditions with the blend combustion caused lower NOx emissions.

5.7.8 Smoke Opacity Emission for Dual Biodiesel with Additives

It is observed from Figure 5.83 and Figure 5.84, the smoke percentage increases with the increase in the engine load. For the maximum load, the smoke for diesel is 33%, whereas DPN 1 gives 30%, DPN 1+E gives 26%, DPN 1+DEE gives 23% and DPN 1+MEA gives 15% with the same maximum load. The DPN blends with ethanol, DEE and MEA additives give lower smoke than the standard DPN blends. MEA additive with DPN blends gives 48% to 54% lower smoke opacity than diesel. The same trend is reported by Yanfeng et al (2007) and Pugazhvadivu & Rajagopan (2009).

![Figure 5.83 Effect of additives on smoke emission](image)
The dual biodiesel of pongamia pinnata oil and neem oil and its blends (DPN 1, DPN 2, DPN 3 and DPN 4) were evaluated with respect to diesel. Experiments were conducted using each fuel thrice for the coated engine and the uncoated engine. The performance and emission analysis of the both the engines was evaluated experimentally with several parameters such as thermal efficiency, brake specific fuel consumption, exhaust gas temperature, hydrocarbon emission, carbon monoxide, carbon dioxide, nitrogen oxides and smoke opacity emission.

The effects of brake thermal efficiency with diesel fuel and dual biodiesel at different loads for both baseline engine and coated engine (CE) are shown in Figure 5.85. From the test results, it is observed that there is a significant increase in efficiency with increase in the load. The thermal efficiency of diesel with baseline engine is 26.3% and those of the dual biodiesel blends DPN 1, DPN 2, DPN 3 and DPN 4 are 25.6%, 25%, 24% and 23.5% whereas those of DPN 1 CE, DPN 2 CE, DPN 3 CE and DPN 4 CE are 29.3%, 28%, 26% and 24.6% respectively.
Figure 5.85 Effect of load on brake thermal efficiency for LHR engine

The thermal efficiency of DPN 1 CE and DPN 2 CE is higher than the other dual biodiesel blends and diesel fuel in the base line engine. The difference between the DPN 1 CE and diesel fuel in the baseline engine is 3%. It is evident that the performance is increased more in all the cases in coated engine than that of the baseline engine. The similar trend is reported by Banapurmath & Tiwari (2009) and Haşimoğlu et al (2008). The specific fuel consumption to the engine in the case of coated engine is less compared to baseline engine which results in increase in efficiency for all the loads.

A comparison of the BSFC for the baseline engine and the coated engine (CE) under different load is shown in Figure 5.86. The BSFC values of DPN 1 CE, DPN 2 CE and DPN 4 CE are 0.31 kg/kWh, 0.32 kg/kWh, 0.34 kg/kWh and 0.37 kg/kWh whereas diesel fuel in baseline engine has 0.36 kg/kWh with maximum load. Specific fuel consumption of the coated engine is lower than that of the baseline engine (Hazar, 2009). Because of the higher surface temperatures of its combustion chamber, the BSFC values of the LHR engine except DPN 4 and DPN 4 CE are lower than those of the baseline engine. Due to higher viscosity and lower calorific value, DPN 4 and DPN 4 CE give higher BSFC.
Figure 5.86 Variations of load on BSFC for LHR engine

The variations of exhaust temperature with load for diesel fuel and dual biodiesel in both the coated engine and the baseline engine is shown in Figure 5.87. Diesel fuel and dual biodiesel in the coated engine indicate a higher exhaust temperature than the baseline engine. This increase in the exhaust gas temperatures for all the test fuels in the CE engine is a result of the decrease in the heat used for cooling and transfer of this heat to the exhaust gases as a result of thermal barrier (Hazar, 2010). For the maximum load, DPN 1 CE, DPN 2 CE and DPN 4 CE give 360°C, 364°C, 369°C and 375°C whereas the diesel fuel in the baseline engine, DPN 1, DPN 2 and DPN 4 gives 300°C, 305°C, 309°C, 315°C and 322°C. The temperature difference between diesel fuel and the dual biodiesel blends in CE is between 60°C and 75°C at the maximum load.
Figure 5.87 Effect of load on exhaust temperatures for LHR engine

Figure 5.88 shows the variations of hydrocarbon emissions depending on the load of the engine. HC emission is low in the coated engine compared with the dual biodiesel blends in the baseline engine for all the test fuels due to the ceramic coating. The HC values of DPN 1 CE, DPN 2 CE, DPN 3 CE and DPN 4 CE are 8 ppm, 8 ppm, 9 ppm and 10 ppm, whereas diesel fuel in the baseline engine has 20 ppm with maximum load. DPN blend fuels in the coated engine give 50% to 60% lower HC emission level compared with that of the reference diesel fuel in the baseline engine. HC emission of the coated engine is lower than that of the baseline engine Banapurmath & Tiwari (2009). The emission of unburned hydrocarbon from the coated engines is more likely to be reduced because of the decreased quenching distance and the increased lean flammability limit. The higher temperatures in the gases and at the combustion chamber walls of the coated engine assist in permitting the oxidation reactions to proceed close to completion.
Figure 5.88 Variations of load on hydrocarbon emission for LHR engine

Figure 5.89 illustrates the effects of carbon monoxide with load for the different fuels. Carbon monoxide (CO) emission is caused by incomplete combustion and it depends mainly on the engine temperature and air/fuel ratio. CO emission is lower in the coated engine, compared with the baseline engine for the dual biodiesels as test fuels. DPN blends (DPN 1 CE, DPN 2 CE and DPN 4 CE) in the coated engine give 33% to 58% lower CO than the reference baseline diesel fuel. This decrease occurs as a result of higher combustion efficiency due to the higher temperatures obtained by the coating. The similar trend is reported by Banapurmath & Tiwari (2009). As the local factors such as temperature, pressure, mixture ratio and oxygen content in the combustion chamber affect combustion and its sustainability in the internal combustion engines, it is seen clearly that ceramic coating improved these local factors.
Figure 5.89 Effect of load on CO emission for LHR engine

The variations of carbon dioxide with load for diesel fuel and dual biodiesel in both the coated engine and baseline engine are shown in Figure 5.90. The dual biodiesel blends (DPN 1 CE, DPN 2 CE and DPN 4 CE) in the coated engine give higher CO$_2$ than the baseline engine diesel fuel. As the local factors such as temperature, pressure, mixture ratio and oxygen content in the combustion chamber affect combustion and its sustainability in the internal combustion engines, it is seen clearly that ceramic coating improved these local factors.

Figure 5.90 Variations of load on CO$_2$ emission for LHR engine
Figure 5.91 shows the variations of nitrogen oxides with load for the different fuels. NOx emission increases in coated engine for all test fuels compared with the baseline engine. For the maximum load, the diesel fuel, DPN 1 CE, DPN 2 CE, DPN 3 CE and DPN 4 CE has 1.5%, 3.7%, 6.2% and 7.8% higher than the reference fuel in the baseline engine. The similar trend is reported by Hazar & Ozturk (2010) and Banapurmath & Tiwari (2009). The blends DPN 1 CE and DPN 2 CE are closer to the reference fuel. The NOx values of diesel fuel in CE, DPN 1 CE, DPN 2 CE and DPN 4 CE are 325 ppm, 332 ppm, 340 ppm and 345 ppm, whereas diesel fuel in the baseline engine has 320 ppm with maximum load. This increase in NOx emission in coated engine is the result of higher temperatures in the combustion chamber caused by the insulation.

![Figure 5.91 Variations of load on NOx emission for LHR engine](image)

Figure 5.92 shows the variations of smoke opacity with load. A significant decrease in the smoke opacity for all the test fuels occurred in the LHR engine as a result of the coating. For the maximum load, DPN 1 CE, DPN 2 CE, DPN 3 CE and DPN 4 CE have the smoke opacity values of 27.1%, 29%, 31% and 32% respectively whereas diesel fuel in the baseline engine has 33%. The smoke values of DPN 1 CE, DPN 2 CE, DPN 3 CE and DPN 4 CE are 17.9%, 12.1%, 6%, and 3% lower than that of the diesel fuel in
baseline engine. The similar trend is reported by Banapurmath & Tiwari (2009).

![Variations of smoke on load for LHR engine](image)

**Figure 5.92 Variations of smoke on load for LHR engine**

## 5.9 WASTE HEAT RECOVERY

The objective of this section is to preheat the DPN biodiesel using a double pipe exhaust gas heat exchanger which utilizes the waste heat from the exhaust gas. The DPN dual biodiesel temperature is maintained at a constant temperature of 60°C and then used as fuel for diesel engine. The performance and the exhaust emission characteristics of a diesel engine fuelled with heated DPN dual biodiesel blends are investigated.

### 5.9.1 Effects of Heat Transfer Enhancement

The double pipe heat exchanger performances are analysed and it is augmented by using the circular plate inserts. The inserts are fitted inside the inner tube of the double pipe heat exchanger. The dual biodiesel is passed through the inner tube and the exhaust gas from the diesel engine is passed through the outer tube of the heat exchanger. The heat exchanger heat transfer rate analyses are carried out with inserts and without inserts for five different
mass flow rates and three different pitch ratios. The circular plate inserts in
the inner tube of the heat exchanger generates better turbulence and thin
boundary layer. This results in an enhancement of the heat transfer rate over
that of the plain tube. The increase in the heat transfer rate with the circular
plate inserts are due to the augmented heat transfer surface area and prolonged
residence time of the flow in the tube enhancing the tangential and radial
turbulent fluctuation in the circular tube. Similar results and trend are
reported by Muthusamy et al (2013).

The presence of the circular plate insert provides a flow barrier in
the space between two consecutive inserts which increases the heat transfer.
The circular plate insert with pitch ratio 5 provides a higher heat transfer rate
compared to the plain tube, circular plate insert with pitch ratio 6 and circular
plate insert with pitch ratio 7.

From the experimental results, the variations of Nusselt number on
Reynolds number are shown in Figure 5.93. It is noted that Nusselt number
increases with the decrease in the pitch ratio. The experimental results of the
circular plate insert with pitch ratio 5 give the maximum heat transfer
coefficient. Small pitch ratio generates more flow barrier providing high
turbulent intensity and better heat transfer.
Figure 5.93 Effect of Nusselt number with Reynolds number

The Nusselt number for circular plate inserts with different pitch ratios is higher than the plain tube. The insert with pitch ratio 5 gives higher Nusselt number than the other inserts with pitch ratios. This is due to the circular inserts which disturb and slow down the DPN dual biodiesel flow. Hence, the DPN dual biodiesel absorbs more heat from the exhaust gas and the rate of heat transfer is increased.

The effect of friction factor on Reynolds number is shown in Figure 5.94. It depicts that friction factor decreases as the Reynolds number increases. This is due to the friction factor which is inversely proportional to Reynolds number (Friction factor, \( f = \frac{64}{Re} \)). The friction factor for the plain tube is lower than those for the other inserts with pitch ratio tube. The circular plate insert with pitch ratio 5 gives 32% higher friction factor than the plain tube. The circular plate insert with pitch ratio 6 and insert with pitch ratio 7 gives 24% and 17% higher friction factor than the plain tube. The circular plate insert with pitch ratio 5 provides to prolong the fluid flow inside the tube and hence, the contact on the tube walls is increased. Similar trends are reported by Muthusamy et al (2013).
The variations of effectiveness on the Reynolds number are shown in Figure 5.95. It depicts that the inner tube of the heat exchanger with the circular plate insert of pitch ratio 5 gives 19% higher effectiveness than the plain tube. The tube with circular plate insert of pitch ratio 6 and pitch ratio 7 gives 14% and 9% higher effectiveness than the plain tube. This is because the heat transfer rate is higher for the tube with inserts. Similar trends are reported by Muthusamy et al (2013).
Figure 5.95 Heat exchanger effectiveness on Reynolds number

5.9.2 Performance Enhancement with Preheated Fuel

The DPN dual biodiesel blends are heated by the exhaust gas utilized double pipe heat exchanger with the circular plate insert of pitch ratio 5. The performance and emission analysis with preheated DPN dual biodiesel are depicted in Figure 5.96 - Figure 5.99.
Figure 5.96 illustrates the effect of load on the brake thermal efficiency for the heated DPN heated blends. From the test results it is observed that the thermal efficiency of the preheated DPN blends is better than that of the unheated DPN blends. The thermal efficiency of heated (preheated) DPN 1, DPN 2, DPN 3 and DPN 4 are 1.5%, 3.1%, 5.8% and 6.7% higher than those of the unheated DPN 1, DPN 2, DPN 3 and DPN 4 respectively. As the temperature of the DPN blends increases, its viscosity decreases. Hence, the heated DPN blends have higher efficiency at all loads than the unheated DPN blends. Similar trends are reported by Agarwal & Rajamanoharan (2009).

![Figure 5.96 Effect of load on brake thermal efficiency for heated DPN](image)

The variations of the load on the carbon dioxide for the heated DPN blends are depicted in Figure 5.97. From the test results, it is observed that the carbon dioxide emission of the heated DPN blends is higher than that of the unheated DPN blends. The CO$_2$ of heated DPN 1, DPN 2, DPN 3 and DPN 1 are 3.3%, 8.5%, 12.7% and 2.2% higher than those of the unheated
DPN 1, DPN 2, DPN 3 and DPN 4 respectively. This is due to the volatility and calorific value of the heated DPN blends which induce complete combustion and results in the heated DPN blends have higher CO$_2$ at all the loads than the unheated DPN blends.

![Graph showing the variations of load on CO$_2$ for heated DPN](image)

**Figure 5.97 Variations of load on CO$_2$ for heated DPN**

The variations of load on nitrogen oxides for the heated DPN blends are depicted in Figure 5.98. The results show that the NOx emission of heated DPN blends is lower than that of the unheated DPN blends. The NOx emission of heated DPN 1, DPN 2, DPN 3 and DPN 1 are 0.6%, 1.5%, 1.5% and 0.6% lower than those of the unheated DPN 1, DPN 2, DPN 3 and DPN 4 respectively. Similar trends are reported by Agarwal & Rajamanoharan (2009). This is due to the oxygen content in the heated DPN blends which induces complete combustion. Hence the NOx emissions of heated DPN blends have lower NOx at all loads than that of the unheated DPN blends.
Figure 5.98 Variations of load on NOx for heated DPN

Figure 5.99 shows the variations of load on the smoke opacity for heated DPN blends. The smoke opacity of heated DPN 1, DPN 2, DPN 3 and DPN 4 are 3%, 3.2%, 6% and 5.9% lower than those of the unheated DPN 1, DPN 2, DPN 3 and DPN 4 respectively. This is due to the viscosity reduction as a result of preheating the DPN blends which have improved the volatility of the fuel which results in better combustion and low smoke opacity. Similar trends are reported by Agarwal & Rajamanoharan (2009).

Figure 5.99 Variations of load on smoke opacity for heated DPN