CHAPTER 5

RESULTS AND DISCUSSION

5.1 INTRODUCTION

In this chapter, the results of the experimental investigations carried out in a DI diesel engine using standard diesel and bio-fuels like poon oil, paradise oil and eucalyptus oil using different methods are discussed under the following heads.

- Blends of vegetable oils - standard diesel
- Blends of methyl esters of vegetable oils - standard diesel
- Blends of eucalyptus oil - standard diesel
- Blends of eucalyptus oil - methyl esters
- Eucalyptus oil with ignition enhancer

5.2 POON OIL AND ITS STANDARD DIESEL BLENDS

In this section the results of the experimental investigations carried out using standard diesel, neat poon oil and its diesel blends are presented.

5.2.1 Ignition delay

The variation of ignition delay with load for different poon oil blends and standard diesel is shown in Figure 5.1. It can be observed that
ignition delay is shorter for poon oil and its diesel blends compared to that of standard diesel. This may be due to the fact that the heavy molecular linoleic fatty acid present in the poon oil splits into lighter compounds when it enters the high temperature combustion chamber resulting in earlier ignition.

Figure 5.1  Variation of ignition delay with load for standard diesel, poon oil and its diesel blends

5.2.2  Cylinder peak pressure

The variation of the cylinder peak pressure with load for different poon oil blends and standard diesel is shown in Figure 5.2. The cylinder peak pressures for neat poon oil and its diesel blends are lower when compared to that of standard diesel. The lower cylinder peak pressure of neat poon oil may be due to slow vaporisation and slow combustion as a result of the high
viscosity of neat poon oil. Peak pressure mainly depends on the combustion rate in the initial stages, which is influenced by the fuel taking part in the premixed combustion heat release phase. However, blends produced comparable peak pressure with that of standard diesel, which may be due to the improvement in the preparation of the fuel air mixture as a result of the reduced viscosity of the blends.

![Graph showing variation of cylinder peak pressure with load for standard diesel, poon oil and its diesel blends](image)

**Figure 5.2** Variation of cylinder peak pressure with load for standard diesel, poon oil and its diesel blends

### 5.2.3 Maximum rate of pressure rise

The variation of the maximum rate of pressure rise with load for different poon oil blends and standard diesel is shown in Figure 5.3. The maximum rate of pressure rise is lower in the case of poon oil and its diesel blends compared to that of standard diesel operation. The high viscosity and low volatility of poon oil lead to poor atomisation and mixture preparation
with air during the ignition delay period which resulted in a lower rate of pressure rise.

![Graph showing the variation of maximum rate of pressure rise with load for standard diesel, poon oil, and its diesel blends.](image)

**Figure 5.3** Variation of maximum rate of pressure rise with load for standard diesel, poon oil and its diesel blends

### 5.2.4 Heat release rate

The variation of the heat release rate with load for different poon oil blends and standard diesel is shown in Figure 5.4. It is seen from the figure that the premixed heat release of poon oil and its blends is lower than that of standard diesel. The quantity of diffusion burning indicated by the area under the second peak is greater for neat poon oil. This is consistent with the expected effects of poon oil viscosity on the fuel spray, and the reduction of air entrainment and fuel/air mixing rates. At the time of ignition, less fuel/air mixture is prepared for combustion with poon oil; therefore, more burning occurs in the diffusion burning phase rather than in the premixed phase.
However, for lower blends like POON20, POON30 the premixed combustion is closer to that of standard diesel, which may be due to the lower viscosity of the blends when compared to that of standard diesel.

Figure 5.4  Variation of heat release rate with crank angle for standard diesel, poon oil and its diesel blends

5.2.5  Brake thermal efficiency

The variation of the brake thermal efficiency with load for different poon oil blends and standard diesel is shown in Figure 5.5. The brake thermal efficiencies of POON20 and POON30 blends are closer to that of standard diesel, which may be due to the closer combustion behavior of POON20 and POON30 blends than that of standard diesel. This may be due to lower viscosity of the blends of lower concentration of vegetable oils. However, the brake thermal efficiencies of neat poon oil and higher blends are very low.
owing to poor mixture formation, as a result of the low volatility and high viscosity of poon oil. High viscosity is believed to lead to higher droplet diameters, which, in combination with higher boiling points of fuel fractions compared to those of standard diesel, will result in poor combustion and lower brake thermal efficiency. It is also clear from the heat release rate analysis that the premixed heat release of poon oil and its diesel blends were lower than that of standard diesel. The brake thermal efficiencies of standard diesel, NEAT POON, and POON20 are 28.87 %, 25.27 % and 26.86 % respectively. Further, it is observed that the brake thermal efficiency decreases with an increasing proportion of poon oil in the blend.

![Graph showing brake thermal efficiency variation with load](image)

**Figure 5.5** Variation of brake thermal efficiency with load for standard diesel, poon oil and its diesel blends

### 5.2.6 Exhaust gas temperature

The variation of the exhaust gas temperature with load for different poon oil blends and standard diesel is shown in Figure 5.6. It can be observed
from the figure, that the exhaust gas temperature at full load for standard diesel, POON20 and NEAT POON are 396 ºC, 404 ºC, 434 ºC respectively. Further, it is seen from the figure that the exhaust gas temperature increases with an increase in the proportion of poon oil in the blend. The reason may be due to the presence of constituents with higher boiling points in poon oil than in standard diesel. Those constituents having higher boiling points were not adequately evaporated during the main combustion phase and continued to burn in the late combustion phase as seen from the Figure 5.4. This resulted in a slightly higher exhaust gas temperature and lower brake thermal efficiency.

![Graph](image)

**Figure 5.6** Variation of exhaust gas temperature with load for standard diesel, poon oil and its diesel blends
5.2.7 Oxides of nitrogen emission

The variation of oxides of nitrogen emission (NOx) emission with load for different poon oil blends and standard diesel is shown in Figure 5.7. Oxides of nitrogen emissions were lower for poon oil and its diesel blends as seen from the figure. The oxides of nitrogen emissions at full load for standard diesel, NEAT POON and POON20 are 1225 ppm, 854 ppm, 1187 ppm respectively. Further, it is seen from the figure that oxides of nitrogen emissions decrease with an increase in the proportion of poon oil in the blend. This may be due to the lowered premixed burning rate as a result of shorter ignition delay and lower volatility and lesser cylinder temperature. It may also be due to the lower heating value and high viscosity of neat poon oil.

![Figure 5.7](image)

Figure 5.7 Variation of oxides of nitrogen emission with load for standard diesel, poon oil and its diesel blends
5.2.8 Smoke emission

The variation of smoke emission with load for different poon oil blends and standard diesel is shown in Figure 5.8. The smoke emission was slightly higher for neat poon oil and its diesel blends due to their higher viscosity, resulting in larger mean fuel droplet sizes and decrease in the fuel air mixing rate. The smoke emissions at full load for standard diesel, NEAT POON and POON20 are 4.1 BSN, 4.8 BSN and 4.2 BSN respectively. Further, it can be seen from the figure that smoke emission increases with an increase in the proportion of poon oil in the blend. The increase in the smoke emission may be attributed to the higher diffusive combustion phase as seen from Figure 5.4.

![Figure 5.8 Variation of smoke emission with load for standard diesel, poon oil and its diesel blends](image)

**Figure 5.8** Variation of smoke emission with load for standard diesel, poon oil and its diesel blends
5.2.9 Hydrocarbon emission

The variation of hydrocarbon emission with load for different poon oil blends and standard diesel is shown in Figure 5.9. Unburned hydrocarbon (HC) emission for poon oil and its diesel blends is higher than that of standard diesel as seen from the figure. The higher viscosity of poon oil may lead to higher fuel spray droplet size for poon oil and its diesel blends compared with that of standard diesel. The HC emissions at full load for standard diesel, NEAT POON and POON20 are 110 ppm, 130 ppm and 114 ppm respectively. It is also seen that HC emission increases with an increase in the proportion of poon oil in the blend. The effect of fuel viscosity on fuel spray quality would be expected to produce some HC increase with vegetable oil fuels.

![Figure 5.9 Variation of hydrocarbon emission with load for standard diesel, poon oil and its diesel blends](image)

Figure 5.9 Variation of hydrocarbon emission with load for standard diesel, poon oil and its diesel blends
5.2.10 Carbon monoxide emission

The variation of carbon monoxide emission with load for different poon oil blends and standard diesel is shown in Figure 5.10. The carbon monoxide emission for poon oil and its diesel blends is higher than that of standard diesel as seen from the figure. The higher viscosity of poon oil may lead to higher fuel spray droplet size for poon oil and its diesel blends compared with that of standard diesel. The CO emissions at full load for standard diesel, NEAT POON and POON20 are 0.45 %, 0.77 % and 0.49 % respectively. Further, it can be seen from the figure that CO emission increases with an increase in the proportion of poon oil in the blend. The effect of fuel viscosity on fuel spray quality would be expected to produce some CO increase with vegetable oil fuels.

Figure 5.10 Variation of carbon monoxide emission with load for standard diesel, poon oil and its diesel blends
5.2.11 Summary

It has been observed from the detailed investigation that neat poon oil and its higher blends like POON40 and POON50 blends resulted in poor combustion due to the high viscosity of poon oil. For higher blends, the reduction in the brake thermal efficiency is higher. However, lower blends like POON20 and POON30 blends performed closer to that of standard diesel, even though their brake thermal efficiencies are lower than that of standard diesel. Based on the performance and emission characteristics, POON20 blend can be selected as the optimum blend among the blends discussed above.

5.3 PARADISE OIL AND ITS STANDARD DIESEL BLENDS

It is seen from the preceding section that, the performance and emission characteristics of neat poon oil and its higher blends are poorer than those of standard diesel. However, lower blends performed closer to that of standard diesel. In order to find the locally available and substitute fuel for poon oil, paradise oil has been found out. From the property analysis, it was found that paradise oil is having lower viscosity and better heating value when compared to those of poon oil.

5.3.1 Ignition delay

The variation of ignition delay with load for different paradise oil blends and standard diesel is shown in Figure 5.11. It can be observed that ignition delay is shorter for paradise oil and its diesel blends compared to standard diesel. This may be due to the fact that heavy molecular oleic fatty acid present in the paradise oil splits into lighter compounds when it enters high temperature combustion chamber resulting in earlier ignition.
Figure 5.11 Variation of ignition delay with load for standard diesel, paradise oil and its diesel blends

5.3.2 Cylinder peak pressure

The variation of cylinder peak pressure with load for different paradise oil blends and standard diesel is shown in Figure 5.12. It can be observed that the cylinder peak pressures for neat paradise oil and its diesel blends are lower when compared to standard diesel. The lower cylinder peak pressure of neat paradise oil may be due to slow vaporisation and slow combustion as a result of high viscosity of neat paradise oil. Peak pressure mainly depends on the combustion rate in the initial stages, which is influenced by the fuel taking part in premixed combustion heat release phase.
Figure 5.12  Variation of cylinder peak pressure with load for standard diesel, and paradise oil and its diesel blends

However, the blends recorded comparable peak pressure with that of standard diesel that may be due to the improvement in preparation of fuel air mixture as a result of reduced viscosity of the blends. Further it is observed that cylinder peak pressure decreases with increase in proportion of paradise oil in the blends. The peak pressure for diesel is 67.5 bar whereas for NEAT PARA, PARA20 and PARA30 blend it was 61 bar, 65.3 bar and 64.8 bar respectively.

5.3.3 Maximum rate of pressure rise

The variation of maximum rate of pressure rise with load for different paradise oil blends and standard diesel is shown in Figure 5.13. The maximum rate of pressure rise is lower in the case of paradise oil and its
diesel blends compared to standard diesel. This may be due to shorter ignition delay of paradise oil and its diesel blends compared to standard diesel. This leads to lower amount of fuel accumulation during delay period and thereby lower rate of pressure rise.

![Graph](image)

**Figure 5.13** Variation of maximum rate of pressure rise with load for standard diesel, paradise oil and its diesel blends

5.3.4 Heat release rate

The variation of the heat release rate with load for different paradise oil blends and standard diesel is shown in Figure 5.14. It is seen that premixed heat release of paradise oil and its blends is lower than that of standard diesel. The quantity of diffusion burning indicated by the area under the second peak is greater for neat paradise oil. This is consistent with the expected effects of paradise oil viscosity on the fuel spray, and reduction of air entrainment and
fuel/air mixing rates. At the time of ignition, less fuel/air mixture is prepared for combustion with paradise oil; therefore more burning occurs in the diffusion burning phase rather than in the premixed phase. However, for lower blends like PARA20, PARA30 the premixed combustion is closer to that of standard diesel which may be due to lower viscosity of blends when compared to standard diesel.

![Graph showing variation of heat release rate with crank angle for standard diesel paradise oil and its diesel blends.](image)

**Figure 5.14** Variation of heat release rate with crank angle for standard diesel paradise oil and its diesel blends

### 5.3.5 Brake thermal efficiency

The variation of brake thermal efficiency with load for different paradise oil blends and standard diesel is shown in Figure 5.15. Owing to poor mixture formation, as a result of the low volatility and high viscosity the brake thermal efficiency is lower with paradise oil and its diesel blends. The decrease in brake thermal efficiency denotes higher fuel consumption. The reason for this may be the differences in density and heating value of paradise
oil and diesel fuel. Poorly formed fuel sprays, smaller fuel spray angles and greater fuel spray penetration adversely affect air entrainment and subsequent fuel/air mixing, affecting engine performance. Brake thermal efficiency decreases with the increasing percentage of paradise oil.

![Graph showing brake thermal efficiency variation with load for standard diesel, paradise oil, and its blends.](image)

**Figure 5.15** Variation of brake thermal efficiency with load for standard diesel, paradise oil and its diesel blends

### 5.3.6 Exhaust gas temperature

The variation of exhaust gas temperature with load for different paradise oil blends and standard diesel is shown in Figure 5.16. It can be observed from figure that the exhaust gas temperature at full load for standard diesel, PARA20 and NEAT PARA are 396 °C, 400 °C, 424 °C respectively. Further, it is seen that exhaust gas temperature increases with the increase in proportion of paradise oil in the blend. The reason may be due to the presence
of constituents with higher boiling points in the paradise oil than in standard diesel. Those constituents having higher boiling points were not adequately evaporated during the main combustion phase and continued to burn in the late combustion phase resulting in slightly higher exhaust gas temperature as reported by Murayama et al (1984).

![Graph showing variation of exhaust gas temperature with load for standard diesel, paradise oil and its diesel blends.](image)

**Figure 5.16** Variation of exhaust gas temperature with load for standard diesel, paradise oil and its diesel blends

### 5.3.7 Oxides of nitrogen emission

The variation of NO\textsubscript{x} emission with respect to the load for different paradise oil blends and standard diesel is shown in Figure 5.17. The NO\textsubscript{x} emission is found to be significantly lower for paradise oil and its diesel blends for the entire load spectrum. The most important factor for the formation of NO\textsubscript{x} is the combustion temperature in the engine cylinder and
the availability of oxygen. The vegetable oils have higher viscosity therefore the fuel droplet size is expected to be larger than that of standard diesel. Larger droplets have longer combustion duration and they demonstrate significant energy release during the late burning phase. This suggests that the peak combustion chamber temperature is possibly lower because of the lower heat release in the premixed combustion phase as well as mixing controlled combustion phase for paradise oil and its diesel blends compared to standard diesel leading to lower formation of NO\textsubscript{x} emission as seen from Figure 5.17.

![Figure 5.17 Variation of oxides of nitrogen emission with load for standard diesel, paradise oil and its diesel blends](image)

**Figure 5.17** Variation of oxides of nitrogen emission with load for standard diesel, paradise oil and its diesel blends

### 5.3.8 Smoke emission

The variation of smoke emission with load for different paradise oil blends and standard diesel is shown in Figure 5.18. The smoke emission is slightly higher for neat paradise oil due to its higher viscosity, resulting in larger mean fuel droplet sizes and a decrease in fuel air mixing rate. The
decrease in smoke emission for paradise oil-diesel blends may be attributed to a reduced droplet size of the spray and better evaporation of the blended fuel compared to neat paradise oil. But this is still higher than standard diesel.

![Graph showing variation of smoke emission with load for standard diesel, paradise oil, and its diesel blends](image)

**Figure 5.18** Variation of smoke emission with load for standard diesel, paradise oil and its diesel blends

### 5.3.9 Hydrocarbon emission

The variation of hydrocarbon emission with load for different paradise oil blends and standard diesel is shown in Figure 5.19. Unburned hydrocarbon (HC) emission for paradise oil and its diesel blends is higher than that of standard diesel as seen from the figure. The higher viscosity of paradise oil may lead to higher fuel spray droplet size for paradise oil and its diesel blends compared with that of standard diesel. The HC emission at full load for standard diesel, NEAT PARA and PARA20 are 110 ppm, 122 ppm and 110 ppm respectively. Further, it is seen that HC emission increases with
increase in proportion of paradise oil in the blend. The effect of fuel viscosity on fuel spray quality would be expected to produce some HC increase with vegetable oil fuels as reported by Barsic et al (1981).

Figure 5.19 Variation of hydrocarbon emission with load for standard diesel, paradise oil and its diesel blends

5.3.10 Carbon monoxide emission

The variation of carbon monoxide emission with load for different paradise oil blends and standard diesel is shown in Figure 5.20. Carbon monoxide emission for paradise oil and its diesel blends was higher than that of standard diesel as seen from the figure. The higher viscosity of paradise oil may lead to higher fuel spray droplet size for paradise oil and its diesel blends compared with that of standard diesel. The CO emission at full load for standard diesel, NEAT PARA and PARA20 are 0.45 %, 0.67 % and 0.47 % respectively. Further, it can be seen from the figure that CO emission
increases with the increase in proportion of paradise oil in the blend. The effect of fuel viscosity on fuel spray quality would be expected to produce some CO increase with vegetable oil fuels.

![Graph showing variation of carbon monoxide emission with load for standard diesel, paradise oil and its diesel blends.](image)

**Figure 5.20** Variation of carbon monoxide emission with load for standard diesel, paradise oil and its diesel blends

### 5.3.11 Summary

From this section it is found that, PARA20 blend is performing in close agreement with standard diesel. The properties of the PARA20 blend are in close agreement with those of standard diesel in terms of viscosity, lower heating value, and cetane number. Based on the performance and emission characteristics PARA20 blend is chosen as the optimum blend.
5.4 METHYL ESTER OF POON OIL AND ITS STANDARD DIESEL BLENDS

It is seen from the preceding sections that, the performance and emission characteristics of poon oil and paradise oil and their higher blends are poorer than those of standard diesel. This is mainly due to their higher viscosities and lower volatility. It is found from the literature that the performance of vegetable oils can be improved by adopting modifications to the fuel system. Hence, in the present work the methyl ester of poon oil is evaluated and the results are discussed in the following sections.

5.4.1 Ignition delay

Figure 5.21 shows the variation of ignition delay with load for different methyl esters of poon oil blends and standard diesel. The ignition delay of the methyl ester of poon oil and its diesel blends is shorter than that of standard diesel. Due to the high in-cylinder temperature existing during fuel injection, biodiesel may undergo thermal cracking; as a result of this, lighter compounds are produced, which might have ignited earlier, resulting in shorter ignition delay. This is due to the fact that the methyl linoleate present in the MEPO split into smaller compounds when it enters the combustion chamber resulting in higher spray angles thus causing earlier ignition as reported in Yu et al (2002). The shorter ignition delay may also be due to the higher cetane number of the methyl ester of poon oil than standard diesel.
Figure 5.21  Variation of ignition delay with load for standard diesel, methyl ester of poon oil and its diesel blends

5.4.2  Cylinder peak pressure

Figure 5.22 shows the variation of the cylinder peak pressure with load for different methyl ester of poon oil blends and standard diesel. It can be observed from the figure that cylinder peak pressures for methyl ester of poon oil and its diesel blends are lower than that of standard diesel. The cylinder peak pressure depends mainly on the combustion rate in the initial stages, which, in turn, is influenced by the fuel taking part in the premixed combustion phase. The combined effect of the shorter ignition delay and reduced lower heating value, resulted in a lower premixed combustion phase which led to lower cylinder peak pressure.
Figure 5.22  Variation of cylinder peak pressure with load for standard diesel, methyl ester of poon oil and its diesel blends

5.4.3 Maximum rate of pressure rise

The variation of the maximum rate of pressure rise with load for different methyl ester of poon oil blends and standard diesel is shown in Figure 5.23. It can be observed from the figure that the maximum rate of pressure rise is lower for methyl ester and its diesel blends. This may be due to the shorter ignition delay; the fuel burned in the premixed combustion is less as reported by Agarwal (2007). The rate of pressure rise decreases as the fraction of methyl ester increases in the blend. This is possibly due to the presence of heavier hydrocarbon molecules in methyl ester of poon oil, which have a higher boiling point and lower volatility.
5.4.4 Heat release rate

The variation of the heat release rate with load for different methyl ester of poon oil blends and standard diesel is shown in Figure 5.24. Due to the vaporisation of the fuel accumulated during the ignition delay period, at the beginning a negative heat release is observed and, after combustion is initiated, this becomes positive. After the ignition delay period, the premixed fuel air mixture burns rapidly releasing heat at a rapid rate, after which diffusion combustion takes place. The premixed heat release is lower for the MEPO and its diesel blends when compared to that of standard diesel, possibly because of the lower heating value of the methyl ester and its diesel blends as reported by Agarwal (2007). As the percentage of MEPO in the blend increases, the maximum heat release rate decreases.
5.4.5 Brake thermal efficiency

The variation of the brake thermal efficiency with load for different methyl ester of poon oil blends and standard diesel is shown in Figure 5.25. Brake thermal efficiency increases upto 40% blend (MEPO40) and after that it starts decreasing. The increase in the brake thermal efficiency may be due to the combined effect of the lower heating value, density, and better lubricity provided by the methyl esters and their fatty ester compositions.
5.4.6 Exhaust gas temperature

The variation of the exhaust gas temperature with load for different methyl ester of poon oil blends and standard diesel is shown in Figure 5.26. The results show that the exhaust gas temperature increased with load in all the cases. It is quite obvious that with bio-diesel due to improved combustion, the temperature in the combustion chamber can be expected to be higher due to the presence of oxygen molecules in the methyl ester. The exhaust gas temperature is found to increase with an increase in the proportion of biodiesel in the blends.
Figure 5.26  Variation of exhaust gas temperature with load for standard diesel, methyl ester of poon oil and its diesel blends

5.4.7 Oxides of nitrogen emission

The variation of oxides of nitrogen emissions with load for different methyl ester of poon oil blends and standard diesel is shown in Figure 5.27. The increase in NO\textsubscript{x} emission is observed for the methyl ester of poon oil and its diesel blends. It may be due to the reason that with biodiesel, the temperature in the combustion chamber can be expected to be higher, leading to the formation of a higher quantity of NO\textsubscript{x} in biodiesel engines. The higher NO\textsubscript{x} emission may also be due to the presence of methyl linoleate which has two double bonds as reported by Ban-Weiss (1997). Another reason for the increase in NO\textsubscript{x} emissions may be due to combustion which starts earlier for biodiesel, partially owing to a shorter ignition delay and partially owing to advanced injection timing (because of the higher bulk modulus and higher density of biodiesel).
5.4.8 Smoke emission

The variation of smoke emission at different loads for the methyl ester of poon oil and its diesel blends is shown in Figure 5.28. The smoke emission is much lower for the methyl ester of poon oil and its diesel blends compared to that of standard diesel. This may be due to the presence of the oxygen molecules in the methyl esters which led to complete combustion. And, also it can be observed from the heat release rate diagram that diffusive combustion is more for methyl esters and their diesel blends. Since the smoke is mainly produced in the diffusive combustion phase, the addition of oxygenated fuel leads to an improvement in diffusive combustion.
5.4.9 Hydrocarbon emission

The variation of hydrocarbon emission at different loads for the methyl ester of poon oil and its diesel blends is shown in Figure 5.29. It is seen that MEPO and its diesel blends give relatively lower HC emission than standard diesel. This is because of the complete combustion of the methyl ester of poon oil and its diesel blends inside the combustion chamber due to the presence of the oxygen molecules in the methyl ester.
Figure 5.29  Variation of hydrocarbon emission with load for standard diesel, methyl ester of poon oil and its diesel blends

5.4.10  Carbon monoxide emission

The variation of carbon monoxide emission at different loads for the methyl ester of poon oil and its diesel blends is shown in Figure 5.30. It can be seen from the figure that CO emission decreases for the blended fuels at higher loads. This may be due to the enrichment of oxygen owing to the methyl ester addition, as increasing the proportion of oxygen will promote the further oxidation of CO during the engine exhaust process.
Figure 5.30  Variation of carbon monoxide emission with load for standard diesel, methyl ester of poon oil and its diesel blends

5.4.11 Summary

From the preceding section it is found that the performance of the MEPO40 blend is better than that of standard diesel. MEPO50 and MEPO100 blends have resulted in lower brake thermal efficiency and higher NOx emissions than other blends.

5.5 METHYL ESTER OF PARADISE OIL AND ITS STANDARD DIESEL BLENDS

It is seen from the preceding section that, the performance and emission characteristics of poon oil methyl ester and its diesel blends are better than those of neat poon oil and neat paradise oil and their diesel blends. However, in order to compare and substitute methyl ester of poon oil, a
methyl ester of paradise oil was prepared and tested. The results are compared with standard diesel and are discussed in the following sections.

5.5.1 Ignition delay

Figure 5.31 shows the variation of ignition delay with load. The ignition delay of methyl ester of paradise oil and its diesel blends is shorter than that of standard diesel. Combustion starts earlier for methyl ester partially owing to a shorter ignition delay and partially owing to advanced injection timing because of a higher bulk modulus and higher density of methyl ester as reported by Cheng et al (2006). As a result of the high in-cylinder temperature existing during fuel injection, methyl ester may undergo thermal cracking; as a result of this, lighter compounds are produced, which might have ignited earlier, resulting in shorter ignition delay. This is due to the fact that methyl oleate present in the MEPS split into smaller compounds when it enters the combustion chamber resulting in higher spray angles and hence causes earlier ignition. It is noticed that for all test fuels the reduction in ignition delay increases with an increase in the load. This may be due to higher combustion chamber wall temperature and reduced exhaust gas dilution at higher loads. The above observations indicate that there is not much variation in combustion behavior between MEPS and standard diesel.
Figure 5.31  Variation of ignition delay with load for standard diesel, methyl ester of paradise oil and its diesel blends

5.5.2  Cylinder peak pressure

Figure 5.32 shows the variation of cylinder peak pressure with load for methyl ester of paradise oil and its diesel blends. The cylinder peak pressure decreases as the proportion of methyl ester in the blends increases. The lower cylinder peak pressure may be due to lower heating value of MEPS and its diesel blends.
Figure 5.32  Variation of cylinder peak pressure with load for standard diesel, methyl ester of paradise oil and its diesel blends

5.5.3 Maximum rate of pressure rise

The variation of maximum rate of pressure rise with load is shown in Figure 5.33. The shorter ignition delay also reduced the maximum rate of pressure rise as seen from the figure. The maximum rate of pressure rise decreases as the proportion of methyl ester increases in the blend. This is possibly because methyl ester contains heavier hydrocarbon molecules, which have a higher boiling point and lower volatility.
Figure 5.33  Variation of maximum rate of pressure rise with load for standard diesel, methyl ester of paradise oil and its diesel blends

5.5.4  Heat release rate

Figure 5.34 shows the comparison of the heat release rate of methyl ester and its diesel blends. The premixed heat release is lower for the MEPS blends compared to that of standard diesel, possibly because of the lower heating value of the methyl ester blends. As the percentage of MEPS in the blend increases, the maximum heat release rate decreases.
Figure 5.34  Variation of heat release rate with crank angle for standard
diesel, methyl ester of paradise oil and its diesel blends

5.5.5  Brake thermal efficiency

The trends of the brake thermal efficiency of methyl ester of
paradise oil and its diesel blends are shown in Figure 5.35. It is observed
from the figure that the brake thermal efficiency for standard diesel is
28.87 %, whereas it is lower for all methyl ester and its diesel blends. The
decrease in brake thermal efficiency may be due to the lower heating value of
methyl ester.
5.5.6 Exhaust gas temperature

Figure 5.36 shows the variation of exhaust gas temperature with load for methyl ester and its diesel blends and diesel. It is observed that the exhaust gas temperature increases with load, because more fuel is burnt at higher loads to meet the power requirement. It is quite obvious, that with methyl esters, due to improved combustion, the temperature in the combustion chamber can be expected to be higher due to presence of oxygen content in the methyl ester. The exhaust gas temperature is found to increase with the increasing proportion of methyl ester in the blends. This could be due to the increased heat losses of the higher blends, which is also evident from their lower brake thermal efficiencies as compared to that of standard diesel.
Figure 5.36  Variation of exhaust gas temperature with load for standard diesel, methyl ester of paradise oil and its diesel blends

5.5.7 Oxides of nitrogen emission

Figure 5.37 shows the variation of NO\textsubscript{x} emission with load for methyl ester of paradise oil and its diesel blends. In general, the NO\textsubscript{x} emission varies linearly with the load of the engine. As the load increases, the overall fuel-air ratio increases resulting in an increase in the average gas temperature in the combustion chamber and hence NO\textsubscript{x} formation, which is sensitive to temperature increase. Combustion starts earlier for methyl ester partly owing to advanced injection timing (because of a higher bulk modulus and higher density of bio-diesel) resulting in higher peak in-cylinder temperatures as reported by Cheng et al (2006). In addition, the oxygen present in the fuel may provide additional oxygen for NO\textsubscript{x} formation, thereby increasing its level of emission.
Figure 5.37 Variation of oxides of nitrogen emission with load for standard diesel, methyl ester of paradise oil and its diesel blends

5.5.8 Smoke emission

Figure 5.38 shows the variation of the smoke emission with load for various methyl ester blends and diesel. There is a reduction of 39.4 % smoke emission for MEPS 100 and 33.5 % reduction for MEPS 50 blend were recorded. It is also interesting to note that a higher reduction in smoke emission is observed with an increase in the percentage of MEPS in the blend, especially at higher loads. The reduction in smoke emission can be explained by the enrichment of oxygen owing to presence of oxygen content in methyl ester of paradise oil. Since the smoke is mainly produced in the diffusive combustion phase, the addition of oxygenated fuel leads to an improvement in diffusive combustion. Higher combustion temperature, longer combustion
duration along with more diffusive combustion may be the reasons for this significant reduction in smoke emission.

![Graph showing variation of smoke emission with load for standard diesel, methyl ester of paradise oil and its diesel blends.](image)

**Figure 5.38** Variation of smoke emission with load for standard diesel, methyl ester of paradise oil and its diesel blends

### 5.5.9 Hydrocarbon emission

Figure 5.39 shows the variation of HC emission with load for methyl ester of paradise oil and its diesel blends. It is known that unburned hydrocarbon is also an important parameter for determining the emission behavior of the engines. It is observed from the figure that neat methyl ester produces relatively lower HC, compared to that of standard diesel. This may be attributed to the availability of oxygen in methyl ester, which facilitates better combustion. Also, it is seen that the hydrocarbon emission decreases with an increase in the percentage of methyl ester in the blend.
Figure 5.39  Variation of hydrocarbon emission with load for standard diesel, methyl ester of paradise oil and its diesel blends

5.5.10  Carbon monoxide emission

The variation of CO emission for methyl esters of paradise oil and its diesel blends at various load conditions is shown in Figure 5.40. The major differences between methyl ester based fuel and diesel, are the oxygen content, heating value and cetane number. During the combustion process, this bounded oxygen may be available locally to enhance the burning process by which most of the carbon available in the fuel may oxidize to CO$_2$ leaving low CO as an intermediate product as reported by Puhan et al (2007).
Figure 5.40 Variation of carbon monoxide emission with load for standard diesel, methyl ester of paradise oil and its diesel blends

5.5.11 Summary

In the preceding section, performance, emission and combustion characteristics of methyl ester of paradise oil are discussed. From the investigations, it is found that the performance of methyl ester of paradise oil is closer to that of standard diesel. The blends containing 40% methyl ester perform closer to that of standard diesel. NO\textsubscript{x} emission is higher for all the blends and MEPS 100. Considering the maximum possible replacement of standard diesel, MEPS 40 blend is chosen as the optimum blend among the blends tested as above.
5.6 EUCALYPTUS OIL – STANDARD DIESEL BLENDS

It is seen from the preceding sections, that the performance and emission characteristics of two vegetable oils and their derivatives are closer to those of standard diesel. In order to find the oil which is performing better than those of derivatives of vegetable oils, an essential oil namely eucalyptus oil is tested in the form of blends with standard diesel. The results are compared with standard diesel and are discussed in the following section.

5.6.1 Ignition delay

The variation of ignition delay for different eucalyptus oil–diesel blends and for standard diesel at various load conditions is shown in Figure 5.41. The addition of eucalyptus oil to standard diesel decreases the cetane number of the blends. The low cetane value of eucalyptus oil will lead to a slowdown in the chemical reaction rate at the early stage and an increase in the ignition delay. The ignition delay increases with an increase in eucalyptus oil addition, while, at a given eucalyptus oil addition, the ignition delay will decrease with an increase in the load. This is due to the decrease in the cetane number of the blended fuels. This trend is in close agreement with the results of Li et al (2008).
Figure 5.41 Variation of ignition delay with load for standard diesel, eucalyptus oil-diesel blends

5.6.2 Cylinder peak pressure

The variation of cylinder peak pressure for different eucalyptus oil-diesel blends and for standard diesel at various load conditions is shown in Figure 5.42. The cylinder peak pressure shows a slight increase with an increase in the eucalyptus oil addition. This is due to the increase in ignition delay and the amount of combustible mixture available within the ignition delay period, which increases the amount of fuel burned in the premixed burning phase. The results also indicate less variation in cylinder peak pressure for eucalyptus oil-diesel blends and this could be regarded as the comprehensive influence of the variation of the cetane number and the heat value of evaporation.
Figure 5.42  Variation of cylinder peak pressure with load for standard diesel, eucalyptus oil-diesel blends

5.6.3  Maximum rate of pressure rise

The variation of maximum rate of pressure rise for different eucalyptus oil-diesel blends and for standard diesel at various load conditions is shown in Figure 5.43. The maximum rate of pressure rise increases with increase in the eucalyptus oil proportion in the blends. This is due to the increase in ignition delay.
5.6.4 Heat release rate

The variation of heat release rate for different eucalyptus oil–diesel blends and for standard diesel at various load conditions is shown in Figure 5.44. It is seen from the figure that the premixed combustion heat release increases with an increase in the eucalyptus oil concentration in the blends, and this would be due to the increase in ignition delay and combustible mixture available during the ignition delay period. The addition of eucalyptus oil increases the fraction of the fuel burned in the premixed combustion phase, thereby reducing the diffusive combustion duration. In addition to this, oxygenated fuel can reduce the over-rich mixture region, improve the mixture quality and increase the burning rate.
5.6.5  Brake thermal efficiency

The variation of brake thermal efficiency for different eucalyptus oil–diesel blends and for standard diesel at various load conditions is shown in Figure 5.45. It is seen that the brake thermal efficiency increases with an increase in the eucalyptus oil proportion in the blends. The decrease in the cetane number of the fuel blends would result in longer ignition delay, which in turn, causes a high combustion rate in the premixed combustion phase and a high cylinder pressure due to the fast heat release rate. In addition to this, the oxygen available in the fuel blends can also improve the combustion rate of the subsequent diffusive burning phase. However, there is not much variation in the trend at low loads. The brake thermal efficiencies at full load
for standard diesel, EU 20, and EU 50 blends are 28.77 %, 29.2 % and 30.2 % respectively.

![Figure 5.45 Variation of brake thermal efficiency with load for standard diesel, eucalyptus oil-diesel blends](image)

5.6.6 Exhaust gas temperature

The variation of exhaust gas temperature for different eucalyptus oil-diesel blends and for standard diesel at various load conditions is shown in Figure 5.46. The exhaust gas temperature of the eucalyptus oil diesel blends is almost similar to that of the standard diesel particularly at low load, beyond which it starts increasing for eucalyptus oil diesel blends. The reason for this increase in the exhaust gas temperature may be due to the presence of oxygen in the eucalyptus oil that leads to complete combustion and higher in-cylinder temperature.
Figure 5.46  Variation of exhaust gas temperature with load for standard diesel, eucalyptus oil-diesel blends

5.6.7  Oxides of nitrogen emission

The variation of NO\textsubscript{x} emission for different eucalyptus oil-diesel blends and for standard diesel at various load conditions is shown in Figure 5.47. The NO\textsubscript{x} emission increases with an increase in the eucalyptus oil addition, which is caused by more premixed burned fuel on account of the longer ignition delay. The presence of the oxygen molecules in the eucalyptus oil will also lead to an increase in NO\textsubscript{x} emission, as the proportion of eucalyptus oil increases in the blend.
Figure 5.47 Variation of oxides of nitrogen emission with load for standard diesel, eucalyptus oil-diesel blends

5.6.8 Smoke emission

The variation of smoke emission for different eucalyptus oil–diesel blends and for standard diesel at various load conditions is shown in Figure 5.48. From the figure it is seen that smoke emission reduced significantly with the addition of eucalyptus oil to standard diesel. Since the smoke is mainly produced in the diffusive combustion phase, the addition of oxygenated fuel leads to an improvement in the diffusive combustion phase. The presence of oxygen in the eucalyptus oil influences the improvement in the diffusive combustion phase, as oxygen is a critical parameter for such phase combustion; this means a short diffusive combustion duration. Hence, a significant smoke emission reduction is observed for eucalyptus oil-diesel blends. This is in general agreement with the results of Huang et al (2004).
Figure 5.48  Variation of smoke emission with load for standard diesel, eucalyptus oil-diesel blends

5.6.9 Hydrocarbon emission

The variation of HC emission for different eucalyptus oil–diesel blends and for standard diesel at various load conditions is shown in Figure 5.49. Eucalyptus oil-diesel blends show a slightly lower HC emission than standard diesel at all the load conditions. The decrease in the hydrocarbon emission may be attributed to better spray formation and air entrainment. This may also be due to the increased combustion temperature and complete combustion.
Figure 5.49  Variation of hydrocarbon emission with load for standard diesel, eucalyptus oil-diesel blends

5.6.10  Carbon monoxide emission

The variation of CO emission for different eucalyptus oil–diesel blends and for standard diesel at various load conditions is shown in Figure 5.50. At part load, the CO emission of eucalyptus oil-diesel blends closely follows that of standard diesel, beyond which the emission deviates drastically from one another. CO emission decreases with an increase in the proportion of eucalyptus in the blends. It may be due to the improved spray performance and combustion behavior of the blends. It may also be due to the presence of oxygen in the eucalyptus and complete combustion. Volatile fuels will improve the mixing process and increase the local air fuel ratios, thereby reducing the CO as reported by Needham et al (1985).
Figure 5.50  Variation of carbon monoxide emission with load for standard diesel, eucalyptus oil-diesel blends

5.6.11 Summary

From the tests conducted with eucalyptus oil-diesel blends, it is concluded that the EU50 blend can be chosen as an optimum blend among the blends tested. The addition of eucalyptus oil to the standard diesel increases the brake thermal efficiency to a maximum extent of 3 % for EU50. NO\textsubscript{x} increases with an increase in the eucalyptus oil proportion in the blend. There was a 8.5% increase in NO\textsubscript{x} emission for the EU50 blend. Smoke, HC and CO emissions decreased by 19.5 %, 11.8 % and 36 % respectively.

5.7  EUCALYPTUS OIL - METHYL ESTERS BLENDS

In this section, the performance and emission characteristics of the blends of MEPS and MEPO with eucalyptus oil are discussed. The presence of eucalyptus oil in the blends improves the viscosity and volatility of the blends. This is in conformity with the observations made by Cheng et al (2008).
5.7.1 Ignition delay

The variation of ignition delay for different eucalyptus oil– MEPS, MEPO blends and for standard diesel at various load conditions is shown in Figure 5.51. The ignition delay of the EU50-MEPS50 and EU50-MEPO50 blends is longer than that of standard diesel. Among these two blends, the ignition delay of the blend containing MEPS is shorter than that of the blend containing MEPO which may be due to the higher cetane number of MEPS. The ignition delay of EU20-MEPS80 and EU20-MEPO 80 blends are slightly shorter than that of standard diesel. This may be attributed to the presence of eucalyptus oil in the blend which decreases the viscosity, improves the volatility and leads to better mixture preparation.

![Figure 5.51 Variation of ignition delay with load for standard diesel, eucalyptus oil-methyl esters blends](image_url)
5.7.2 Cylinder peak pressure

The variation of cylinder peak pressure for different eucalyptus oil–MEPS, MEPO blends and for standard diesel at various load conditions is shown in Figure 5.52. The cylinder peak pressure mainly depends on the combustion rate in the initial stages, which is influenced by the fuel taking part in the premixed combustion heat release phase. The presence of eucalyptus oil in the blend decreases the viscosity and improves the volatility, which leads to better atomisation and mixture preparation with air during the ignition delay period. The cylinder peak pressures for EU50-MEPS50 and EU50-MEPO50 are higher than those of standard diesel, EU20-MEPS 80 and EU20-MEPO80 blends. This may be due to the longer ignition delay in the higher blends of eucalyptus oil. The addition of eucalyptus oil into MEPO and MEPS leads to the decrease in cetane number and results in longer ignition delay.

![Variation of cylinder peak pressure with load for standard diesel, eucalyptus oil-methyl esters blends](image)

Figure 5.52 Variation of cylinder peak pressure with load for standard diesel, eucalyptus oil-methyl esters blends
5.7.3 Maximum rate of pressure rise

The variation of maximum rate of pressure rise for different eucalyptus oil–MEPS, MEPO blends and for standard diesel at various load conditions is shown in Figure 5.53. The maximum rate of pressure rise shows a slight increase with an increase in the eucalyptus oil proportion in the blend. The higher premixed combustion rate can be attributed to the higher value of the maximum rate of pressure rise. The longer ignition delay resulted in a higher premixed combustion rate and thereby higher maximum rate of pressure rise. Higher proportion of methyl esters resulted in reduced lower heating value of the blends and thereby lower rate of pressure rise. The maximum rate of pressure rise for EU50-MEPS50 and EU50-MEPO50 are higher than those of standard diesel, EU20-MEPS 80 and EU20-MEPO80 blends.

Figure 5.53 Variation of maximum rate of pressure rise with load for standard diesel, eucalyptus oil-methyl esters blends
5.7.4 Heat release rate

The variation of heat release rate at full load for different eucalyptus oil– MEPS, MEPO blends and for standard diesel is shown in Figure 5.54. The fuel blends showed similar combustion behaviour as that of standard diesel. All the fuel blends experienced a rapid premixed combustion followed by a diffusion combustion period, which is a typical combustion process in naturally aspirated diesel engines. It can be observed from the figure that the heat release rate for the fuel blends is higher for higher percentage of eucalyptus oil when compared to standard diesel. The presence of eucalyptus oil in the blends decreases their viscosity and improves their volatility, which leads to better atomisation and mixture preparation with air during the ignition delay period. But, however, the heat release patterns of the EU20-MEPS80 and EU20-MEPO80 blends are similar to that of standard diesel.

![Figure 5.54: Variation of heat release rate with crank angle for standard diesel, eucalyptus oil-methyl esters blends](image-url)
diesel. This may be due to the shorter ignition delay in the case of EU20 blends when compared to EU50 blends.

### 5.7.5 Brake thermal efficiency

The variation of brake thermal efficiency for different eucalyptus oil–MEPS, MEPO blends and for standard diesel at various load conditions is shown in Figure 5.55. The higher proportion of eucalyptus oil in the blend increases the ignition delay, leading to a large percentage of fuel burning in the premixed mode. This leads to an increase in the brake thermal efficiency. The brake thermal efficiency of the EU50-MEPS50 blend was better than that of the other blends and standard diesel. Further, the reduction in viscosity leads to improved atomisation, fuel vapourisation and combustion. This may be the other reason for the improvement in brake thermal efficiency in higher blends of eucalyptus oil.

![Figure 5.55 Variation of brake thermal efficiency with load for standard diesel, eucalyptus oil-methyl esters blends](image)

**Figure 5.55** Variation of brake thermal efficiency with load for standard diesel, eucalyptus oil-methyl esters blends
5.7.6 Exhaust gas temperature

The variation of exhaust gas temperature for different eucalyptus oil– MEPS, MEPO blends and for standard diesel at various load conditions is shown in Figure 5.56. The increase in the exhaust temperature may be due to complete combustion. The cetane number of the blend is reduced with an increase of the eucalyptus oil content in the blend because of the low cetane number of eucalyptus oil. A lower cetane number means an increase in the ignition delay and more accumulated fuel/air mixture, which causes a rapid heat release in the beginning of the combustion, resulting in high exhaust gas temperature.

![Figure 5.56](image)

**Figure 5.56** Variation of exhaust gas temperature with load for standard diesel, eucalyptus oil-methyl esters blends

5.7.7 Oxides of nitrogen emission (NO\textsubscript{x})

The variation of NO\textsubscript{x} emission for different eucalyptus oil– MEPS, MEPO blends and for standard diesel at various load conditions is shown in
Figure 5.57. It can be observed from the figure that NO$_x$ emission increases with the increase in the eucalyptus oil proportion in the blends. The increase in NO$_x$ emission may be due to the presence of oxygen in both the fuels, which leads to complete combustion. Normally, complete combustion will create higher combustion temperature, which will cause high NO$_x$ formation. Another reason for the increase of NO$_x$ emissions is the decrease of the cetane number with a higher eucalyptus oil proportion. A lower cetane number means an increase in the ignition delay and more accumulated fuel/air mixture, which causes a rapid heat release in the beginning of the combustion, resulting in high temperature and high NO$_x$ formation as reported by Kwanchareon et al (2007).

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5_57}
\caption{Variation of oxides of nitrogen emission with load for standard diesel, eucalyptus oil-methyl esters blends}
\end{figure}
5.7.8 Smoke emission

The variation of smoke emission for different eucalyptus oil–MEPS, MEPO blends and for standard diesel at various load conditions is shown in Figure 5.58. The significant reduction in smoke emission may be due to the complete combustion caused by the oxygenated blends. This may also be due to an improvement in diffusive combustion.

![Figure 5.58 Variation of smoke emission with load for standard diesel, eucalyptus oil-methyl esters blends](image)

5.7.9 Hydrocarbon emission

The variation of HC emission for different eucalyptus oil–MEPS, MEPO blends and for standard diesel at various load conditions is shown in Figure 5.59. It is seen from figure that at low load and medium loads, HC emissions of the blends were not much different from that of standard diesel. However, at full load, HC emissions of the blends decreased significantly.
when compared with that of standard diesel. This can be due to the presence of oxygen in both the fuels.

![Figure 5.59 Variation of hydrocarbon emission with load for standard diesel, eucalyptus oil-methyl esters blends](image)

**Figure 5.59** Variation of hydrocarbon emission with load for standard diesel, eucalyptus oil-methyl esters blends

### 5.7.10 Carbon monoxide emission

The variation of CO emission for different eucalyptus oil– MEPS, MEPO blends and for standard diesel at various load conditions is shown in Figure 5.60. It is seen from the figure that at low and medium loads, CO emissions of the blends were not much different from that of standard diesel. However, at full load, CO emissions of the blends decreased significantly when compared with that of standard diesel. This can be explained by the presence of oxygen in both the fuels.
Figure 5.60 Variation of carbon monoxide emission with load for standard diesel, eucalyptus oil-methyl esters blends

5.7.11 Summary

From the combustion analysis it is found that the ignition delay of EU20–MEPS80 blend is shorter than that of standard diesel and other blends. Cylinder peak pressure, maximum rate of pressure rise and heat release rate of EU20–MEPS80 blend are similar to those of standard diesel. From the emission analysis, it is found that CO, HC and smoke are lower for EU20–MEPS80 blend when compared to standard diesel. Among all the blends, NO\textsubscript{x} emission is lower for EU20–MEPS80 blend but slightly higher than that of standard diesel. The brake thermal efficiency of EU20–MEPS80 blend is slightly higher than that of standard diesel. On the whole, it is found that performance and emission characteristics of EU20–MEPS80 blend are closer to those of standard diesel.
5.8 EUCALYPTUS OIL WITH IGNITION ENHANCER

In this work, 100% replacement of standard diesel by a low cetane fuel namely eucalyptus oil is tried. For this, an ignition enhancer, di-ethyl ether (DEE), was aspirated into the engine cylinder through the intake manifold. Eucalyptus oil was directly injected into the engine cylinder at the end of compression (23° BTDC) by the conventional fueling method. The results of this method are discussed in this section.

5.8.1 Percentage of energy share by diethyl ether

The di-ethyl ether (DEE) was aspirated into the engine at the rate of 85 g/hr, 175 g/hr, and 260 g/hr for all engine loads. The variation of DEE energy share for different DEE flow rates with load is shown in Figure 5.61. It can be observed that, when the load increased the energy share of diethyl ether decreased. This may be due to the higher cylinder temperature at higher engine loads as reported by Murayama (1992). Thus, as the amount of energy needed increases, the fraction of the energy provided by the DEE decreases.

5.8.2 Ignition delay

The variation of the ignition delay with load for neat eucalyptus oil, eucalyptus oil with DEE and for standard diesel is shown in Figure 5.62. The ignition delay of neat eucalyptus oil is higher than that of standard diesel and of eucalyptus oil with DEE, which may be due to lower cetane number of eucalyptus oil. When DEE induction increases, the ignition delay decreases as can be seen from the figure. The combined effect of high volatility, low viscosity and low self ignition temperature of DEE resulted in earlier combustion which led to the high pressure and temperature of the gas present inside the cylinder. This helps in the self-ignition of the injected eucalyptus oil, resulting in shorter ignition delay.
Figure 5.61  Variation of DEE energy share with load for different DEE flow rates

Figure 5.62  Variation of ignition delay with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE
5.8.3 Cylinder peak pressure

The variation of the cylinder peak pressure with load for neat eucalyptus oil, eucalyptus oil with DEE and for standard diesel is shown in Figure 5.63. It can be observed from the figure that the cylinder peak pressure is higher for neat eucalyptus oil which is due to high premixed combustion as a result of longer ignition delay. However, the cylinder peak pressure decreased for eucalyptus oil with DEE induction due to shorter ignition delay. The pre-combustion of DEE helps to self-ignite the injected eucalyptus oil, thereby reducing the ignition delay. It can also be noted that the cylinder peak pressures are reduced when the DEE flow rate is increased.

![Graph showing variation of cylinder peak pressure with load](image)

**Figure 5.63** Variation of cylinder peak pressure with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE
5.8.4 Maximum rate of pressure rise

The variation of the maximum rate of pressure rise with load for neat eucalyptus oil, eucalyptus oil with DEE and for standard diesel is shown in Figure 5.64. It can be observed from the figure that the maximum rate of pressure rise is higher for neat eucalyptus oil, due to the longer ignition delay of eucalyptus oil. However, the maximum rate of pressure rise decreased for eucalyptus oil with DEE induction when compared with neat eucalyptus oil. The maximum rate of pressure rise is lower for 260 g/hr of DEE flow rate among other flow rates, because of the suppression of the air temperature and the higher latent heat of vapourisation of the DEE when increasing the quantity of DEE as reported by Murayama (1992).

![Figure 5.64 Variation of maximum rate of pressure rise with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE](image-url)
5.8.5 Heat release rate

The variation of the heat release rate with load for neat eucalyptus oil, eucalyptus oil with DEE and for standard diesel is shown in Figure 5.65. There is a two-stage combustion of DEE in the compression stroke. This is due to the pre-combustion of DEE which creates the appropriate conditions for the main fuel (eucalyptus oil) to facilitate the ignition and enhance the main combustion. The heat release peak obtained may be the secondary heat release curve which belongs to the main combustion of the eucalyptus oil. These results indicate earlier combustion and very short ignition delay when the engine runs on eucalyptus oil with DEE. This is in general agreement with the results of Armbruster et al (2003), Murayama (1992) and Gjirja et al (1998).

![Figure 5.65 Variation of heat release rate with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE](image-url)
5.8.6 Brake thermal efficiency

The variation of the brake thermal efficiency with load for neat eucalyptus oil, eucalyptus oil with DEE and for standard diesel is shown in Figure 5.66. The brake thermal efficiencies of neat eucalyptus oil and eucalyptus oil with different DEE flow rates are lower than that of standard diesel. It is also seen that the brake thermal efficiency improved for the eucalyptus oil with DEE flow rate of 175 g/hr. For the 260 g/hr of DEE flow rate, the brake thermal efficiency reduced very much due to the higher latent heat of vaporisation of DEE resulting in lower combustion temperature. The decreased brake thermal efficiency for increased DEE quantities is due to a decrease in the degree of constant volume combustion and the increased cooling loss caused by the more extensive DEE combustion at earlier timings. The decreased brake thermal efficiency for 85 g/hr of DEE flow rate may be due to unstable combustion with misfiring (Murayama 1992).

![Figure 5.66 Variation of brake thermal efficiency with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE](image-url)
5.8.7 Exhaust gas temperature

The variation of the exhaust gas temperature with load for neat eucalyptus oil, eucalyptus oil with DEE and for standard diesel is shown in Figure 5.67. The exhaust gas temperature of neat eucalyptus oil is higher than those of standard diesel and eucalyptus oil with different DEE flow rates. It can be observed that the difference in the exhaust gas temperature is marginal between the different DEE flow rates. At full load the exhaust gas temperature for eucalyptus with DEE varies from 406°C to 438°C.

Figure 5.67 Variation of exhaust gas temperature with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE
5.8.8 Oxides of nitrogen emission

The oxides of nitrogen emission of eucalyptus oil with various mass flow rates of DEE is compared with that of standard diesel and neat eucalyptus oil as shown in Figure 5.68. The emission of oxides of nitrogen (NO\textsubscript{x}) is significantly influenced by the in-cylinder gas temperature and availability of oxygen during combustion. It can be observed that NO\textsubscript{x} is decreased with an increase in the DEE flow rate. This is due to the reduction in the charge temperature due to the vaporisation of the diethyl ether. The high flame velocity of DEE and eucalyptus oil will also improve the overall combustion process resulting in higher NO\textsubscript{x} emissions.

![Figure 5.68 Variation of oxides of nitrogen emission with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE](image)

**Figure 5.68** Variation of oxides of nitrogen emission with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE
5.8.9 Smoke emission

The smoke emission of eucalyptus oil with various mass flow rates of DEE is compared with that of standard diesel and neat eucalyptus oil as shown in Figure 5.69. For eucalyptus oil with DEE, it varies from 0.2 BSN to 3.0 BSN. The slight increase in smoke emission in the case of DEE induction may be due to the reduced combustion temperature because of the higher latent heat of vapourisation of DEE. The smoke emission for the DEE flow rate of 175 g/hr is 2.5 BSN, which is lower than that of standard diesel and higher flow rate.

![Figure 5.69 Variation of smoke emission with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE](image-url)
5.8.10 Hydrocarbon emission

The hydrocarbon emission of eucalyptus oil with various mass flow rates of DEE is compared with that of standard diesel and neat eucalyptus oil as shown in Figure 5.70. It increases by increasing the flow rate of DEE. This increase in HC emission may be attributed to two factors: one is the greater quantity of DEE introduced along with the intake air in the form of premixed charge. This premixed charge would occupy the crevice volumes where the flames cannot penetrate. The other factor is the lower temperature formed inside the engine cylinder due to the higher latent heat of vapourisation of DEE. The hydrocarbon emission varies from 84 ppm to 98 ppm. The same trend has been reported by Murayama et al (1992) when they tried to aspirate di methyl ether (DME) with low cetane fuel of methanol.

![Figure 5.70 Variation of hydrocarbon emission with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE](image)
5.8.11 Carbon monoxide emission

The carbon monoxide emission of eucalyptus oil with various mass flow rates of DEE is compared with that of standard diesel and neat eucalyptus oil as shown in Figure 5.71. CO emission increases with increase in DEE flow rate. This may be due to the lower temperature formed inside the engine cylinder due to the higher latent heat of vapourisation of DEE. The CO emission varies from 0.26 to 0.4.

![Graph showing CO emission with load](image)

**Figure 5.71 Variation of carbon monoxide emission with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE**

5.8.12 Summary

From the investigations, it has been found that neat eucalyptus oil produced longer ignition delay and higher maximum rate of pressure rise. Lower brake thermal efficiency and higher NO\textsubscript{x} emissions were observed for neat eucalyptus oil operation. The aspiration of an ignition enhancer, diethyl
ether, resulted in improved brake thermal efficiency and better emission reduction. The higher brake thermal efficiency is obtained for eucalyptus oil with DEE (175g/hr flow rate) than eucalyptus oil with other DEE flow rates. Smoke emission for eucalyptus oil with DEE (175 g/hr flow rate) is lower than standard diesel and eucalyptus oil with DEE (260 g/hr flow rate). NO\textsubscript{x} emission is lower than standard diesel. On the whole, it is found that the performance and emission characteristics of eucalyptus oil with DEE (175 g/hr flow rate) are better than those of standard diesel and eucalyptus oil with DEE (85 g/hr and 260 g/hr flow rates).

5.9 EUCALYPTUS OIL WITH IGNITION ENHANCER AT OPTIMUM CONDITIONS

To improve the performance and reduce the emissions, the DEE flow rate and injection timing of eucalyptus oil were optimised and their results are presented in the following section.

5.9.1 Optimisation of DEE flow rate and injection timing of eucalyptus oil

From Figure 5.72, it is seen that the brake thermal efficiencies of eucalyptus oil with DEE at different flow rates of 85 g/hr, 175 g/hr and 260 g/hr, are 27.9 %, 28.54 % and 26.80 % respectively. Among these flow rates, the 175 g/hr DEE flow rate resulted in higher brake thermal efficiency. Hence, 175 g/hr DEE flow rate has been chosen as the optimum DEE flow rate. At the optimum DEE flow rate, the engine was operated at different injection timings namely, 17° BTDC, 19° BTDC, 21° BTDC and 23° BTDC. The performance of the engine operating on eucalyptus oil-DEE could be improved by injecting eucalyptus oil closer to TDC, thereby reducing the amount of fuel burned during the compression stroke. From Figure 5.73, it is seen that at 19° BTDC, the brake thermal efficiency was higher.
Table 5.1 it is observed that smoke emission was lower at 19° BTDC when compared with those of other injection timings.

Figure 5.72 Variation of brake thermal efficiency of eucalyptus oil with different DEE flow rates

Figure 5.73 Variation of brake thermal efficiency of eucalyptus oil with optimised DEE at different injection timings
Table 5.1  Performance and emissions at various injection timings for the optimum DEE flow rate (175 g/hr)

<table>
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<th>NO\textsubscript{x}, ppm</th>
<th>Smoke, BSN</th>
<th>HC, ppm</th>
<th>CO, %</th>
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<td>1204</td>
<td>2.7</td>
<td>107</td>
<td>0.4</td>
</tr>
</tbody>
</table>

5.9.2  Ignition delay

Figure 5.74 shows the variation of ignition delay with load for standard diesel, neat eucalyptus oil and optimised conditions of eucalyptus oil with DEE. The ignition delay for EU with DEE at optimum conditions was closer to that of standard diesel. This may be due to the injection of eucalyptus oil closer to the TDC.

5.9.3  Cylinder peak pressure

Figure 5.75 shows the variation of cylinder peak pressure with load for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE. The cylinder peak pressure was lower for eucalyptus oil with DEE than for neat eucalyptus oil and standard diesel. This may be due to the fact that there is less after-compression of the earlier burnt gas.

5.9.4  Maximum rate of pressure rise

Figure 5.76 shows the variation of the maximum rate of pressure rise with load for standard diesel, neat eucalyptus oil and eucalyptus oil with
DEE. The maximum rate of pressure rise was lower for eucalyptus oil with DEE than for neat eucalyptus oil and standard diesel. This may be due to the shorter ignition delay of eucalyptus oil with DEE as it minimises the rate of pressure rise. This may also be due to the fact that there is less after-compression of the earlier burnt gas, so it does not reach as high a maximum rate of pressure rise as that in the standard diesel engine and neat eucalyptus oil.

![Variation of ignition delay with load for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions](image)

**Figure 5.74** Variation of ignition delay with load for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions
Figure 5.75  Variation of cylinder peak pressure with load for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions

Figure 5.76  Variation of maximum rate of pressure rise with load for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions
5.9.5 Heat release rate

Figure 5.77 shows the variation of the heat release rate with crank angle for standard diesel, neat eucalyptus oil and eucalyptus oil with DEE. The heat release peak shown in the figure for eucalyptus oil with DEE belongs to the secondary heat release peak as discussed in the previous section. The secondary heat release differs for the different injection timings. As seen from the figure, the secondary heat release peak (premixed combustion phase) of eucalyptus oil with DEE decreased due to the shorter ignition delay and drop in cylinder peak pressure due to the retarded injection timing.

![Graph showing variation of heat release rate with crank angle for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions](image)

**Figure 5.77** Variation of heat release rate with crank angle for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions
5.9.6 Brake thermal efficiency

Figure 5.78 shows the variation of the brake thermal efficiency with load for standard diesel, neat eucalyptus oil and optimised eucalyptus oil with DEE. The brake thermal efficiency obtained with eucalyptus oil with DEE is higher than that of standard diesel and neat eucalyptus oil. The brake thermal efficiency obtained with standard diesel is 28.87 %, and with neat eucalyptus oil, it is 27.6 %, whereas for eucalyptus oil with DEE, it is 31.2 %. It is observed that there is an improvement in the brake thermal efficiency at optimised injection timing. The reason for the increase in the brake thermal efficiency for optimised eucalyptus oil with DEE may be due to the injection of eucalyptus oil closer to TDC, thereby reducing the amount of fuel burned during the compression stroke. By retarding the injection timing, the

![Brake thermal efficiency graph](image)

Figure 5.78 Variation of brake thermal efficiency with load for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions
combustion begins later than for a standard engine. This means that there is less after-compression of the earlier burnt gases, so it does not reach as high a temperature as in the standard case.

5.9.7 Exhaust gas temperature

Figure 5.79 shows the variation of the exhaust gas temperature with load for standard diesel, neat eucalyptus oil and optimised eucalyptus oil with DEE. The exhaust gas temperature may be regarded as a parameter to determine whether the combustion is efficient. The exhaust gas temperature is lower for eucalyptus oil with DEE compared to that of neat eucalyptus oil and standard diesel. At full load, the exhaust gas temperature for neat eucalyptus oil is 462 °C, for eucalyptus oil with DEE it is 380 °C, and for standard diesel it is 394 °C. However, with retarded injection timing there is a reduction in the exhaust gas temperature indicating efficient combustion.

![Graph showing variation of exhaust gas temperature with load](image)

**Figure 5.79** Variation of exhaust gas temperature with load for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions
5.9.8 Oxides of nitrogen emission

Figure 5.80 shows the variation of oxides of nitrogen emission with load for standard diesel, neat eucalyptus oil and optimised eucalyptus oil with DEE. NO\textsubscript{x} emissions are proportional to the peak temperature and amount of time spent at high temperature, as reported by Michael et al (1991). By injecting eucalyptus oil closer to TDC, thereby reducing the amount of fuel burned during the compression stroke, NO\textsubscript{x} emissions can be reduced significantly. The maximum NO\textsubscript{x} emission for neat eucalyptus oil is 1517 ppm, for standard diesel it is 1255 ppm, and for eucalyptus oil with DEE it is 1174 ppm. This reduction may be due to a shift in the combustion process and hence lesser combustion temperature.

Figure 5.80 Variation of oxides of nitrogen emission with load for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions
5.9.9 Smoke emission

Figure 5.81 shows the variation of smoke emission with load for standard diesel, neat eucalyptus oil and optimised eucalyptus oil with DEE at different load conditions. The smoke emission is higher for standard diesel. Lower smoke emissions were obtained for neat eucalyptus oil and optimised eucalyptus oil with DEE. But, there is a slight increase in smoke emission for optimised eucalyptus oil with DEE, because of late combustion and reduced combustion temperature.

![Graph showing variation of smoke emission with load](image)

**Figure 5.81** Variation of smoke emission with load for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions
5.9.10 Hydrocarbon emission

Figure 5.82 shows the variation of HC emissions with load for standard diesel, neat eucalyptus oil and optimised eucalyptus oil with DEE. Lower HC emissions were obtained for neat eucalyptus oil. There is a slight increase in HC emission for optimised eucalyptus oil with DEE but lower than that of standard diesel. This may be due to the retarded injection timing and lower combustion temperature.

![Graph showing variation of hydrocarbon emission with load](image)

Figure 5.82 Variation of hydrocarbon emission with load for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions

5.9.11 Carbon monoxide emission

Figure 5.83 shows the variation of CO emission with load for standard diesel, neat eucalyptus oil and optimised eucalyptus oil with DEE.
Lower CO emissions are observed for neat eucalyptus oil and optimised eucalyptus oil with DEE. There is a slight increase in CO emission for eucalyptus oil with DEE due to the retarded injection timing.

![Graph showing CO emission with load for different fuels](image)

**Figure 5.83** Variation of CO with load for standard diesel, neat eucalyptus oil, and eucalyptus oil at optimised conditions

### 5.9.12 Summary

At optimum conditions of eucalyptus oil with DEE the NO\textsubscript{x} emission decreased from 1517 ppm of neat eucalyptus to 1174 ppm and the brake thermal efficiency increased from 27.6 % to 31.5 %. Smoke emission increased slightly from 2.0 BSN to 2.4 BSN, but it is lower than that of standard diesel. HC, CO emissions increased slightly when compared with those of neat eucalyptus oil, but were lower than those of standard diesel. On the whole, it is concluded that DEE can be inducted at the flow rate of 175 g/hr and eucalyptus oil can be injected at 19° BTDC.