CHAPTER- 6

EXPERIMENTS WITH STRAIGHT VEGETABLE OILS

After thorough review of literature it was observed that the researchers concentrated mainly on locally available edible/non edible oils for their experimentation. In majority of the cases the oils chosen were transesterified and modified to bio diesel form and later they were used directly or blended with diesel and performance evaluations were made. In the present experimentation three types of locally available non edible oils viz. 1) tobacco seed oil, 2) pongamia oil and 3) mahua oil which are readily available to the farming community are chosen for the experimentation. Tobacco seed oil is grown by the farming community as commercial crop and pongamia and mahua oils are extracted from the seeds collected from the local forest area. They are also available with Girijan co-operative marketing stores. The main objective is to generate data pertaining to the best suitable fuel injection pressure and fuel injection timing to use these oils during emergency situations like floods and natural calamities or diesel fuel shortage for emergency and short term applications for the benefit of the farmers.

6.1 EXPERIMENTAL PROCEDURE

A four stroke single cylinder direct injection water cooled computerized Kirloskar TV1 diesel engine shown in Plate. 5.1 is used for testing the performance by enhancing fuel injection pressure and fuel injection timing. Two fuel tanks were used for fuelling the engine. The first fuel tank supplied by the manufacturer is used for base line diesel fuel and the second fuel tank was used for filling the test fuel which has got the flexibility of frequent removal and fixing. Necessary fuel valves are
provided to change over from base line diesel to the desired test fuel while the engine is in running condition.

After completion of initial check up like fuel oil, lubricating oil, water level in the water sump (a separate water pump is provided to supply cooling water to the engine, exhaust gas calorimeter and to the eddy current dynamometer) and the systems like computer, engine control unit, five gas exhaust gas analyzer, smoke meter etc, were switched on. Ambient temperature, atmospheric pressure and the water temperature were recorded. After ensuring no load on the eddy current dynamometer the engine was started on base line diesel and performance emission and combustion tests were conducted using base line diesel as fuel at manufacturers recommended fuel injection pressure of 205 bar and fuel injection timing of 23° BTDC(static). Readings like, load on the engine dynamometer, speed of the engine, fuel consumption time, inlet manifold manometer reading, air box manometer reading, exhaust gas temperature, engine cooling water temperature, exhaust gas calorimeter temperature, smoke meter reading and five gas exhaust gas analyzer readings were recorded by varying load in steps of 20, 40, 60, 80 and 100% of full load. The performance emission and combustion characteristics are plotted for the base line diesel operation after conducting several trial runs and selected the best performance values and these values are represented as base line diesel values in all the graphs which are supposed to be the best operational values for this particular engine. These test values are compared with the experimental results using various test fuels selected for the experimental programme at various operating conditions.
encountered by enhancing fuel injection timing and fuel injection pressure.

The performance and emission tests were conducted using the three non-edible vegetable oils i.e 1)tobacco seed oil, 2) pongamia oil and 3) mahua oil following the above procedure to evaluate the performance and emission analysis at different injection pressures (205, 220, 240 and 260 bar) and keeping the fuel injection timing at 23° BTDC (static). Before introducing the straight vegetable oil as test fuel, the engine was run on base line diesel for 10 to 15 minutes and after stabilizing the engine parameters, the test fuel was introduced. After running the engine for 10-15 minutes on the test fuel and stabilizing the parameters with the test fuel the readings were recorded and after completion of the tests with non-edible oils the engine was switched over to base line diesel and run for 10 to 15 minutes on base line diesel before stopping the engine to avoid cold starting and fuel injector and fuel pump plunger sticking problems.

The above test procedure is repeated by keeping the fuel injection timing (static) at 26° and 28° BTDC (static) and the fuel injection pressure at 205, 220, 240 and 260 bar.

The experimental investigations were carried out on all the test fuels at different fuel injection pressures and fuel injection timing (static) to optimize best fuel injection pressure and the fuel injection advance (static). As the experimental data obtained is too large to explain all the test results for arriving at best fuel injection pressure and fuel injection timing, tobacco seed oil data is taken as an example and presented in the form of graphs in section 6.1.1 which are self explanatory. The similar procedure has been adopted for rest of the test fuels to arrive at best fuel
injection pressure and fuel injection timing. Based on which the remaining experimentation has been conducted.

6.1.1 Tobacco seed oil data at various fuel injection pressures and fuel injection timing.

As discussed above the sample data of tobacco seed oil at various fuel injection pressure and fuel injection timing are presented in the form of graphs (Fig.6.1 to 6.14) which clearly explains the effect of variation of fuel injection pressure and fuel injection timing to arrive at best operating condition.
Variation of fuel injection pressure

Fig.6.1 BSFC Vs Brake Power of tobacco seed oil at 205, 220, 240 and 260 bar fuel injection pressure and 26° BTDC fuel injection timing.

Fig.6.2 Exhaust Gas Temperature Vs Brake Power of tobacco seed oil at 205, 220, 240 and 260 bar fuel injection pressure and 26° BTDC fuel injection timing.
Fig.6.3 Brake Thermal Efficiency Vs Brake Power of tobacco seed oil at 205, 220, 240 and 260 bar fuel injection pressure and 26° BTDC fuel injection timing.

Fig.6.4 Unburnt Hydro Carbon Vs Brake Power of tobacco seed oil at 205, 220, 240 and 260 bar fuel injection pressure and 26° BTDC fuel injection timing.
Fig. 6.5 Carbon Monoxide Vs Brake Power of tobacco seed oil at 205, 220, 240 and 260 bar fuel injection pressure and 26° BTDC fuel injection timing.

Fig. 6.6 Oxides of Nitrogen Vs Brake Power of tobacco seed oil at 205, 220, 240 and 260 bar fuel injection pressure and 26° BTDC fuel injection timing.
Fig. 6.7 Smoke Opacity Vs Brake Power of tobacco seed oil at 205, 220, 240 and 260 bar fuel injection pressure and 26° BTDC fuel injection timing.

**Variation of fuel injection timing**

Fig. 6.8 BSFC Vs Brake Power of tobacco seed oil at 260 bar fuel injection pressure and 23°, 26° and 28° BTDC fuel injection timing.
Fig. 6.9 Exhaust Gas Temperature Vs Brake Power of tobacco seed oil at 260 bar fuel injection pressure and 23°, 26° and 28° BTDC fuel injection timing.

Fig. 6.10 Brake Thermal Efficiency Vs Brake Power of tobacco seed oil at 260 bar fuel injection pressure and 23°, 26° and 28° BTDC fuel injection timing.
Fig.6.11 Unburnt Hydro Carbon Vs Brake Power of tobacco seed oil at 260 bar fuel injection pressure and 23°, 26° and 28° BTDC fuel injection timing.

Fig.6.12 Carbon Monoxide Vs Brake Power of tobacco seed oil at 260 bar fuel injection pressure and 23°, 26° and 28° BTDC fuel injection timing.
Fig. 6.13 Oxides of Nitrogen Vs Brake Power of tobacco seed oil at 260 bar fuel injection pressure and 23°, 26° and 28° BTDC fuel injection timing.

Fig. 6.14 Smoke Opacity Vs Brake Power of tobacco seed oil at 260 bar fuel injection pressure and 23°, 26° and 28° BTDC fuel injection timing.
6.2 RESULTS AND DISCUSSIONS

The results obtained from the experiments conducted with straight tobacco seed oil, pongamia oil and mahua oil are discussed in the following sections.

6.2.1 Tobacco seed oil

The variation of brake specific fuel consumption of tobacco seed oil with respect to brake power is presented in Fig.6.15. For both diesel and tobacco seed oil operation the brake specific fuel consumption was decreased with increase of brake power up to 80% load and there after an increasing trend in brake specific fuel consumption is seen in all the cases. The lowest brake specific fuel consumption for diesel, tobacco seed oil at standard setting of injection pressure and timing and tobacco seed oil at best injection pressure and timing are 0.305, 0.428, 0.370 Kg/kWh respectively and all obtained at the same load of 80%. Throughout the operating range the brake specific fuel consumption values of tobacco seed oil are higher than diesel. At 80% load there is 21.2% increase in brake specific fuel consumption with best injection pressure and timing and 40.2% increase in brake specific fuel consumption with standard setting by using tobacco seed oil when compared to diesel operation. This is due to lower heating value and poor spray characteristics leading to inefficient combustion of tobacco seed oil as compared to diesel. However there is 19% decrease in brake specific fuel consumption value of tobacco seed oil with best injection pressure and timing over standard setting of injection pressure and timing.

Fig.6.16. shows the variation of exhaust gas temperature with brake power. The exhaust gas temperature with tobacco seed oil is lower than
diesel operation. This is due to high heating value of diesel fuel. However
with tobacco seed oil at standard setting of injection pressure and timing
the exhaust gas temperatures are very close to diesel operation indicates
the ineffective combustion due to lower injection pressure and leads to
after burning.

The variation of brake thermal efficiency with brake power is
shown in Fig.6.17. The highest brake thermal efficiency is obtained at
around 4 kW with both diesel and tobacco seed oil. Throughout the
operating range the brake thermal efficiency is higher with diesel than
tobacco seed oil. The peak brake thermal efficiency with diesel, tobacco
seed oil at best setting and tobacco seed oil at standard setting of injection
pressure and timing are 28.05%, 24.92%, 21.54% respectively. The
decreased values of brake thermal efficiency with tobacco seed oil over
diesel indicates lower heating value and poor combustion due to high
viscosity of tobacco seed oil. However with best setting of fuel injection
pressure and timing there is 15.7% increase in brake thermal efficiency
over standard setting with tobacco seed oil. This improvement in brake
thermal efficiency can be attributed to improved combustion due to higher
injection pressure and advanced injection timing.
Fig. 6.15 BSFC Vs Brake Power of tobacco seed oil at standard and best injection pressure and timing.

Fig. 6.16 Exhaust Gas Temperature Vs Brake Power of tobacco seed oil at standard and best injection pressure and timing.
Fig.6.17 Brake Thermal Efficiency Vs Brake Power of tobacco seed oil at standard and best injection pressure and timing.

Fig.6.18 Unburnt Hydro Carbon Vs Brake Power of tobacco seed oil at standard and best injection pressure and timing.
Concentration of unburnt hydrocarbon emission variation with brake power is represented in Fig.6.18. Higher values of unburnt hydrocarbon with tobacco seed oil over diesel indicates improper combustion of tobacco seed oil due to more heterogeneous mixture formation resulting from higher viscosity and low volatility. It is observed that there is reduction in unburnt hydrocarbon with tobacco seed oil at best injection pressure and timing over standard setting. This is due to enhanced combustion with an increase of injection pressure. At the point of best brake thermal efficiency there is an increase of 30 ppm unburnt hydrocarbon with tobacco seed oil at standard setting and 18 ppm at best setting when compared to base line diesel operation.

Emission of carbon monoxide variation with brake power is indicated in Fig.6.19. The carbon monoxide emissions are very low in all the cases as expected in any of the compression ignition engines due to the presence of excess air. However there is an indication of slightly higher values of carbon monoxide with tobacco seed oil over diesel operation due to incomplete combustion.

The variation of Oxides of Nitrogen emissions with brake power is shown in Fig.6.20. There is higher Oxides of Nitrogen concentration in the exhaust of tobacco seed oil operation as compared to diesel. This is obvious due to the more availability of oxygen with tobacco seed oil as the fuel itself contains oxygen in its molecular structure. However with tobacco seed oil at best injection pressure and timing the Oxides of Nitrogen emissions are
Fig. 6.19 Carbon Monoxide Vs Brake Power of tobacco seed oil at standard and best injection pressure and timing.

Fig. 6.20 Oxides of Nitrogen Vs Brake Power of tobacco seed oil at standard and best injection pressure and timing.
higher over that of at standard setting due to prevailing of higher combustion temperatures. When the engine was operated on tobacco seed oil at best setting of injection pressure and timing at 80% load, Oxides of Nitrogen emissions were 425 ppm and that of base line diesel operation were 126 ppm. At standard setting of injection pressure and timing Oxides of Nitrogen were 299 ppm.

Fig.6.21. shows the variation of smoke opacity with brake power. The smoke intensity is higher with tobacco seed oil as compared to diesel due to higher viscosity of tobacco seed oil leading to thermal cracking. At 80% load when the engine operated on tobacco seed oil at best setting of injection pressure and timing smoke level is 46% lower compared to the tobacco seed oil operation at standard setting of injection pressure and timing.

Fig.6.22. explains pressure versus Crank Angle data pertaining to tobacco seed oil at standard and best injection pressure at 80% load. The effect of increase in fuel injection pressure from 205 bar to 260 bar and advancing the fuel injection timing from 23° BTDC to 26° BTDC which improves the peak pressure from 65.38 bar to 74.9 bar (both occurring at 369 °Crank Angle), the ignition delay decreases due to the fuel injection timing advance which improves initial phase of combustion and improves the thermal efficiency.
Fig. 6.21 Smoke Opacity Vs Brake Power of tobacco seed oil at standard and best injection pressure and timing.

Fig. 6.22 Pressure Vs Crank angle of tobacco seed oil at standard and best injection pressure and timing at 80% load.
Fig. 6.23. indicates the rate of pressure rise versus Crank Angle and when the injection pressure is increased the maximum rate of pressure rise increased from 3.77 bar/°Crank Angle to 4.85 bar/°Crank Angle, occurred at 360 °Crank Angle and 357 °Crank Angle respectively.

Fig. 6.24. shows the highest net heat release rate which increases from 35.9 Joules/°Crank Angle to 44.11 Joules/°Crank Angle indicating the improvement of net heat release rate with the increase in fuel injection pressure and advanced fuel injection timing.

The cumulative heat release is shown in Fig. 6.25. There is an improvement of highest cumulative heat release from 1.14 kJ at 509 °Crank Angle to 1.17 kJ at 423 °Crank Angle. For diesel the highest cumulative heat release value of 0.91 kJ at 391 °Crank Angle was observed.

The mass fraction burnt in % is shown in Fig. 6.26. The 5% mass fraction burnt for diesel, tobacco seed oil at standard and best settings are 354, 358 and 354 °Crank Angle respectively. The 90% mass fraction burnt for diesel, tobacco seed oil at standard and best settings are 375, 381 and 379 °Crank Angle respectively. The 4° and 2° Crank Angle advance in case of best setting for 5% and 90% mass fraction burnt (62) clearly indicates enhanced combustion.
Fig.6.23 Rate of Pressure Rise Vs Crank angle of tobacco seed oil at standard and best injection pressure and timing at 80% load.

Fig.6.24 Net Heat Release Vs Crank angle of tobacco seed oil at standard and best injection pressure and timing at 80% load.
Fig. 6.25 Cumulative Heat Release Vs Crank angle of tobacco seed oil at standard and best injection pressure and timing at 80% load.

Fig. 6.26 Mass Fraction Burnt Vs Crank angle of tobacco seed oil at standard and best injection pressure and timing at 80% load.
6.2.2 Pongamia oil

Fig. 6.27 presents the variation of brake specific fuel consumption of pongamia oil with respect to brake power. The usual trend of decrease in the brake specific fuel consumption up to 80% load and there after increase in brake specific fuel consumption is observed for pongamia oil and base line diesel operation. The lowest brake specific fuel consumption at 80% load for diesel, pongamia oil at standard setting of injection pressure and timing and pongamia oil at best injection pressure and timing are 0.305, 0.460, 0.390 Kg/kWh respectively. For all loading conditions the brake specific fuel consumption values of pongamia oil are higher than diesel. At 80% load there is 27.7% increase in brake specific fuel consumption with best injection pressure and timing and 50.7% increase in brake specific fuel consumption with standard setting with pongamia oil compared to diesel operation. The cause for improvement in brake specific fuel consumption of pongamia oil at best setting can be attributed to the enhanced fuel injection pressure and timing leading to better spray formation which results in better combustion.

The variation of exhaust gas temperature of pongamia oil with respect to brake power is plotted in Fig. 6.28. The exhaust gas temperature with pongamia oil at best brake thermal efficiency with best and standard fuel injection pressure and timing are 3% and 9% higher respectively than base line diesel operation. This indicates post burning of pongamia oil. However lower exhaust gas temperature with pongamia oil
Fig. 6.27 BSFC Vs Brake Power of pongamia oil at standard and best injection pressure and timing.

Fig. 6.28 Exhaust Gas Temperature Vs Brake Power of pongamia oil at standard and best injection pressure and timing.
at best setting over standard setting shows improved in cylinder combustion.

The trend of brake thermal efficiency with brake power of pongamia oil is shown in Fig.6.29. The highest brake thermal efficiency of 28.05% and 24.85% is obtained at around 4 kW with diesel and pongamia oil at best setting of fuel injection pressure and timing. The highest brake thermal efficiency of 21.25% is obtained at 3 kW with pongamia oil at standard setting of fuel injection pressure and timing. The decreased values of brake thermal efficiency with pongamia oil over diesel indicates lower calorific value, higher density and poor combustion due to high viscosity of pongamia oil. However with best setting of fuel injection pressure and timing there is 18% increase in brake thermal efficiency over standard setting with pongamia oil. This improvement in brake thermal efficiency can be credited to improved combustion due to higher injection pressure and advanced injection timing.

Fig.6.30 represents unburnt hydrocarbon emission with brake power of pongamia oil. At 4 kW of brake power the unburnt hydrocarbon emissions with pongamia oil are higher than base line diesel.

Carbon monoxide emission with brake power is indicated in Fig.6.31. The excess air present in diesel engines leads to low carbon monoxide emissions. The carbon monoxide emissions with pongamia oil over diesel operation are high due to poor combustion characteristics of pongamia oil.
Fig. 6.29 Brake Thermal Efficiency Vs Brake Power of pongamia oil at standard and best injection pressure and timing.

Fig. 6.30 Unburnt Hydro Carbon Vs Brake Power of pongamia oil at standard and best injection pressure and timing.
The Oxides of Nitrogen emissions with brake power are shown in Fig. 6.32. When the engine operated on base line diesel, pongamia oil at standard and best setting of injection pressure and timing Oxides of Nitrogen levels are 126, 121 and 504 ppm respectively. Though the molecular structure of pongamia oil contains oxygen, due to prevailing of lower temperatures at standard setting the Oxides of Nitrogen levels are almost similar to that of diesel. However with best setting operation with pongamia oil the Oxides of Nitrogen emissions are higher due to both oxygen availability and higher combustion temperature compared to base line diesel operation.

Fig. 6.33. shows the variation of smoke opacity with brake power. The smoke intensity is higher with pongamia oil as compared to diesel due to higher viscosity and higher carbon residue of pongamia oil. At 80% load when the engine operated on pongamia oil at best setting of injection pressure and timing smoke level is 53.2% lower compared to the pongamia oil operation at standard setting of injection pressure and timing.

The pressure versus Crank Angle data of pongamia oil at standard and best injection pressure at 80% load are presented in Figs. 6.34. The maximum pressures developed at respective Crank Angle by diesel, pongamia oil operation at standard and best injection pressure and timing are 72.72 (369 °Crank Angle), 66.17 (369 °Crank Angle) and 75.13 (369 °Crank Angle) bar respectively. The enhanced injection pressure and timing improves the brake thermal efficiency.
Fig.6.31 Carbon Monoxide Vs Brake Power of pongamia oil at standard and best injection pressure and timing.

Fig.6.32 Oxides of Nitrogen Vs Brake Power of pongamia oil at Standard and best injection pressure and timing.
Fig. 6.33 Smoke Opacity Vs Brake Power of pongamia oil at standard and best injection pressure and timing.

Fig. 6.34 Pressure Vs Crank angle of pongamia oil at standard and best injection pressure and timing at 80% load.
Fig 6.35. indicates the maximum rate of pressure rise versus Crank Angle of pongamia oil at standard best injection pressure and timing at 80% load. There is an improvement of 1.45 bar /°Crank Angle for pongamia oil operation at best injection pressure and timing.

Fig 6.36. exhibits the net heat release of pongamia oil at standard and best injection pressure and timing at 80% load. The value of highest net heat release at standard injection pressure and timing is 26.9 J/°Crank Angle which occurs at 366°Crank Angle and for best injection pressure and timing the value is 40.54 J/°Crank Angle which occurs at 357°Crank Angle. The 9°Crank Angle difference between standard and best setting indicates better combustion leading to higher brake thermal efficiency, improved brake specific fuel consumption and reduced smoke levels.
Fig. 6.35 Rate of Pressure Rise Vs Crank angle of pongamia oil at standard and best injection pressure and timing at 80% load.

Fig. 6.36 Net Heat Release Vs Crank angle of pongamia oil at standard and best injection pressure and timing at 80% load.
The cumulative heat release for pongamia oil is shown in Fig. 6.37. For standard setting of injection pressure and timing the highest cumulative heat release is 1.14 kJ at 503 °Crank Angle compared to best setting of fuel injection pressure and timing which is 1.1 kJ occurring at 398 °Crank Angle. The vast difference in °Crank Angle clearly indicates early heat release in case of best setting which is very much desirable for achieving better performance. The 90% mass fraction burnt for pongamia oil at standard and best settings with 2°Crank Angle difference also support the improvement in cumulative heat release for pongamia oil at best setting.

The mass fraction burnt in % for pongamia oil at standard and best setting at 80% load is explained in Fig. 6.38. The 5% mass fraction burnt for diesel, pongamia oil at standard and best settings are 354, 356 and 355°Crank Angle respectively. The 90% mass fraction burnt for diesel, pongamia oil at standard and best settings are 375, 383 and 381°Crank Angle respectively. The 1° and 2°Crank Angle advance in case of best setting for 5% and 90% mass fraction burnt clearly indicates enhanced combustion
Fig. 6.37 Cumulative Heat Release Vs Crank angle of pongamia oil at standard and best injection pressure and timing at 80% load.

Fig. 6.38 Mass Fraction Burnt Vs Crank angle of pongamia oil at standard and best injection pressure and timing at 80% load.
6.2.3 Mahua oil

Fig. 6.39. exhibits the variation of brake specific fuel consumption of mahua oil with respect to brake power. The commonly observed trend of decreased brake specific fuel consumption up to the point of best brake thermal efficiency and there after increased trend is observed in case of mahua oil and base line diesel operation. The brake specific fuel consumption at 1kW and 2kW is varying by 0.15% and 4% respectively compared to base line diesel operation. In case of tobacco seed oil and pongamia oil for the above condition the variation is 9% and 14% and 9% and 12% respectively. This indicates better performance of mahua oil at lower loads. The lowest brake specific fuel consumption at 80% load for diesel, mahua oil at standard setting of injection pressure and timing and mahua oil at best injection pressure and timing are 0.305, 0.387, 0.365 Kg/kWh respectively. At 80% load there is 19.5% increase in brake specific fuel consumption with best injection pressure and timing and 26.75% increase in brake specific fuel consumption with standard setting by using mahua oil when compared to diesel operation. The cause for improvement in brake specific fuel consumption of mahua oil with best setting is due to the enhanced fuel injection pressure leading to better spray formation and combustion.

The variation of exhaust gas temperature of mahua oil with respect to brake power is plotted in Fig. 6.40. The exhaust gas temperature with mahua oil with best fuel injection pressure and timing is lower than diesel operation up to 60% load and indicates better conversion of thermal energy and no post burning. This is due to the effective combustion arising by employing higher injection pressure for the mahua oil operation at best fuel injection pressure.
Fig. 6.39 BSFC Vs Brake Power of mahua oil at standard and best injection pressure and timing.

Fig. 6.40 Exhaust Gas Temperature Vs Brake Power of mahua oil at standard and best injection pressure and timing.
The brake thermal efficiency with brake power of mahua oil is shown in Fig.6.41. The highest brake thermal efficiency of 28.05%, 23.9%, 25.36% is obtained at around 4 kW with diesel and mahua oil at standard and best setting of fuel injection pressure and timing. At 1 kW and 2 kW power output the brake thermal efficiency is 7.88% and 3.89% higher than base line diesel for mahua oil operation at best setting of fuel injection pressure and timing. This has already reflected in brake specific fuel consumption and exhaust gas temperature also. The increased values of brake thermal efficiency up to 2 kW with mahua oil over diesel indicates that mahua oil performance at lower loads is encouraging and performing better than base line diesel operation even with low calorific value of mahua oil. However with best setting of fuel injection pressure and timing there is 6.1% increase in brake thermal efficiency over standard setting with mahua oil. This improvement in brake thermal efficiency is the effect of improved combustion due to higher injection pressure.

Fig.6.42 represents unburnt hydrocarbon emission variation with brake power of mahua oil. Higher values of unburnt hydrocarbon with mahua oil at standard setting over diesel indicates incomplete combustion of mahua oil due to poor spray characteristics because of the high viscosity. It is observed that there is reduction in unburnt hydrocarbon with mahua oil at best injection pressure and timing over standard setting due to higher fuel injection pressure leading to the formation of more homogeneous mixture. At best brake thermal efficiency operation base line diesel, best and standard setting of fuel injection pressure produced 19, 39 and 49 ppm of Unburnt hydrocarbon respectively.
Fig. 6.41 Brake Thermal Efficiency Vs Brake Power of mahua oil at standard and best injection pressure and timing.

Fig. 6.42 Unburnt Hydro Carbon Vs Brake Power of mahua oil at standard and best injection pressure and timing.
Emission of carbon monoxide variation with brake power is indicated in Fig. 6.43. Up to 60% load the carbon monoxide emissions are very low in all the cases as in any of the compression ignition engines due to excess air. However there is an indication of slightly higher values of carbon monoxide with mahua oil from 60% to full load over diesel operation.

The variation of oxides of nitrogen emissions with brake power is shown in Fig. 6.44. There are higher oxides of nitrogen concentration in the exhaust of mahua oil operation as compared to diesel. The brake thermal efficiency values at part load operation are higher than base line diesel operation and which confirm higher in cylinder temperature and leads to the formation of higher oxides of nitrogen. More over the mahua oil also contains in built oxygen in its fuel structure, which provides necessary oxygen for the increased formation of oxides of nitrogen. The oxides of nitrogen emissions of base line diesel, standard and best setting of injection pressure at best brake thermal efficiency occurrence of 80% load are 126, 271 and 315 ppm respectively.
Fig. 6.43 Carbon Monoxide Vs Brake Power of mahua oil at standard and best injection pressure and timing.

Fig. 6.44 Oxides of Nitrogen Vs Brake Power of mahua oil at standard and best injection pressure and timing.
Fig. 6.45. shows the variation of smoke opacity in HSU with brake power. The smoke intensity is higher with mahua oil as compared to diesel due to higher viscosity of mahua oil leading to formation of large size fuel particles compared to diesel fuel, which lead to incomplete combustion resulting in higher smoke emission.

The peak pressure values of mahua oil at standard and best injection timing at 80% load are shown in Figs. 6.46. The maximum pressure values for diesel, mahua oil at standard and best injection timing and pressure are 72.72, 58.87 and 75.53 bar which is occurring at 368, 374 and 370° Crank Angle. By simply increasing the fuel injection pressure from 205 bar to 260 bar the pressure increased from 58.87 to 75.53 bar which is higher than base line diesel value. This may be the reason for improved brake thermal efficiency.

Fig. 6.47. shows the rate of pressure rise for mahua oil at standard and best setting of injection pressure and timing. At standard setting the maximum rate of pressure rise is 2.58 bar/°Crank Angle which occurs at 364 °Crank Angle, at best setting 4.08 bar/°Crank Angle which occurs at 358 °Crank Angle. The increase in fuel injection pressure from 205 bar to 260 bar at 23° BTDC is causing 1.5 bar/°Crank Angle improvement in maximum rate of pressure rise with 6°Crank Angle difference. Hence mahua oil can be used at manufacturer's fuel injection timing by simply changing the fuel injection pressure from 205 bar to 260 bar.
Fig. 6.45 Smoke Opacity Vs Brake Power of mahua oil at standard and best injection pressure and timing.

Fig. 6.46 Pressure Vs Crank angle of mahua oil at standard and best injection pressure and timing at 80% load.
Fig 6.48 explains highest net heat release of mahua oil. At standard setting 36.64 J/°Crank Angle at 373°Crank Angle is observed and at best setting 38.85 J/°Crank Angle is observed at 359° Crank Angle. For diesel operation this value is 68.85 J/°Crank Angle which is occurring at 358°Crank Angle.

Fig 6.49 gives the highest cumulative heat release values for diesel, mahua oil at standard and best injection pressure and timing which are occurring at respective °Crank Angle indicated in the parenthesis are 0.91 (391 °Crank Angle), 1.05 (399 °Crank Angle) and 1.16 (406 °Crank Angle)kJ respectively.

The mass fraction burnt in % is shown in Fig 6.50. The °Crank Angle for 5% mass fraction burnt for diesel, mahua oil at standard and best setting are 354, 359 and 354°Crank Angle. The °Crank Angle for 90% mass fraction burnt for diesel, mahua oil at standard and best setting are 375, 383 and 381°Crank Angle. This clearly indicates the effect of increase in injection pressure and improved combustion parameters due to improved fuel spray.
Fig. 6.47 Rate of Pressure Rise Vs Crank angle of mahua oil at standard and best injection pressure and timing at 80% load.

Fig. 6.48 Net Heat Release Vs Crank angle of mahua oil at standard and best injection pressure and timing at 80% load.
Fig. 6.49 Cumulative Heat Release Vs Crank angle of mahua oil at standard and best injection pressure and timing at 80% load.

Fig. 6.50 Mass Fraction Burnt Vs Crank angle of mahua oil at standard and best injection pressure and timing at 80% load.
6.2.4 Comparison Of tobacco seed oil, pongamia oil and mahua oil

The variation of brake specific fuel consumption of tobacco seed oil, pongamia oil and mahua oil with respect to brake power is presented in Fig.6.51. For diesel, tobacco seed oil, pongamia oil and mahua oil operation the brake specific fuel consumption was decreased with increase of brake power up to 80% load and there after an increasing trend in brake specific fuel consumption is seen in all the cases. The lowest brake specific fuel consumption for diesel, tobacco seed oil, pongamia oil and mahua oil at respective best setting of injection pressure and timing are 0.305, 0.370, 0.390 and 0.365 Kg/kWh respectively and all obtained at the same load of 80%. Throughout the operating range the brake specific fuel consumption values of tobacco seed oil, pongamia oil and mahua oil are higher than base line diesel. At 80% load mahua oil recorded 1.64% and 8.19% decrease in brake specific fuel consumption when compared to, tobacco seed oil and pongamia oil respectively. This indicates that mahua oil is the best choice based on brake specific fuel consumption values. This is due to slightly higher heating value of mahua oil compared to other two oils as shown in Table.4.1.

Fig.6.52. shows the variation of exhaust gas temperature with brake power of tobacco seed oil, pongamia oil and mahua oil. The exhaust gas temperature of mahua oil up to 60% loading is lower than base line diesel operation and from 80% to full load it is higher than base line diesel operation. This is due to better combustion of mahua oil at lower loads indicating no post burning. However with tobacco seed oil the exhaust gas temperatures are lower than diesel operation.
Fig. 6.51 BSFC Vs Brake Power of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing.

Fig. 6.52 Exhaust Gas Temperature Vs Brake Power of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing.
The variation of brake thermal efficiency with brake power of tobacco seed oil, pongamia oil and mahua oil is shown in Fig.6.53. The highest brake thermal efficiency is obtained at around 4 kW with diesel, tobacco seed oil, pongamia oil and mahua oil. Throughout the operating range the brake thermal efficiency is higher with diesel than tobacco seed oil, pongamia oil and mahua oil. The peak brake thermal efficiency with diesel, tobacco seed oil, pongamia oil and mahua oil at respective best setting of injection pressure and timing are 28.05%, 24.92%, 24.85% and 25.36% respectively. The mahua oil brake thermal efficiency compared with tobacco seed oil and pongamia oil at 80% load are 1.76% and 2% higher respectively. This improvement can be attributed to the slightly higher heating value of mahua oil. Earlier it was observed that for mahua oil operation at 1 kW and 2 kW the brake thermal efficiency is 7.88% and 3.89% higher than base line diesel. This improvement in brake thermal efficiency can be attributed to improved combustion due to higher injection pressure. Based on brake thermal efficiency mahua oil can be adjudged as better fuel compared to tobacco seed oil and pongamia oil.

Concentration of unburnt hydrocarbon emission variation with brake power of tobacco seed oil, pongamia oil and mahua oil is represented in Fig.6.54. Higher values of unburnt hydrocarbon with tobacco seed oil, pongamia oil and mahua oil over diesel indicates improper combustion due to more heterogeneous mixture formation resulting from higher viscosity and low volatility characteristics of the vegetable oils. It is observed that lower unburnt hydrocarbon emissions with mahua oil operation at best injection pressure and timing over the other two oils. This is due to better combustion of mahua oil.
Fig. 6.53 Brake Thermal Efficiency Vs Brake Power of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing.

Fig. 6.54 Unburnt Hydro Carbon Vs Brake Power of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing.
Emission of carbon monoxide variation of tobacco seed oil, pongamia oil and mahua oil with brake power is indicated in Fig. 6.55. The carbon monoxide emissions for tobacco seed oil, pongamia oil and mahua oil are very low in all the cases as expected in any of the diesel engine operation due to excess air availability.

The variation of Oxides of Nitrogen emissions of tobacco seed oil, pongamia oil and mahua oil with brake power is shown in Fig. 6.56. There is higher Oxides of Nitrogen concentration in the exhaust of tobacco seed oil, pongamia oil and mahua oil operation as compared to diesel. This is obvious due to the more availability of oxygen in the straight vegetable oils as the vegetable oils contain oxygen in its basic composition. However with mahua oil at best injection pressure and timing the Oxides of Nitrogen emissions are lower compared to tobacco seed oil and pongamia oil.

Fig. 6.57. shows the variation of smoke in Hatridge Smoke Units of tobacco seed oil, pongamia oil and mahua oil with brake power. The smoke intensity is higher with tobacco seed oil, pongamia oil and mahua oil as compared to diesel due to higher viscosity of these straight vegetable oils leading to thermal cracking. Except at 80% and full load mahua oil smoke levels are lower compared to the tobacco seed oil and pongamia oil operation.

The pressure versus Crank Angle of tobacco seed oil, pongamia oil and mahua oil at 80% load are shown in Fig. 6.58. The peak pressure values of diesel tobacco seed oil, pongamia oil and mahua oil are 72.72 (368° Crank Angle), 74.9 (369° Crank Angle), 75.13 (370° Crank Angle) and 75.53 (370° Crank Angle) bar respectively. The reason for higher
Fig. 6.55 Carbon Monoxide Vs Brake Power of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing.

Fig. 6.56 Oxides of Nitrogen Vs Brake Power of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing.
Fig. 6.57 Smoke Opacity Vs Brake Power of tobacco seed oil, Pongamia oil and mahua oil at respective best injection pressure and timing.

Fig. 6.58 Pressure Vs Crank Angle of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing at 80% load.
brake thermal efficiency in the case of mahua oil can be attributed to the higher peak pressure.

Fig.6.59. shows the maximum rate of pressure rise values for tobacco seed oil, pongamia oil and mahua oil at 80% load. The values for diesel, tobacco seed oil, pongamia oil and mahua oil are 7.37 (358° Crank Angle), 4.85 (357° Crank Angle), 4.58 (357° Crank Angle) and 4.08 (358° Crank Angle) bar/°Crank Angle respectively.

Fig.6.60. explains highest net heat release of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing. The net heat release values of diesel, tobacco seed oil, pongamia oil and mahua oil are 68.85 (358° Crank Angle), 44.11 (358° Crank Angle), 40.54 (357° Crank Angle) and 38.85 (359° Crank Angle) J/°Crank Angle respectively.

Fig.6.61. gives the highest cumulative heat release values of diesel, tobacco seed oil, pongamia and mahua oil and the values are 0.91 (391° Crank Angle), 1.17 (423° Crank Angle), 1.1 (398° Crank Angle) and 1.16 (406° Crank Angle) kJ respectively.

Fig.6.62. explains the mass fraction burnt versus Crank Angle values of diesel, tobacco seed oil, pongamia oil and mahua oil. The °Crank Angle for 5% mass fraction burnt for diesel, tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing are 354, 354, 355 and 354°Crank Angle. The °Crank Angle for 90% mass fraction burnt for diesel, tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing are 375, 381, 381 and 381°Crank Angle.
Fig. 6.59 Rate of Pressure Rise Vs Crank angle of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing at 80% load.

Fig. 6.60 Net Heat Release Vs Crank angle of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing at 80% load.
Fig. 6.61 Cumulative Heat Release Vs Crank angle of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing at 80% load.

Fig. 6.62 Mass Fraction Burnt Vs Crank angle of tobacco seed oil, pongamia oil and mahua oil at respective best injection pressure and timing at 80% load.